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EVALUER LA DURABILITÉ DES SYSTEMES DE CULTURE DANS UN CONTEXTE DE TRANSITION RAPIDE D'UNE AGRICULTURE FAMILIALE S'INTEGRANT AU MARCHÉ

Cas de la monoculture mécanisée du maïs en Asie du Sud-est

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Merci, ຂອບໃຈຫຼາຍໆ

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Résumé

L'évaluation de la durabilité des systèmes de culture est un enjeu particulier dans des exploitations de subsistance proches du seuil de pauvreté, s'intensifiant et s'intégrant rapidement au marché. Le défi est double : prendre en compte à la fois les objectifs socio-économiques à court terme des agriculteurs (sortir de la pauvreté, sécurité alimentaire, revenus) tout en fournissant des indications sur la manière d'éviter que les transitions rapides conduisent à une agriculture conventionnellement intensifiée avec des dommages sociaux et environnementaux irréversibles. L'objectif de cette thèse est de contribuer aux travaux sur les méthodes d'évaluation intégrée et multicritère discutant de compromis localement les plus acceptables entre objectifs socio-économiques de court terme et objectifs de durabilité à long terme pour des systèmes de culture dans des fermes en transition.

La thèse développe une approche originale qui combine de nombreux outils méthodologiques en 3 étapes: 1) Identification de critères de durabilité localement pertinents en associant les perspectives des agriculteurs aux résultats d'un diagnostic agronomique adapté, 2) Diagnostic agro-environnemental pour quantifier les indicateurs de durabilité de différents types de système de culture pratiqués par les agriculteurs et quantification des marges de progrès pour améliorer la durabilité suivant les zones biophysiques auxquelles les agriculteurs accèdent, 3) Evaluation de la variabilité des marges de manœuvre pour augmenter la durabilité suivant le type de ferme et les objectifs des agriculteurs.

Le cas d'étude est le Nord-Laos. Des systèmes de culture de subsistance à base de riz pluvial se sont transformés en 20 ans en monoculture mécanisée de maïs hybride avec des risques accrus sur l'environnement. Dans ces systèmes de production qui combinent une production autoconsommée et une agriculture orientée vers le marché, l'étape 1 de cette thèse montre que les agriculteurs ont des préoccupations socio-économiques à court-terme (revenu, sécurité alimentaire) mais aussi des préoccupations à moyen et long-terme (transmission de leur ferme, risques liés aux herbicides, fertilité). Le diagnostic agronomique de l'étape 1 indique que l'échec de la mise en culture du maïs est le principal facteur à l'origine de faibles rendements et de la forte utilisation d'herbicide. L'étape 2 montre qu'un système alternatif avec une mise en culture réussie, pourrait doubler les performances de durabilité sur les critères suivants : utilisation des herbicides, productivité de la terre, sensibilité aux adventices et au stress hydrique et productivité du travail. Toutefois, l'alternative évaluée réduit les performances en matière d'efficacité de l'azote et d'érosion. L'étape 3 montre qu'augmenter la productivité du maïs ne permettra pas une sortie de la pauvreté des fermes les plus pauvres et les plus contraintes en capitaux (terres, main d'œuvre, trésorerie). L'amélioration de la mise en culture est le plus bénéfique pour la durabilité des fermes déjà les mieux dotées en capitaux car elle permet de réduire significativement leur utilisation d'herbicide et augmente leur revenu.

Abstract

Assessing the sustainability of cropping systems is particularly challenging when subsistence-oriented farms close to the poverty line are rapidly moving to intensive and market-integrated systems. The challenge for the assessment is twofold: to consider both the short-term socio-economic objectives of farmers (moving out of poverty, food security, income) while at the same time providing indications on how to avoid rapid transitions to lead to conventionally intensified agriculture with irreversible social and environmental damage. This thesis contributes to advancement in the field of integrated and multicriteria assessment methods of cropping systems in transitioning farms. We combine several methodological tools in 3 steps: 1) Identification of locally relevant sustainability criteria by combining farmers' perspectives with the results of an agronomic diagnosis. 2) Quantification of sustainability indicators of different cropping systems practiced by farmers and quantification of the potentials to improve sustainability according to the biophysical areas to which farmer have access. 3) Assessment of potentials to increase farm sustainability according to farm structure and farmer objectives.

We apply the approach to a case study of maize monocropping in northern Laos where mechanized hybrid maize monocropping has replaced extensive slash-and-burn upland rice in less than 20 years. Step 1 shows that farmers have short-term socio-economic concerns (income, food security) but also medium- and long-term sustainability concerns (farm transmissibility, risks relative to herbicide use, fertility). The agronomic diagnosis indicates that crop establishment failure is the main driver leading to low yields and high herbicide use. Step 2 shows that an alternative system with successful crop establishment could double the sustainability performance on the following criteria: herbicide, land productivity, weed and water stress susceptibility and work productivity. However, the alternative reduces performance in terms of nitrogen use efficiency and erosion. Step 3 shows that increasing maize productivity will not lift the poorest farms out of poverty. Improving crop establishment has the potential to improve significantly the sustainability of the already wealthiest farms. The consequence would be a significant reduction of herbicide use and improvement of farm income.

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Chapitre 1 : Introduction générale

1 Introduction

Le défi pour l'agriculture de demain est double : nourrir la planète tout en limitant les impacts négatifs sur les ressources naturelles (Tilman *et al.*, 2002). Pour l'agriculture familiale des pays les plus pauvres, des défis supplémentaires se posent : sortir de la pauvreté, être résilient aux aléas d'aujourd'hui et de demain dans un contexte de changement climatique ou de fluctuation des prix, améliorer la sécurité alimentaire et préserver les écosystèmes, support de leur capital productif à long-terme (Schindler *et al.*, 2015).

L'agriculture est encore un pilier du développement économique dans de nombreux pays et un tremplin pour la sortie de la pauvreté des ménages ruraux (Dixon *et al.*, 2001). Dans les années 1960, le modèle de la révolution verte d'intensification des systèmes de culture s'est basé sur le triptyque « semences, engrais, herbicides » pour augmenter la productivité d'agricultures de subsistance (Pingali, 2012). Aujourd'hui, une autre révolution est en marche intensifiant les systèmes de culture : l'intégration au marché et le développement d'une petite mécanisation de plus en plus accessible aux fermes de petites tailles.

Les moteurs de ces transformations sont multiples. A l'échelle des fermes, l'intensification des systèmes de culture permet d'augmenter le revenu des agriculteurs via une meilleure productivité du travail et de la terre, deux ressources se raréfiant simultanément ou non dans les pays émergents et en développement (Hebinck, 2018; Ojha *et al.*, 2017). Ce revenu agricole supplémentaire est essentiel pour des agriculteurs toujours au seuil de pauvreté luttant chaque jour pour accéder à une alimentation, un logement, des soins de santé ou à l'éducation pour leurs enfants. Toutefois, si cette intensification est mal maîtrisée, elle se fait au détriment de l'environnement et peut même être à l'origine de l'accroissement des inégalités et de l'endettement des agriculteurs (Hepp *et al.*, 2019; Nesheim *et al.*, 2014).

Dans ce contexte, l'intensification agricole s'accompagne souvent d'une simplification des systèmes de culture et une spécialisation des fermes : des systèmes diversifiés, extensifs et itinérants se fixent en monoculture pour produire une unique culture de rente. La

simplification des systèmes de culture entraîne des perturbations de l'écosystème (Hooper *et al.*, 2005; Altieri, 1999) compensées par toujours plus d'intrants ou de mécanisation (Altieri, 1999; Altieri *et al.*, 1983; Meynard *et al.*, 2013). Pour les agriculteurs amorçant tout juste cette transition, les systèmes de culture pluviaux s'intensifient sont encore loin d'atteindre les niveaux de productivité escomptés et les performances restent très variables suivant les capitaux auxquels accèdent les agriculteurs : foncier (qualité et quantité), finances (trésorerie), et main d'œuvre.

Une transformation profonde de l'agriculture familiale des pays émergents est donc nécessaire pour créer des systèmes alimentaires sains, équitables, résilients et durables. Bien qu'il soit réducteur d'opposer systématiquement environnement et développement économique, ces agricultures familiales en transition semblent logiquement faire face à des compromis entre le court et le long-terme (Lipton, 1997). Le long-terme, inhérent au concept de durabilité, semble peu souvent être une préoccupation pour ces agriculteurs au seuil de pauvreté dans ces contextes de transitions rapides tirées par le marché. Mais est-ce vraiment le cas ? Est-il possible de trouver des compromis de durabilité localement acceptables afin d'amorcer une transition plus durable des systèmes de culture ? Est-ce qu'une meilleure maîtrise des itinéraires techniques, réduisant les impacts environnementaux et augmentant les performances agronomiques, pourrait significativement augmenter la durabilité de ces fermes en transition ?

Cette thèse contribue aux recherches sur l'évaluation intégrée de la durabilité des systèmes de culture dans le cas spécifique d'agricultures en transition des pays en voie de développement. La monoculture du maïs au Nord-Laos est pris comme cas d'étude. Une démarche d'évaluation multicritère est développée et mise en œuvre pour atteindre deux objectifs : i) discuter de compromis de durabilité localement les plus acceptables, ii) quantifier les gains de durabilité (à l'échelle du système de culture et de la ferme) permis par une meilleure maîtrise des itinéraires techniques moto-mécanisés de la culture du maïs.

Dans un premier chapitre, nous présentons une synthèse des méthodes d'évaluation multicritère existantes et de leurs limites dans ce contexte particulier. Ce chapitre présente également les questions scientifiques, la problématique et les enjeux auxquels la thèse se propose de contribuer ainsi que les étapes méthodologiques mises en place pour y répondre. Trois chapitres présentent ensuite les différentes étapes de la démarche sous forme d'articles

scientifiques en anglais. Un dernier chapitre présente les sources d'incertitudes liées à la méthodologie et les fronts de recherche à investir pour les réduire. Des recommandations locales et les perspectives globales de l'étude sont également développées dans ce dernier chapitre.

2 Quelle évaluation de la durabilité pour une agriculture familiale s'intégrant au marché ?

2.1 Durabilité en agriculture : un cadre réflexif plus qu'un concept stabilisé

Le concept de développement durable a émergé lors de la Commission mondiale sur l'environnement et le développement en 1987 (Brundtland *et al.*, 1987). Cette commission définit que le développement durable doit satisfaire les besoins du présent sans compromettre la capacité des générations futures à satisfaire les leurs.

A partir de cette définition intergénérationnelle, plusieurs paradigmes économiques se sont développés au fil des années, opposant « durabilité faible » à « durabilité forte » (Neumayer, 2003). La durabilité faible priorise l'économie sur l'environnement en spécifiant que tout impact environnemental ou social peut être compensé si par ailleurs la dimension économique est améliorée. La durabilité forte au contraire, stipule que le capital naturel est non-substituable par le capital économique : il constitue un socle à préserver avant que tout développement économique durable puisse se réaliser. A mi-chemin entre ces deux visions, une autre approche concilie la protection de l'environnement, l'équité sociale et le développement économique en trois dimensions égales du développement durable.

Suivant les approches, la durabilité est représentée avec trois sphères se recoupant (économie, environnement, social), trois sphères concentriques par ordre d'importance ou encore comme une liste de propriétés systémiques : productivité, stabilité, fiabilité, résilience, adaptabilité, équité et autonomie (López-Ridaura *et al.*, 2002).

Face à ces nombreuses acceptions, il apparaît que la durabilité soit un cadre réflexif plutôt qu'un concept stabilisé défini clairement. Appliquer ce cadre réflexif à l'agriculture et à ses défis est pourtant pertinent. En premier lieu car l'agriculture est multidimensionnelle, elle est faite de compromis et doit répondre à différents enjeux pour l'avenir de la planète. De nombreux objectifs du développement durable (ODD) sont liés à l'agriculture (FAO, 2018) :

pas de pauvreté, zéro faim, lutte contre le changement climatique, vie aquatique et terrestre. Enfin, l'agriculture a des effets positifs et négatifs sur la durabilité qu'il convient de quantifier et de comprendre : elle peut être source d'emplois, de sécurité alimentaire, d'entretien des paysages mais aussi d'impacts environnementaux comme l'érosion ou la pollution des cours d'eau. Une agriculture durable répond aux besoins des générations actuelles et futures (Tilman *et al.*, 2002). Elle limite les impacts environnementaux, améliore la sécurité alimentaire, la résilience face aux aléas climatiques ou économiques et assure sa continuité sur le long-terme (Pretty, 2008). La durabilité d'une agriculture ne se caractérise pas par un ensemble de pratiques, mais par une trajectoire dans un contexte particulier. En effet, il n'existe pas de pratique agricole dont la durabilité serait immuable et assurée partout et pour tous, indépendamment du contexte ou du lieu (Schaller, 1993).

2.2 Les enjeux de l'évaluation de la durabilité

2.2.1 *Evaluer, pour quoi faire?*

Les finalités de l'évaluation de la durabilité sont multiples (Lairez *et al.*, 2016) : sensibiliser (ex : auto-évaluation de la ferme avec la méthode IDEA (Zahm *et al.*, 2019)), rendre compte d'une conformité réglementaire (ex : certification Haute Valeur Environnementale), fournir des connaissances (comparaison diachronique ou synchronique de systèmes), identifier les éléments à améliorer et faire des recommandations ou concevoir de nouveaux systèmes.

L'évaluation de la durabilité de l'agriculture est devenue un défi majeur pour la recherche et l'appui au développement des politiques agricoles (van Cauwenbergh *et al.*, 2007).

Nous nous positionnons dans cette thèse sur les deux dernières finalités de l'évaluation. C'est-à-dire de réaliser une évaluation pour i) diagnostiquer la durabilité des systèmes agricoles actuels et comprendre les facteurs bloquant ces systèmes agricoles dans des trajectoires non durables, ii) identifier de meilleures trajectoires, afin d'*in fine* appuyer le développement de politiques agricoles avec des connaissances scientifiques.

2.2.2 *Enjeux globaux : complexité de l'évaluation et rôle de la science*

L'évaluation de la durabilité est complexe, car elle est multifacette, subjective, difficile à quantifier et les multiples dimensions à évaluer sont parfois antagonistes :

- Il s'agit d'un cadre réflexif dépendant du contexte : ce qui sera durable pour un agriculteur à un moment et un endroit donné ne le sera pas forcément pour un autre.

- Il est rare qu'un système soit performant sur l'ensemble des dimensions de la durabilité, il y a souvent des compromis à réaliser (Kanter *et al.*, 2018). Répondre à la question « quel compromis est le plus acceptable pour plus de durabilité » relève parfois davantage d'un projet de société que d'une question scientifique lorsque les dimensions sont incomparables (par exemple risques d'érosion du sol *versus* utilisation d'herbicide, ou pénibilité du travail *versus* biodiversité).
- Le niveau de durabilité d'un système agricole ne peut se mesurer en tant que tel (López-Ridaura *et al.*, 2002) et il est très difficile de prévoir le niveau actuel de durabilité qui garantira une durabilité suffisante pour les générations futures.

La science a pourtant un rôle déterminant à jouer dans l'évaluation de la durabilité. Elle permet d'objectiver, autant que possible, un concept subjectif afin de limiter les idées préconçues. Cela requiert des méthodes mixtes de production de connaissances combinant des approches qualitatives et quantitatives (Gough *et al.*, 1998) mêlant les perspectives des agriculteurs à la connaissance scientifique. Ces approches sont pertinentes pour appréhender la durabilité dans toute sa complexité suivant plusieurs perspectives complémentaires.

2.2.3 Revue des méthodes d'évaluation existantes

De nombreux outils et méthodes d'évaluation ont été développés pour accompagner des transitions durables de l'agriculture. L'évaluation peut se réaliser à différentes échelles allant du système de culture au territoire. Les revues de la littérature suivantes synthétisent et classifient différents types de méthode d'évaluation : (Ness *et al.*, 2007; Bockstaller *et al.*, 2008; Gasparatos and Scolobig, 2012; Schindler *et al.*, 2015; Smith *et al.*, 2017; Deytieux *et al.*, 2016; Lairez *et al.*, 2016; Diaz-Balteiro *et al.*, 2017).

En résumé, les évaluations de la durabilité qui concernent notre finalité se catégorisent en trois grands types (Ness *et al.*, 2007): les indices composites (empreinte écologique, note globale de durabilité par exemple), les évaluations à l'échelle de cycle de vie de produits, et les évaluations intégrées.

L'évaluation intégrée est le type d'évaluation sur laquelle cette thèse se propose d'apporter des avancées méthodologiques. Elle requiert l'utilisation d'approches multicritères considérant l'ensemble des composantes constituant la durabilité (Deytieux *et al.*, 2016). Ce type d'évaluation se base sur des méthodes multi-attributs ou sur des méthodes d'optimisation sous contraintes (Affholder *et al.*, 2019).

Dans les approches multi-attributs, les indicateurs sont organisés en niveaux hiérarchiques représentés sous forme d'arbres (exemples : SAFA (Scialabba, 2014), MASC : (Sadok *et al.*, 2009)), SAFE (van Cauwenbergh *et al.*, 2007)). La durabilité y est décomposée en enjeux, dimensions/attributs, critères puis indicateurs élémentaires permettant la quantification. Les méthodes d'optimisation sous contraintes simulent la décision des agriculteurs sur le choix de leurs activités en vue de la maximisation d'un ou plusieurs objectifs liés à la durabilité. Ces méthodes permettent d'identifier les compromis entre différents objectifs de durabilité.

2.2.4 *Enjeux spécifiques de l'évaluation pour les agricultures en transition*

Les transitions rapides des systèmes agricoles des pays émergents complexifient davantage l'évaluation de la durabilité pour plusieurs raisons :

- *L'accès limité aux données*

A cause des transitions rapides, il y a un risque d'évaluer des systèmes qui n'existeront plus demain. L'évaluation doit donc être prospective, mais cela nécessite des données permettant, en premier lieu de comprendre les systèmes actuels pour réaliser une analyse prospective robuste.

Il s'agit d'aller au-delà de la simple comparaison des performances et impacts « système innovant durable vs. système actuel », et d'être en mesure de réaliser des extrapolations spatiales des résultats obtenus dans un champ et pour un agriculteur particulier : un système performant à un endroit donné le sera-t-il dans un autre milieu biophysique ? Le sera-t-il toujours une année sèche ou très humide ou si l'agriculteur adapte la technique ? Comme il n'est pas possible de multiplier à l'infini les situations évaluées au champ, il faut plutôt décrire en détail les processus biophysiques pour être en mesure d'extrapoler les résultats par la modélisation. Pour ce faire, certains indicateurs clefs sont à connaître sur les systèmes actuels et innovants : rendement, biomasse, flux et risques environnementaux, temps de travaux, etc.

Cependant, dans ces contextes d'agriculture en transition rapide, même pour les systèmes actuels, les données sont rares et peu fiables, car souvent uniquement basée sur les déclarations des agriculteurs (Lobell *et al.*, 2019). En comparaison aux contextes d'agriculture industrialisée, il n'existe pas nécessairement de cadastre pour les surfaces cultivées, ni de livres de comptabilité pour l'estimation des revenus des agriculteurs et les données précises sur le climat ou le sol sont moins facilement accessibles. Ce sont pourtant des données

indispensables à l'objectivation de la durabilité et à la compréhension des processus biophysiques clefs à l'origine des performances et des impacts des systèmes actuels.

- *Des enjeux d'évaluation à contextualiser*

Cet enjeu n'est pas nécessairement expliqué par le caractère rapide de la transition, mais plutôt lié au fait qu'il s'agisse d'agriculteurs pauvres encore très dépendants des processus biophysiques avec une forte variabilité des impacts et performances des systèmes qu'ils mettent en place.

La hiérarchie des enjeux de durabilité n'est pas la même dans ce contexte que pour les agricultures industrialisées pour lesquelles la plupart des méthodes d'évaluation ont été développées. Une attention particulière doit être portée à la contextualisation des enjeux de l'évaluation et l'identification des compromis localement acceptables entre les objectifs socio-économiques de court terme des agriculteurs (sortie de la pauvreté, sécurité alimentaire) et les impacts environnementaux de long terme. Il faut également pouvoir identifier les contraintes des fermes limitant la durabilité à long terme et imaginer des systèmes plus durables, mais adoptables au vu de ces contraintes et des objectifs des agriculteurs.

2.3 Objectifs scientifiques généraux de la thèse

Cette thèse contribue aux recherches sur l'évaluation intégrée de la durabilité des systèmes de culture dans le cas spécifique d'agricultures au seuil de pauvreté des pays en voie de développement ou émergents. L'objectif de la thèse est de contribuer à répondre aux enjeux globaux et spécifiques décrits précédemment :

- Objectiver la durabilité par la production d'indicateurs fiables dans un contexte de rareté des données
- Prendre en compte le contexte local dans l'évaluation en mêlant différentes perspectives complémentaires
- Identifier des compromis localement acceptables pour des agriculteurs au seuil de pauvreté
- Prendre en compte la variabilité des performances et des impacts des systèmes de culture dans l'évaluation

3 Application de l'évaluation à un cas d'étude : le maïs au Laos

3.1 La monoculture du maïs au Nord-Laos

Le cas d'étude du maïs hybride cultivé au Nord-Laos a été choisi pour son caractère emblématique de l'intensification rapide des systèmes de culture et de la spécialisation des fermes sur une culture de rente en Asie du Sud-Est.

La province de Xieng Khouang au Nord du Laos connaît des transformations agraires rapides depuis une dizaine d'années (Castella *et al.*, 2012; Castella and Nanthavong, 2014; Lienhard *et al.*, 2020). Dans les années 2000, les systèmes de culture itinérants de riz pluvial avec jachère et abatis-brulis se transforment en monoculture de maïs hybride fixée et moto-mécanisée (services de labour avec tracteurs et charrues). Le riz pluvial, essentiellement cultivé pour l'autoconsommation en complément du riz de bas-fond, a donc été remplacé par une culture de rente de maïs pour l'alimentation animale à l'export vers le Vietnam. Le maïs a d'abord été cultivé avec très peu d'intrants, profitant du stock initial de fertilité et du peu de adventices permis par les jachères longues. Depuis quelques années les herbicides sont de plus en plus utilisés (Bartlett, 2016; Shattuck, 2019) et des engrais minéraux sont apportés ponctuellement en faible quantité. Une autre transformation en cours est la mécanisation du semis pour certains agriculteurs pouvant y accéder.

Le bassin de Kham (Figure 1 et Figure 2) dans la province de Xieng Khouang a été pris comme cas particulièrement représentatif de l'intensification par le maïs dans une plaine propice à la mécanisation de l'agriculture. Le paysage est aujourd'hui couvert de maïs hybride, en dehors du compartiment irrigable en bordure des cours d'eau, qui reste le domaine privilégié pour la production de riz (Figure 3).



Figure 1: Vue aérienne du bassin de Kham dans la province de Xieng Khouang (zone plus claire au centre de la photo), une plaine propice à l'agriculture entourée de montagnes (source : google earth)

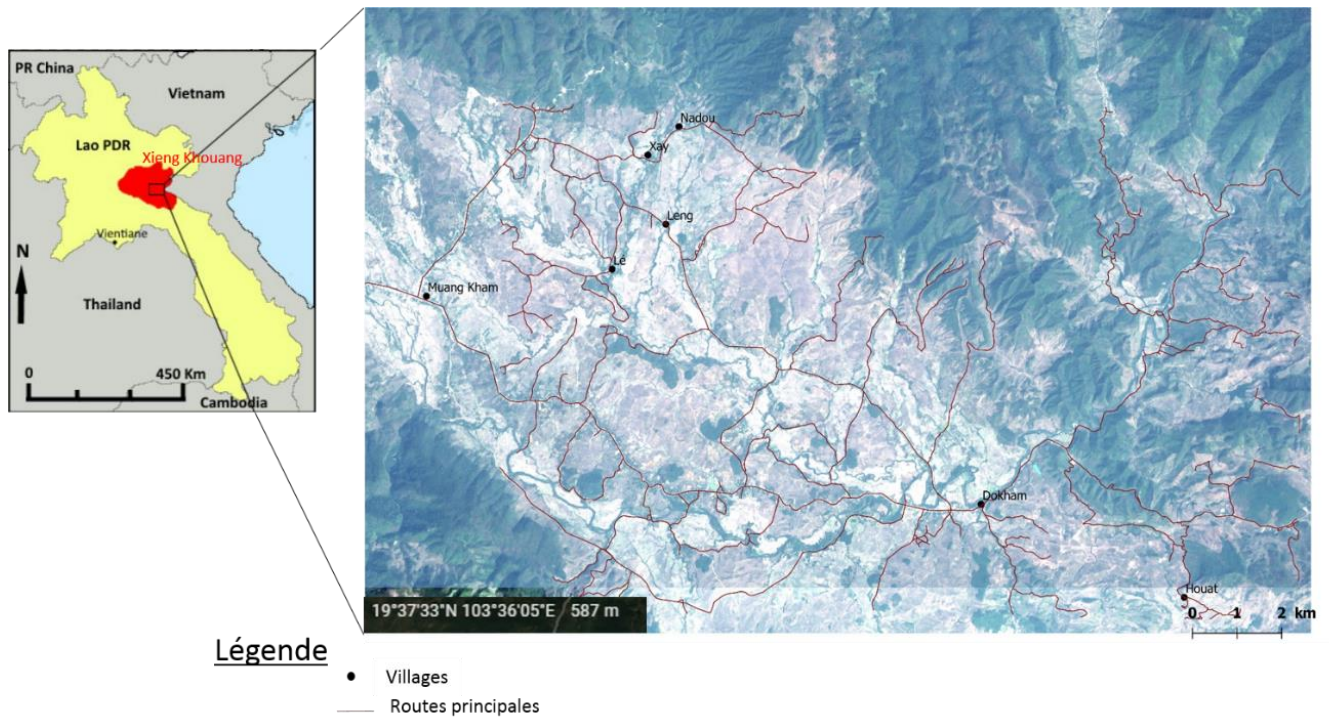


Figure 2: Carte localisant les villages étudiés dans le bassin de Kham dans la province de Xieng Khouang au Nord-Laos.



Figure 3: La plaine de maïs dans le bassin de Kham

3.2 Pourquoi évaluer la durabilité du maïs au Nord-Laos ?

L'évaluation de la durabilité de la culture du maïs est un cas d'étude intéressant, car les performances actuelles des systèmes à base de maïs ne semblent pas avoir atteint leur potentiel et sont très variables. De plus, les risques d'impacts environnementaux et sociaux semblent accrus depuis la transition : effets négatifs sur les paysages et les moyens de subsistance locaux (Ornetsmüller *et al.*, 2018; Viau *et al.*, 2009; Kallio *et al.*, 2019), érosion (Dupin *et al.*, 2009), risques sur la santé des agriculteurs et des travailleurs agricoles à cause des herbicides (Shattuck, 2019), et risques sur l'endettement des ménages ruraux (Hepp *et al.*, 2019).

Les points précédents (faibles rendements, impacts environnementaux et sociaux) poussent les acteurs du développement rural à appeler à l'abandon du maïs pour le remplacer par une autre culture. La culture du maïs est pointée du doigt pour ne plus être une option viable pour les agriculteurs. Elle est qualifiée d'agriculture minière, avec des effets négatifs sur l'environnement, notamment une érosion accrue des sols, une perte de fertilité des sols et une forte pollution chimique causée par les herbicides (ACIAR, 2014 ; Bartlett, 2016 ; Julien *et al.*, 2008).

Mais aucune évaluation quantitative intégrée de la durabilité des systèmes de culture maïs n'a été menée à ce jour au Laos. Les causes à l'origine de la variabilité des performances et des impacts n'ont pas été étudiées, de même que la variabilité des marges de manœuvre des fermes pour augmenter leur durabilité. Malgré tous les côtés négatifs du maïs décrits précédemment, il a été un tremplin pour la sortie de l'extrême pauvreté pour beaucoup de ménages ruraux (Douangsavanh and Bouahom, 2006; Vongvisouk *et al.*, 2016). Ses débouchés sont assurés sur un marché en expansion grâce à une forte demande régionale en aliments pour le bétail. Enfin, la zone d'étude semble posséder des avantages comparatifs à produire du maïs par rapport au reste du Nord-Laos très montagneux. Dans cette zone, les pentes restent relativement modérées (voir photo Figure 3).

Ce cas d'étude est donc très intéressant, car de nombreuses dimensions doivent être considérées pour objectiver l'évaluation de la durabilité et imaginer les trajectoires des fermes de demain. La question de l'abandon du maïs n'est pas si évidente que cela. Pour appuyer le développement de politiques agricoles accompagnant des transitions durables des systèmes agricoles, il convient de répondre au préalable aux questions suivantes :

- © Question 1 : Quelle est la durabilité actuelle du maïs dans ces fermes en transition rapide ? Quels sont les déterminants de la variabilité ?

Hypothèse 1 : Le système actuel a une faible durabilité à cause de faibles performances et de forts impacts sur l'environnement.

Hypothèse 1' : Mais il y a une forte variabilité de durabilité à cause de milieux biophysiques, de pratiques et de fermes contrastés.

- © Question 2 : Quels sont les compromis localement les plus acceptables entre objectifs économiques de court-terme et objectifs de durabilité à long-terme ?

Hypothèse 2 : Les agriculteurs ont en priorité des objectifs socio-économiques, car ils sont au seuil de pauvreté.

Hypothèse 2' : Une évaluation intégrée, multicritère et contextualisée permet d'identifier ces compromis locaux et de les quantifier pour accompagner la transition vers des systèmes plus durables.

- © Question 3 : Quelles sont les perspectives de transition vers des systèmes de culture à moindres impacts sur l'environnement et avec de meilleures performances ?

Hypothèse 3 : Augmenter le rendement et diminuer les impacts environnementaux permettrait d'augmenter significativement la durabilité des systèmes de culture, mais aussi des fermes.

4 Démarche méthodologique

La thèse met en œuvre une démarche d'évaluation intégrée et multicritère. Une approche méthodologique originale est développée combinant plusieurs outils/méthodes, pour mieux considérer le contexte local et les perspectives des agriculteurs, la diversité des systèmes de culture et des fermes dans les évaluations multicritères.

4.1 Vision de la durabilité, objectif et périmètre de l'évaluation retenus

La vision de la durabilité développée dans cette thèse est celle faite de compromis, à mi-chemin entre la durabilité forte et la durabilité faible, représentée dans ses multiples dimensions avec plusieurs critères.

L'évaluation se centre sur le système de culture, mais elle est contextualisée à l'échelle de l'exploitation. Les échelles supérieures à la ferme (village, territoire, pays, atmosphère) ne sont pas prises en compte, mais uniquement abordées dans les différentes discussions au fil des chapitres.

Par cette thèse, nous argumentons qu'il est primordial d'évaluer précisément les systèmes existants avant d'élaborer une analyse ambitieuse de scénarios en rupture dits « agroécologiques ». Dans cette étude, la priorité de l'évaluation est donc mise sur les systèmes actuels posant un problème de durabilité. Ces systèmes de culture sont bien trop souvent méconnus, mais pourtant souvent mis de côté par les acteurs du développement. Dans le cadre limité d'une thèse et face aux enjeux méthodologiques déjà conséquents décrits précédemment, les scénarios alternatifs en rupture dits « agroécologiques », ou « d'intensification écologique » n'ont donc pas été évalués.

L'objectif principal donné à cette évaluation intégrée est de comprendre la variabilité i) des performances et impacts des systèmes actuels et ii) des marges de manœuvre pour plus de durabilité.

4.2 Etapes méthodologiques

La première étape est l'identification de critères de durabilité (chapitre 1) qui serviront de base à l'évaluation au niveau du système de culture (chapitre 2) et à l'évaluation à l'échelle des fermes (chapitre 3) (Figure 4).

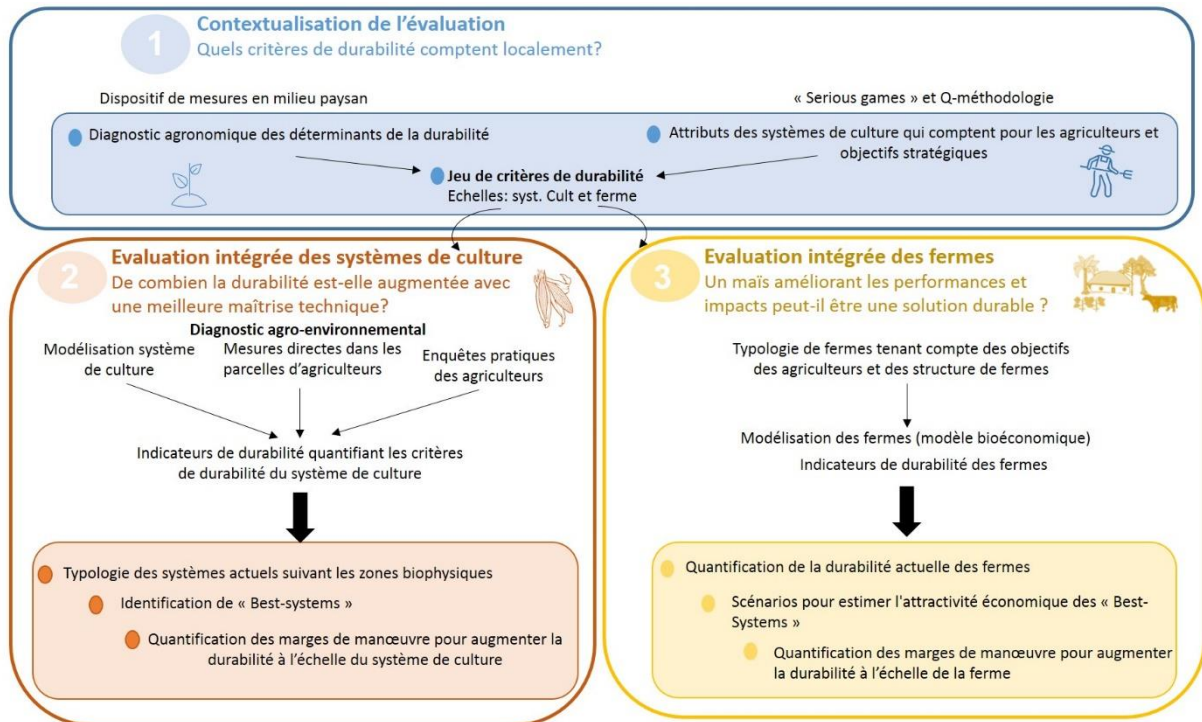


Figure 4: Les étapes méthodologiques de l'évaluation intégrée de la durabilité, organisées en 3 parties. Les cadres bleu, orange et jaune représentent les résultats de chaque étape.

La première étape réalise un diagnostic des enjeux clés à considérer pour l'évaluation de la durabilité dans une petite région agricole dans un contexte où très peu de données sont disponibles sur les systèmes actuels pour quantifier précisément leurs performances et leurs impacts. Elle mobilise une combinaison originale de méthodologies : jeux sérieux, Q-méthodologie, diagnostic agronomique adapté. Cette étape aboutit à un jeu de critères de durabilité aux échelles du système de culture et de la ferme, les critères étant définis comme des enjeux non directement quantifiables décrivant la durabilité d'un système agricole.

Dans l'étape 2, le jeu de critères à l'échelle du système de culture est utilisé comme cadre pour l'évaluation quantifiée avec des indicateurs. Un diagnostic agro-environnemental est développé et appliqué. Les indicateurs utilisent des données de sources variées : modélisation, enquêtes sur les pratiques des agriculteurs ainsi que des mesures directes. Cette étape tient compte de la variabilité des systèmes de culture et des performances et impacts.

A partir du diagnostic de l'étape 1 identifiant les facteurs de risque sur la durabilité, ce chapitre quantifie les gains d'amélioration de la durabilité permis par un prototype de système de culture limitant les impacts sur l'environnement et augmentant le rendement.

Dans l'étape 3, l'évaluation réalisée précédemment à l'échelle du système de culture est contextualisée au niveau d'exploitations contrastées par leurs structures et les objectifs des agriculteurs. Un modèle de ferme est créé pour évaluer les critères de durabilité à l'échelle de la ferme identifiés dans l'étape 1. Le prototype de système de culture de l'étape 2 est évalué en comparaison aux systèmes actuels et à la lumière des compromis ou synergies qu'ils engendrent dans les objectifs des agriculteurs et suivant les types de ferme.

Chapitre 2 : Quels critères de durabilité comptent localement ?

Ce chapitre présente la première étape de la démarche de diagnostic et d'identification de critères de durabilité, avant l'évaluation à proprement parler (l'évaluation sera l'objet des chapitres 3 et 4 suivants).

Il s'agit d'un article publié intitulé :

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Cette étape a les objectifs suivants :

- 1) Identifier les objectifs stratégiques des agriculteurs et comprendre leurs priorités, pour l'allocation des ressources au niveau de l'exploitation et la gestion tactique des cultures au niveau de la parcelle, par le biais de jeux sérieux et de la Q-méthodologie.
- 2) Identifier les déterminants et la variabilité de la durabilité du maïs par un diagnostic agronomique adapté.
- 3) Combiner les perspectives des agriculteurs et le diagnostic agronomique pour aboutir à un jeu de critères de durabilité, qui servira de base à l'évaluation intégrée des chapitres 3 et 4.

Les références et les annexes de l'article sont données à la fin du manuscrit.

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

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Abstract

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

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

Combining the perspectives of scientists and farmers led to the following set of locally-relevant criteria: i) at farm level: farm income, diversity of activities, farmer autonomy, farmer health, workload peaks, soil fertility transfer between agroecological zones in the landscape, rice and forage

self-sufficiency; ii) at field level: resource use efficiency, soil fertility, erosion and herbicide risks, susceptibility to pests, weeds and climate variability, biodiversity, land productivity, economic performance, labour productivity and work drudgery. Our approach helped to identify key relevant sustainability criteria and could be useful for designing alternatives to current maize-based cropping systems, and contributed to informing priority-setting for institutional development and agricultural policies in the region.

Keywords: Sustainability, Multi-criteria assessment, Classification and regression tree, Serious games, Maize yield gap, Laos.

1 Introduction

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

The sustainability concept is multidimensional and embodies ecological, economic and social dimensions (Hansen, 1996; Binder *et al.*, 2010). Analysing farming system sustainability in South-East Asia along these dimensions is crucial for taking up the challenges ahead for these farming systems, and for identifying their strengths and weaknesses. In developing countries sustainable agriculture embodies natural resource and ecosystem preservation, enhances resiliency to change and is the driver for improving food security and poverty reduction (Schindler *et al.*, 2015; Schader *et al.*, 2014). Poor smallholder farmers are expected to face trade-offs between short-term socio-economic objectives (e.g. income, food security) and long-term environmental objectives (e.g. soil fertility, water pollution by pesticides) (Shiferaw and Holden, 1998; Lipton, 1997). This calls for an integrated assessment of farming systems that quantifies the trade-offs between socio-economic and

environmental dimensions across a set of criteria, to explore the sustainability of agricultural changes (Ness *et al.*, 2007). By “criteria”, we mean the issues, themes, principles, goals, “abstract indicators”, or attributes describing the sustainability of agricultural systems (different uses of terminology are described in (Reed *et al.*, 2006; Binder *et al.*, 2010; Niemeijer and de Groot, 2008; de Olde *et al.*, 2017; van Cauwenbergh *et al.*, 2007). Criteria are not directly measurable, but they link sustainability dimensions to quantifiable indicators.

Multi-criteria tools are used to compare alternatives (e.g. different cropping or farming systems) against a set of criteria for decision-support (Boggia and Cortina, 2010; Wolfslehner *et al.*, 2012; Sadok *et al.*, 2008). Multi-criteria sustainability assessment is a useful approach when there are multiple, non-commensurate, and possibly conflicting criteria (Alrøe *et al.*, 2016). Numerous systemic and generic multi-criteria tools have been developed to assess farming system sustainability (see, for example, some indicator-based tools at farm level: 4Agro (Bertocchi *et al.*, 2016), IDEA (Zahm *et al.*, 2019), APOIA-NovoRural (Stachetti Rodrigues *et al.*, 2010), MOTIFS (Meul *et al.*, 2008), SAFE (van Cauwenbergh *et al.*, 2007), RISE (Häni *et al.*, 2003)). Most of the existing approaches assess farming systems against a set of criteria meant to be universal. As such, generic tools often contain preconceived ideas of sustainability (Bosshard, 2000) and usually overlook the contextual prioritization emphasized in local sustainability assessments (Barbier and López-Ridaura, 2010; Gasparatos, 2010; Gasparatos *et al.*, 2008). Sustainability is a matter of perspective and relevant criteria often depend on the local context (Zhen and Routray, 2003; Reed *et al.*, 2006; Bond *et al.*, 2011; Lairez *et al.*, 2016; Lele and Norgaard, 1996). For example, in a case study of Danish maize value chains for German biogas, Gasso *et al.* (2015) compared key sustainability criteria identified by stakeholders with criteria identified in generic frameworks. They showed that the generic frameworks covered context-specific environmental issues, but not context-specific socio-economic issues. Other sustainability assessment methods overcome this weak point by considering farmer and/or stakeholder perspectives to select evaluation criteria (e.g. Roy *et al.*, 2013; Coteur *et al.*, 2016; Coteur *et al.*, 2018; López-Ridaura *et al.*, 2002; Ssebunya *et al.*, 2016; Yegbemey *et al.*, 2014; Sydorovych and Wossink, 2008). Farmers are the key decision-makers, so their perspective is essential. However, data collected from interviews alone are often inadequate for quantifying and understanding sustainability issues (Fraser *et al.*, 2006). Moreover, the span of a farmer’s perspective can be incomplete in times of rapid change (Klapwijk *et al.*, 2014).

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

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

The objective of our study was to identify relevant criteria for a sustainability assessment of farming systems in northern Laos, with specific emphasis on combining farmer and scientist perspectives and documenting how the criteria were chosen. The set of criteria identified would be the first step for then defining, in a later study, some specific indicators to be quantified for analysing the conditions under which maize cultivation can be sustainable for different farm types in the region. The specific objectives of this study were to (i) identify farmers’ objectives and to understand their priorities and perceptions with regard to sustainability, for farm-level strategic resource allocation and plot-level

tactical crop management, by way of serious games and Q-methodology, (ii) identify the determinants and criteria of maize cropping system sustainability through a plot-level scientific agronomic diagnosis, and (iii) aggregate farmers' perspectives and insights from the agronomic diagnosis into a set of sustainability criteria that could inform multi-criteria sustainability assessment. The region of Xieng Khouang province in northern Laos was chosen as a typical case study of the market integration of farming systems.

2 Methods

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

2.1 Overview of the method

To inform the selection of locally relevant and scientifically sound criteria for sustainability assessment, we combined different approaches and methods. Serious games were used to identify farmers' objectives (see section 2.3.), Q-methodology was applied to better understand farmers' perceptions of soil fertility (see section 2.3.) and an agronomic diagnosis was used to identify factors determining the agronomic and environmental performance of crop management (see section 2.4.) (Figure 5). At the end of each step described below, i.e. serious games, Q-methodology and agronomic diagnosis, outputs were summarized into lists of criteria. Eventually, these lists were aggregated into a final list of sustainability criteria.

We carried out a card game in four villages (Lé, Xay, Leng and Dokham) and a group game in three villages (Lé, Xay and Leng). Q-methodology was implemented in four villages that captured farm and soil type variability (Lé, Leng, Nadou and Xay). Field monitoring for the agronomic diagnosis was set up in three villages (Xay, Nadou and Leng) covering an area of 7 km² (Appendix 1). The villages of Lé, Leng and Dokham were selected because an exhaustive agricultural census was available describing all farm households using basic variables (cropped areas, head of cattle and number of people per family). The villages of Xay and Nadou had soils with a high sand content and were added to increase the representativeness of soil type variability.

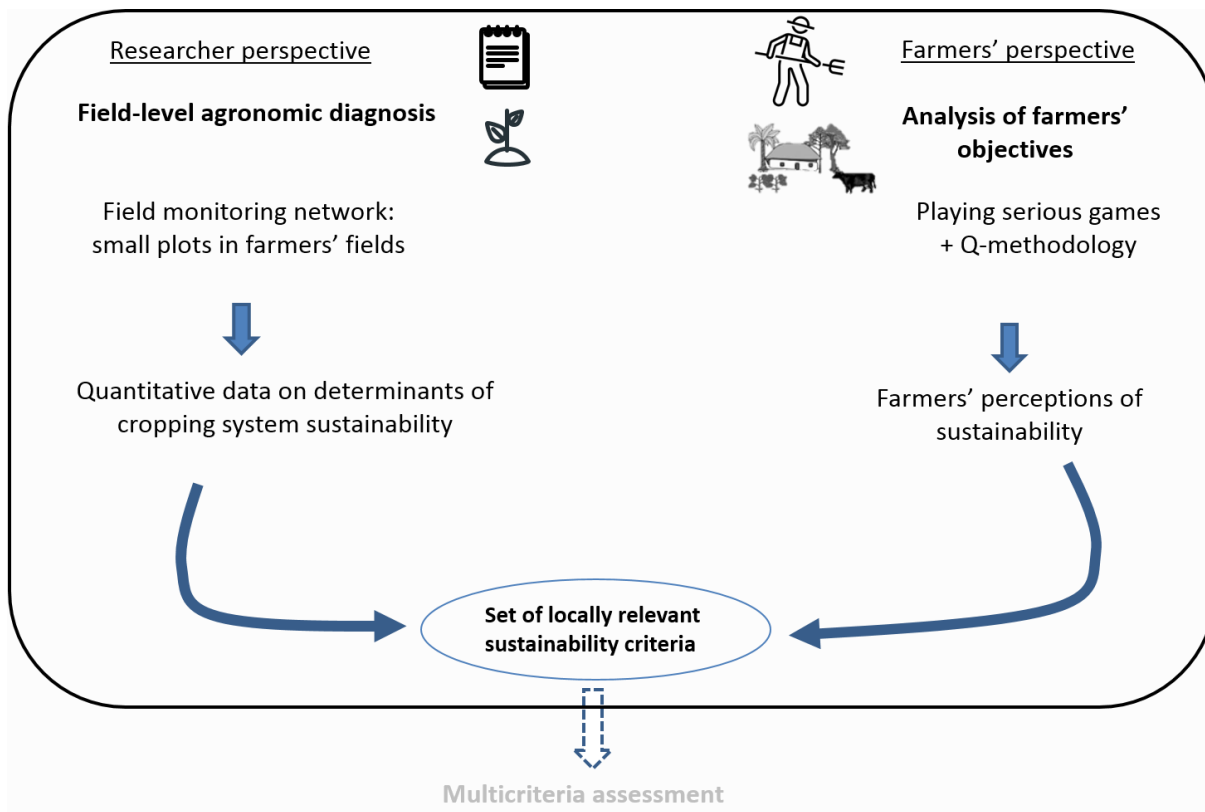


Figure 5: General approach of this study to identify complementary perspectives and determine a set of locally relevant sustainability criteria

2.2 Site description

We selected the Kham district in Xieng Khouang province located in northern Laos, close to the Vietnamese border (19°38'N, 103°33'E; 605 m above sea level) (Appendix 1) as a typical case of the market integration of farming systems with the commercialisation of hybrid maize. Over the past two decades, farmers have switched from extensive manually cultivated upland rice systems to cash crop systems with hybrid maize cultivation, combined with the use of moto-mechanization, herbicides and mineral fertilizers. This rapid switch to maize cultivation was favoured by the increase in maize prices and in the demand for maize from the thriving livestock feed industry in Vietnam in the 2000s. Today, rural development stakeholders in northern Laos commonly believe that maize cultivation is not sustainable and refer to it as 'resource-mining' agriculture with a negative impact on the environment, i.e. leading to increased soil erosion, loss of soil fertility and chemical pollution (Bartlett, 2016; ACIAR, 2014; Julien *et al.*, 2008). In the peer-reviewed literature for Laos, maize cultivation was found to increase production costs (Luangduangsitthideth *et al.*, 2018) and soil erosion (Dupin *et al.*, 2009). In Thailand, Bruun *et al.* (2017) found that maize cultivation had an impact on soil quality. Other studies, analysing farmer perceptions and practices in Laos and the subregion, showed that maize might increase environmental degradation (Kallio *et al.*, 2019;

Southavilay *et al.*, 2012a; Tuan *et al.*, 2014; Epper *et al.*, 2020). There is nevertheless limited empirical evidence to support claims of environmental degradation (Lestrelin, 2010).

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

2.3 Farmer perspective: serious games and Q-methodology

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

Individual card game to determine farmers' objectives

The aim of the individual card game, designed by the authors, was to reveal farmers' main objectives at farm level with a five-year perspective. Following the approach of Berbel and Rodriguez-Ocaña (1998), we related farmers' objectives to "values" that guide action or change. Values are defined as "permanent property of the individuals, less liable to change with time and circumstances" (Berbel and Rodriguez-Ocana, 1998). Values fall into four categories (Gasson, 1973): 1) *Instrumental values*,

e.g. maximizing income, saving income or expanding business. (2) *Social values*, e.g. belonging to a farming community, maintaining traditions, working with the family, respecting the village committee decisions, or doing what others do. (3) *Expressive values*, e.g. gaining self-respect, meeting a challenge. (4) *Intrinsic values*, e.g. enjoying working tasks, preferring healthy practices, valuing hard work, independence and freedom.

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

The game was composed of three sets of cards: "activity cards" representing farming activities, such as paddy rice, maize, cattle or off-farm job; "asset cards" representing assets, such as a motorbike or a sowing machine, and "bonus cards" representing extra resources, such as a labour workforce, land and money (Figure 6A). In a first step, the farmers were invited to discover and understand the cards. Then, each farmer was asked to tell the story of their farm and to explain the main choices they had had to make since they had become the head of the household. During the storytelling, the interviewer asked questions to elicit the reasons for the farmers' decisions and illustrated the changes by adding or removing activity and asset cards. The farmer was invited to validate or modify the deck to get accustomed to the use of the cards. The card combination at the end of the game represented the current farm situation (see example in Figure 6B). In a second phase, the farmer was invited to expose and explain their future five-year perspective with cards. Then, the interviewer substituted some activities by others to provoke the farmer's reaction. If the farmer rejected the proposed additional changes due to land, money or labour constraints, the interviewer displayed the corresponding bonus cards. Bonus cards were useful to avoid finishing the game with only a list of farmers' constraints rather than farmers' objectives. In a final step, the interviewer reformulated farmer choices and reactions until a list of objectives corresponding to the Gasson (1973) classification of values was found. The list was then shown to the farmer, who validated it and the interviewer asked the farmer to choose the three most important objectives. The results per objective were gathered for the four villages. The researchers then selected objectives as relevant criteria when more than 7% of the farmers selected the objective (i.e. two farmers out of the 30 interviewed).

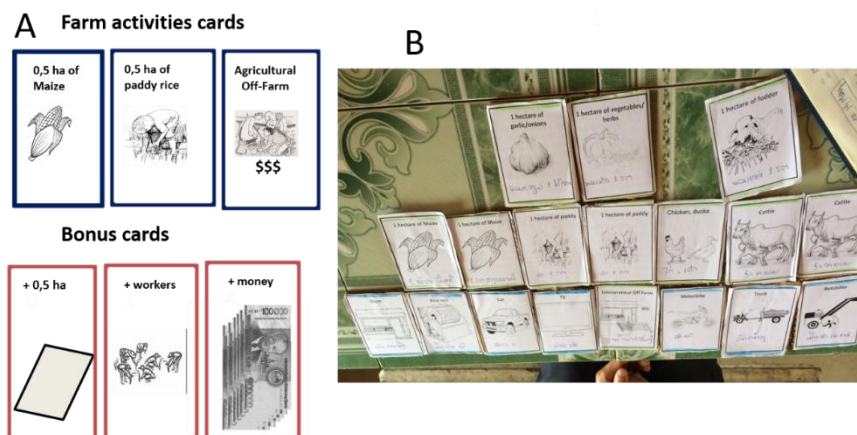


Figure 6: Examples of cards used in the individual card game (A) and picture of a deck obtained representing current farmers' activities and assets (B)

Group game on important crop attributes

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

fourth step was a discussion to identify farmers' criteria underlying their questions. For further details on the TAKIT methodology, the reader can refer to Ornetsmüller *et al.* (2018). Eventually, questions were grouped per village and an aggregated score was given to the questions by summing the scores given by farmers. The researchers selected questions with a score above one and aggregated them into a relevant list of criteria.

Soil fertility perception: Q-methodology

Q-methodology was not directly used to identify criteria, but rather as a complementary method to deepen our understanding of the farmer discourses used to select criteria during the group game and the individual card game. The group game revealed that farmers were concerned with soil fertility when deciding which crop to grow (See section 3.1.). We used a Q-methodology design (Brown, 1993) to study farmers' subjective perspectives when dealing with soil fertility by confronting them with a *Q-set*, i.e. a sample of 47 statements representing contrasting narratives on soil fertility (Appendix 2). Statements were selected to maximize the diversity of opinions about soil fertility based on narratives the researchers heard during the three years of the study. We sampled 19 farmers in four villages (seven in Leng, five in Lé, four in Xay and three in Nadou). The sample maximized the diversity of soil types and degree of intensification in maize cropping systems. The Q-methodology was carried out individually with each farmer. Statements were written on cards in the Lao language and the interviewer first read all the cards to allow the farmer to ask questions for clarification. The farmers were first asked to divide the statements into three piles during the reading, i.e. statements they (i) agreed with, ii) disagreed with and iii) were neutral, doubtful or undecided about. The farmers were then asked to read the 47 cards and place them on the floor following a design that mimicked a normal distribution (Appendix 3). The design had to be filled incrementally from left with cards they mostly disagreed with (score of -5) to right with cards they mostly agreed with (score of +5).

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

2.4 Researcher perspective: agronomic diagnosis

Field monitoring network

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

At the end of field monitoring, a soil typology was established with hierarchical clustering (R software, 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, 1998), followed by hierarchical clustering. The variables used to cluster the cropping systems were soil type, slope, land preparation type, sowing tool and weed management.

Table 1 shows the monitored variables. Due to losses at harvest, 99 plots (out of 111) had observations for all the variables monitored: weed cover, pests, nutrient deficiency, yield components, crop management, soil analysis and weather data.

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		

Analysis of variability in agronomic and environmental performance at plot level

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

The relative yield gap, water stress, nitrogen balance (N balance), nutrient deficiency, weed cover and pest damage score were considered as variables related to agronomic performance. The PYE model was used to simulate the potential (Y₀) and water-limited (Y_w) yields of the 111 monitored plots that informed the relative yield gap calculation. Y₀ is the yield achieved when water and nutrient supplies exceed crop requirements and biotic stresses are absent. Factors determining potential yield are incoming solar radiation, temperature, atmospheric [CO₂], crop genetic characteristics and canopy light interception ability (van Ittersum *et al.*, 2013; van Ittersum and Rabbinge, 1997). Y_w is similar to Y₀, but with actual water supply that may limit crop growth (van

Ittersum *et al.*, 2013). gives more details on the calculation of the variables related to agronomic performance. The herbicide treatment index and erosion risks approximated with the length of the bare-soil period from ploughing to sowing, N balance and fertilizer doses, were considered as variables related to environmental performance (Table 2).

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

Table 2: Variables used to explain plot-level agronomic and environmental performance (with units in brackets).

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

	Calculation	Type of indicator computation
Agronomic performance		
Relative yield gap (%)	$(Yw - Ya)/Yw * 100$	Direct measurement; PYE model simulation
Water stress (-)	$LAIw/LAIO$ Yw/YO	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>	$Nmin + Nfert - Nuptake$ Where -Nmin= $(30/20)*68*[NtotSoil]$ if $pH > 7$ and -Nmin= $(30/20)*0.25*([pH]-3)*68*[NtotSoil]$ if $pH < 7$ (QUEFTS model, Sattari et al. 2014) -Nuptake= $Yw*21$ (21 is N (kg) taken up per ton of maize grain at 12% humidity (Stanford, 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 ($\text{kg} \cdot \text{ha}^{-1}$)	Doses	Farmer survey

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

3 Results

3.1 Serious games and Q-methodology

Individual card game to determine farmers' objectives

For respectively 83% and 80% of farmers, the objectives “be rice self-sufficient” and “have high incomes for savings” were the most important objectives (Table 3). The objectives “reduce work and

effort” (77%), “have small regular incomes monthly for family expenditures” (77%), “diversify income” (63%) and “reduce cash-flow needed” (33%) were also frequently mentioned. A substantial share of farmers valued objectives related to sustainability: “transfer a viable farm to the next generation” (27%) and “avoid herbicides” (23%).

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

- 1) “Farm income - amount, consistency, cash-flow and risks”, synthesized from the objectives “have high income for savings”, “have small regular incomes monthly for family expenditures”, “diversify income” and “reduce cash-flow needed”
- 2) “Diversity of activities”, synthesized from the objectives “diversify income” and “obtain incomes during the dry season”
- 3) “Workload peak and drudgery of work”, synthesized from the objectives “improve work productivity” and “reduce work and efforts”
- 4) “Rice and forage self-sufficiency”, related to the objectives “be rice self-sufficient” and “be self-sufficient in animal feed”
- 5) “Farmer health”, related to the objective “Avoid herbicides” because it expressed farmers’ health concerns when spraying herbicide.

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

Table 3: Farmers' objectives and important crop attributes resulting from card and group games carried out with farmers in three villages of northern Laos. For the group game the final score was obtained by summing the scores given by farmers in a given village (see section 2.3)

Village	Farmers' objectives (five-year perspective) (card game)	% farmers
Lé, leng, Xay and Dokham	Be self-sufficient in rice	83%
	Have high incomes for savings	80%
	Reduce work and efforts	77%
	Have small regular incomes monthly for family expenditures	77%
	Diversify income	63%
	Reduce cash-flow needed	33%
	Transfer a viable farm to the next generation	27%
	Avoid herbicides	23%
	Improve work productivity	17%
	Obtain income during the dry season	13%
	Perform activities that are easily manageable	7%
	Be self-sufficient in animal feed	7%
	Preserve a traditional activity	7%
	Have free time for family	3%
	Protect the environment	3%
	Have a healthy lifestyle	3%
Reduce the work needed on uplands to focus on paddy rice	3%	
Group lands together around the farm	3%	
Be self-sufficient in clothes	3%	
Crop attributes important for farmers (Takit group game) = answer to the question "I am a trader and I have the best upland crop ever, what question would you like to ask me, in order to know if you would decide to grow it or not?"		Score
Leng	Is it suitable for village soils?	28
	Does it improve the soil?	27
	Does the crop have a good selling price?	8
	Does it have a good market (lot of buyers)?	5
	Does it have a high yield?	4
	Is it expensive to grow it?	2
	Can the project help us for the implementation?	0*
	Is it a crop susceptible to pests?	0*
Lé	Is it storable?	20
	Is it easy to grow?	20
	Does it require a lot of labour?	7
	Does it have a good market (lot of buyers)?	6
	Does it improve the soil?	6
	Does the crop have a good selling price?	5
	Is it suitable for village soils?	3
	Can we use it for our own consumption?	3
	Does it require a lot of fertilizer?	2
	Does it have a good yield?	2
	Can we get a good benefit from it?	1
	Does it require irrigation?	1
	Is it good for the environment?	1
	Is the price stable?	1
	Can we grow it together with another crop?	0
	Is it a dry-season crop?	0
Is it a crop susceptible to pests?	0	
Is it a rainy season crop?	0	
Xay	Does it have a good yield?	30
	Is it easy to grow?	15
	Do technicians recommend us to grow it?	12
	Does the crop have a good selling price?	10
	Is it suitable for village soils?	7
	Does it have any contracts with a company to grow it?	6
	Is it a healthy crop?	5
Does it have a good market (lot of buyers)?	3	

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

Group game on important crop attributes

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

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

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

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

The TAKIT game, although played to identify plot-level criteria, informed the identification of a farm-level criterion “farm autonomy”. Farm autonomy was related to the questions “Can we use it for our

own consumption?” and “Is it storable”. Farmers were willing to cultivate upland crops to reduce food purchases (meaning lower autonomy) and farmers related storability to their ability to choose marketing timing and prices.

Q-methodology on soil fertility perception

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

Table 4 : Farmers’ soil fertility perception based on a sample of statements representing contrasting narratives on soil fertility. The three types of opinions (O1, O2 and O3) were identified with the centroid method and a varimax rotation (see section 2.2). Only the statements that created the most distinguishing classification among the different opinions are shown. The full list of statements can be found in Appendix 2.

	Average score			%farmers score<-1
	O1	O2	O3	
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% between opinions)				
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%

Table 4 (continued): Farmers' soil fertility perception based on a sample of statements representing contrasting narratives on soil fertility.

Statements describing O1	O1	O2	O3
- 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

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

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

3.2 Agronomic diagnosis

Constraints and sustainability issues possibly occurring in maize areas, as found during a review of local knowledge and used to set up field monitoring, can be found in Appendix 4. Farmers distinguished three soil types during participatory mapping: red-sandy soils (low yields), loamy-clayey soils (medium to high yields) and yellow sandy soils (medium to high yields). Farmers identified three types of crop management: high-input intensified systems (mechanical sowing, harrowing after ploughing, fertilizer and herbicide use), medium-input intensified systems (mechanical sowing, no harrowing, herbicide or fertilizer) and low-input intensified systems (hand sowing, no harrowing and herbicide). The participatory mapping combined with the review of local knowledge and field visits helped identify the following criteria to select the plots to monitor: farmer-reported yields, slope, level of agricultural intensification, soil type and soil quality as visually appraised by the farmer.

After monitoring, five contrasting types of cropping systems were identified (Table 5) depending on slope, type of sowing (mechanical or manual), amount of herbicide use, and time between soil preparation and sowing.

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 2 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

Clayey-loamy soils, the dominant soil type in the monitored plots, had, on average, an organic nitrogen content of 0.096%, a soil organic matter content of 2.44%, a total cationic exchange capacity of 9.7 me/100g and a pH of 6.01 (see Appendix 5 for detailed results of soil analysis and soil type). Herbicide application varied greatly (Table 5). The herbicide treatment index for cropping system 3 (moderate slopes, hand or mechanical sowing on clayey-loamy soils, short period of bare soil before sowing) was more than three times the recommended dose, whereas it was equal to 0 for cropping system 4 (flat land, mechanical sowing on clayey-loamy soils, medium period of bare soil). Fertilization rates were low with 20 kg of N ha⁻¹, on average, in fertilized plots and never exceeded 40 kg N ha⁻¹. The potential N balance was below -10 kg ha⁻¹ for 90% of the plots (Table 5). The potential N balance was lowest on the sandy soils of cropping system 2 (flat land, mechanical sowing on low-fertility sandy soils, medium period of

bare soil). Risks of erosion were either due to slopes or due to a long period between ploughing and sowing. The number of days between ploughing and sowing varied from 3 to 108 and averaged 29 days. Cropping systems 3 and 5 had contrasting erosion risks, the former having a short bare soil period before crop installation and the latter a long period, due to a false seed-bed practice to reduce weed pressure.

The average potential (Y_0) and water limited (Y_w) yields were 6.2 t ha^{-1} and 6.0 t ha^{-1} , respectively, for the 111 plots simulated with the crop model. The limited difference between Y_0 and Y_w indicated a low impact of water stress on yields in the monitored plots. This was not surprising because northern Laos has a humid sub-tropical climate. The Kham basin had a total annual rainfall of 854, 875 and 1569 mm in 2016, 2017 and 2018, respectively. The observed maize yields (Y_a) in the monitored plots were markedly below Y_w 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 all, 25% of the plots had a yield below 1.9 t ha^{-1} . The relative yield gap ranged from 8% to 89%, and 25% of the plots had a very high relative yield gap above 68%.

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

	Yield (t ha^{-1})	Relative Yield Gap, water limited (%)	Plant density at harvest (plants m^{-2})	Sowing hole density (holes m^{-2})
Min.	0.7	8	1.9	1.1
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

Field monitoring revealed the prevalence of weed infestation to explain yield variability, itself mainly explained by sowing hole density. Yields were correlated to “Highest weed score” ($R^2=0.19$, $P<0.001$) and potential N balance ($R^2=0.08$, $P<0.005$). Weed infestation was significantly correlated with sowing hole density (Figure 7).

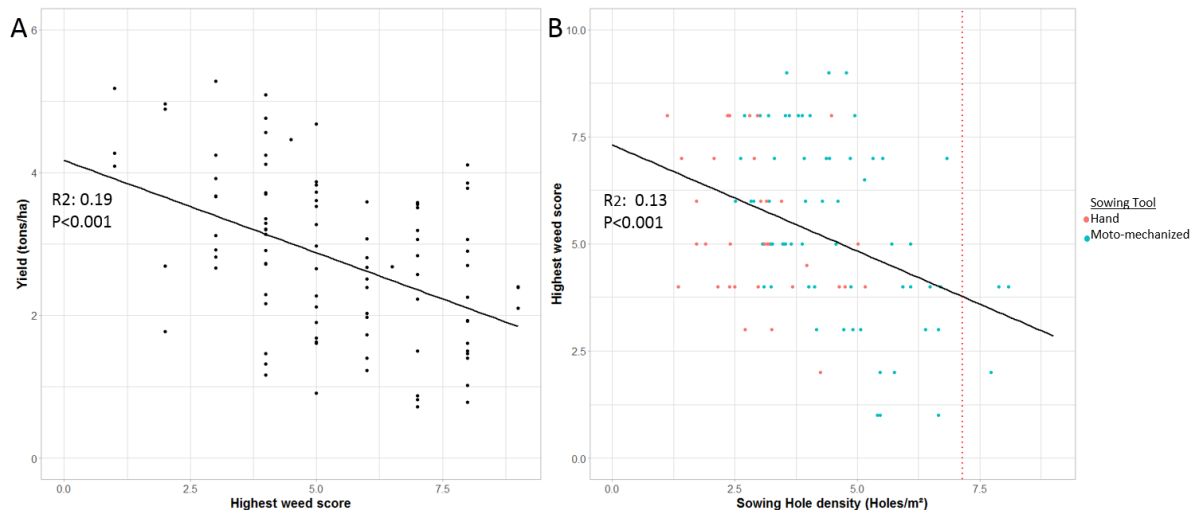


Figure 7: Effect of highest weed score on maize grain yield (7A) and effect of sowing hole density on highest weed score (7B). The red dotted line (7B) is the optimal sowing density allowed by the seed drill (7.1 plants m⁻²)

When dealing with crop competition with weeds in our context, sowing hole density mattered more than plant density. Indeed, farmers dropped two seeds into each hole by hand, while the seed drill dropped one seed per hole. Therefore, for the same sowing hole density, manual sowing led to a plant density double that achieved with the seed drill, but with the same space (and light for weeds) between holes. Sowing hole density varied greatly from 1.1 to 8.1 sowing holes m⁻². A higher sowing hole density was achieved with mechanical sowing compared with manual sowing (Figure 7B), but only 4% of farmers achieved the optimum sowing hole density of 7.1 plant m⁻² enabled by the seed drill. Pest stress was not identified as an explanatory variable of yield variation, as only 6% of the plots experienced it.

In CART, “Highest weed score” was the main variable explaining relative yield gap variability (Figure 8A). The plot relative yield gap (Yr) was categorized in eight groups (R²=0.37) according to criteria of decreasing importance: highest weed score, potential N balance, and plant density. The average relative yield gap was 59% for plots with “Highest weed scores” above 4.8, and 45% for plots below 4.8. For plots with a high weed score, Yr was 69% when the potential N balance was below -78 kgN ha⁻¹ and 54% when the N balance was above that threshold. Similar interpretations could be derived by reading the other branches of the tree. Weed infestation variability was first explained by sowing hole density (Figure 8B), followed by herbicide doses and number of days between the last soil tillage and sowing (R²=0.47).

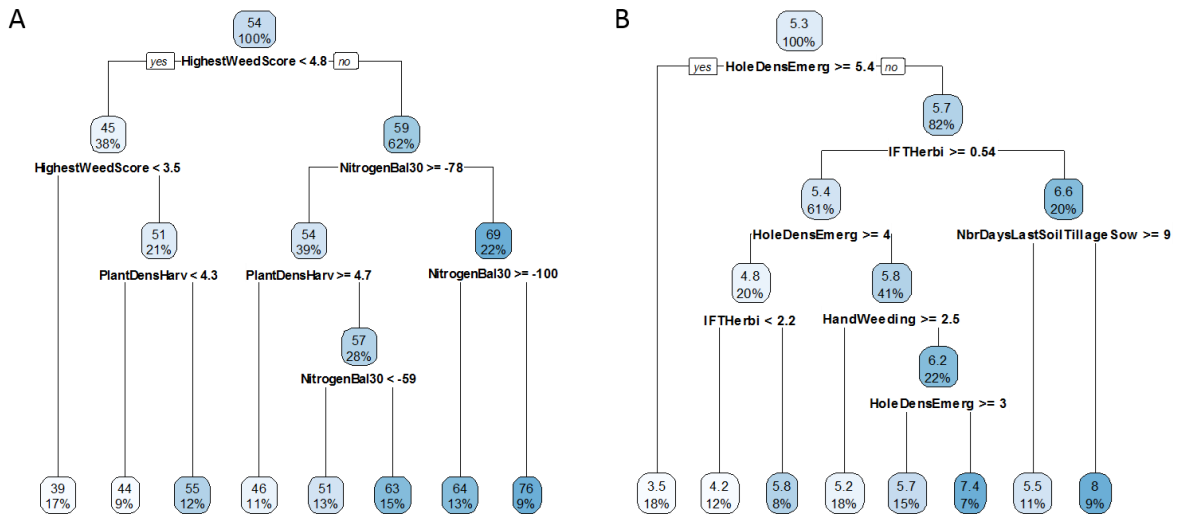


Figure 8 : Classification and regression tree models to describe relative yield gap as a function of yield constraining variables (A), and highest weed score as a function of technical management variables (B). In each box, the predicted value is on top and the percentage of observations below. highestWeedScore: 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.

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

The outcomes of the agronomic diagnosis informed the determination of the following plot-level criteria: 1) Land productivity: yield variability and risk of failure, 2) Soil erosion, 3) Susceptibility to weeds, 4) Resource use efficiency, 5) Work productivity and drudgery, 6) Herbicide risks, 7) Economic performance. At farm level the agronomic diagnosis informed the determination of the criterion “Fertility transfer”.

Eventually, we added criterion sensitivity to climate variability, because environmental impacts (e.g. erosion, herbicide leaching) were also related to rainfall events. We added susceptibility to pests and biodiversity criteria, because the agronomic diagnosis revealed that

maize fields were managed in a sole stand mono-cropping system, reinforcing weed infestation over the years.

3.3 Integration of knowledge to select the final set of criteria

Plot-level sustainability criteria

Figure 9 shows the final set of criteria resulting from an integration of farmer and scientist perspectives. Every criterion identified can be quantified with indicators. On the left-hand side of the figure, the final plot-level criteria are displayed combining the serious games and Q-methodology results with the agronomic diagnosis: economic performance, land productivity, susceptibility to pests, weeds, diseases and climate variability, work productivity and drudgery, soil erosion, herbicide risks, biodiversity, soil fertility, and resource use efficiency. To establish this final list, the criteria originating from the serious games were grouped with those from the agronomic diagnosis, e.g. “economic performance” includes gross margin (derived from the TAKIT game), return on investment (derived from the agronomic diagnosis and the TAKIT game) and cash flow (derived from the card game and the TAKIT game).

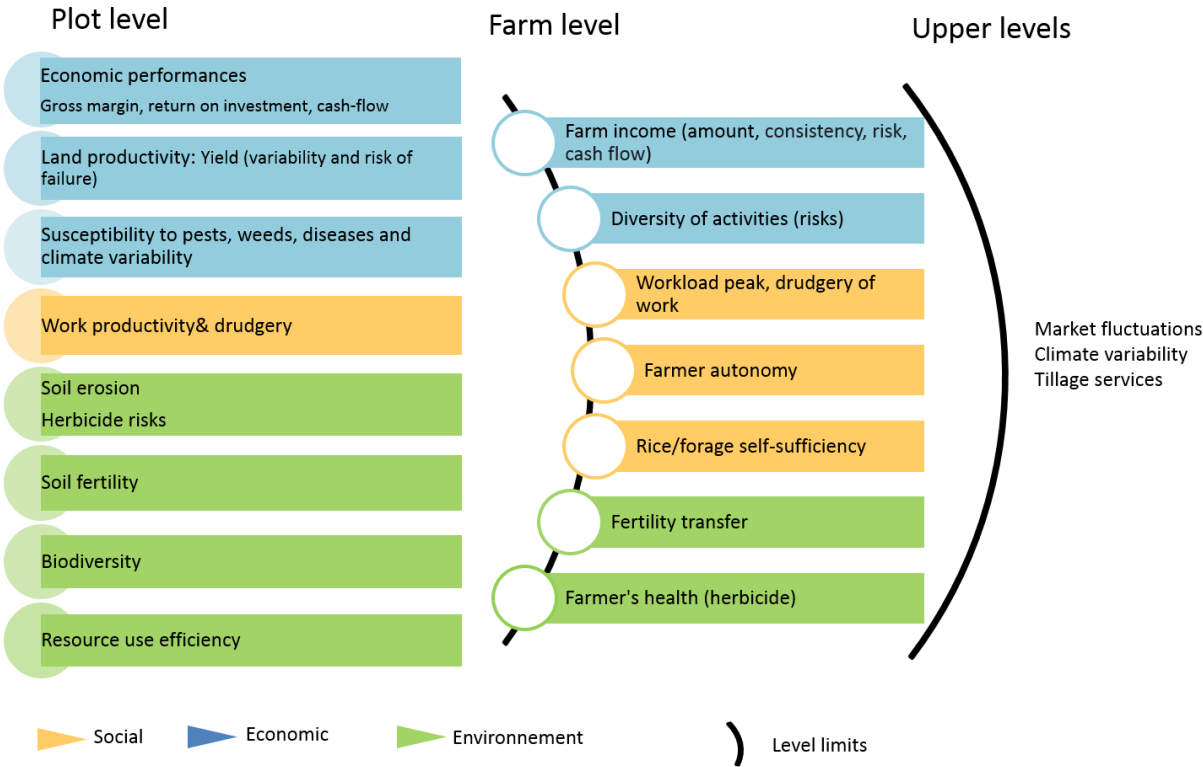


Figure 9 : Final set of locally relevant criteria. The reader is referred to the web version of this article for interpretation of references to colors.

Farm-level sustainability criteria

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

4 Discussion

4.1 Strengths and pitfalls of each part of the method

Long-term perspective with serious games and Q-methodology

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

Drivers of cropping systems sustainability with the agronomic diagnosis

Maize cropping system performance varied widely, but single factors (weed and pest competition, N balance, and water stress) explained only 19% ($r^2=0.19$) of the variations (at best) and CART 37% (at best). Substantial remaining unexplained variation is, however, a common feature of on-farm trials in a smallholder context (Baudron *et al.*, 2012; Falconnier *et al.*, 2016; Naudin *et al.*, 2010). An unexpected result of field monitoring compared to the local discourse (Appendix 4) was the predominance of weed pressure over soil fertility to explain yield variability. Soil fertility remains an issue for the long-term sustainability of cropping systems, given the negative farm-level nutrient balance found in the region (Epper *et al.*, 2020), but weed pressure and plant (and sowing hole) density drive maize cropping system sustainability. With mechanical sowing, the low sowing density was probably due to a malfunctioning of the seed drill. The seed drill opens by friction with the ground surface. Sub-optimum soil moisture conditions after tillage created large soil clods and could have prevented the seed driller from operating properly. Sub-optimum soil conditions can be due to: i) limited access to ploughing services, compromising the timeliness of the operations and ii) a short time window for rice and maize establishment, with farmers focusing on rice cultivation, hurrying maize sowing to spare time for paddy rice preparation. Beyond yield variability, poor crop establishment also favoured detrimental environmental impacts, such as herbicide overuse to control weeds, and potentially risks of erosion and nitrogen leaching.

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

4.2 Added value of our approach combining two perspectives

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

Integration of multiple perspectives

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

Combining the two perspectives, we showed that farmers' willingness to maintain soil fertility contrasted with current soil management associated with negative N balances and risks of erosion. Field monitoring showed that, in the current state of maize cropping systems, it was probably not profitable for farmers to invest time and money for fertility management in fields with poor crop performance, partly due to poor crop establishment and the resulting weed pressure. Our study revealed discrepancies between farmers' perspectives and agronomic facts: farmers generally disagreed with the statement "Low maize density is the main cause of low yield compared with low soil fertility" (See section 3.1), while field monitoring revealed the crucial role of a low plant density and subsequent weed infestation in explaining low yields. An interesting result of the agronomic diagnosis to complement farmers' perspective was the three criteria not explicitly mentioned by farmers in the serious games and Q-methodology: erosion risks due to bare soil, low sowing density leading to risks of high weed

pressure, herbicide overuse and leaching risks due to weed pressure. Van Asten *et al.* (2009) showed that farmers struggle to identify yield-constraining factors when constraints are uniform in time and space. Co-learning cycles engaging farmers and researchers, with quantitative field monitoring and feedback sessions, can contribute to the convergence of farmers' and scientists' views (Falconnier *et al.*, 2017; Hanna *et al.*, 2014).

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

Consideration of the local context to select criteria

We compared our final set of criteria with some other sets used in existing generic methods (Gomiero and Giampietro, 2001; Dalsgaard and Oficial, 1997; Liebig *et al.*, 2001; Hassall&associates, 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 susceptibility to weeds" as identified with field monitoring. A focus on soil fertility, as emphasized in most existing methods, would certainly have hidden the importance of other yield-constraining factors, such as weed infestation linked to sowing density and appropriate crop establishment.

Transparency regarding scientific logical reasoning

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

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

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

5 Conclusion

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

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

that it is mainly inadequate crop management during crop installation that leads to low resource use efficiency and unsustainable trajectories.

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

Acknowledgements

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Chapitre 3 : Evaluation intégrée de la durabilité des systèmes de culture

Ce chapitre présente la deuxième étape de la démarche : l'évaluation de la durabilité des systèmes de culture en tant compte de la variabilité biophysique exploitée par les agriculteurs. Le diagnostic agronomique utilisé au chapitre 2 est approfondi sur sa composante environnementale pour réaliser un diagnostic agro-environnemental.

La durabilité des systèmes actuels est évaluée ainsi que les gains d'amélioration permis par un prototype de système de culture limitant les herbicides et augmentant le rendement. Nous définissons et utilisons des indicateurs pertinents au niveau local représentant les objectifs socio-économiques des agriculteurs, les risques pour l'environnement et les interactions entre le type de sol, l'itinéraire technique et le climat.

Cette étape a les objectifs suivants :

- 1) Evaluer les performances agronomiques et environnementales des systèmes de culture tels que pratiqués par les agriculteurs.
- 2) Identifier comment la diversité des pratiques et des situations biophysiques influence ces performances.
- 3) Evaluer dans quelle mesure la durabilité à l'échelle du système de culture pourrait être améliorée par une meilleure gestion de l'itinéraire technique.

Les références et les annexes de l'article sont données à la fin du manuscrit.

Sustainability assessment of maize cropping systems managed by resource-poor farmers.

How far could sustainability be improved with better crop management?

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1 Introduction

In Asia, the growing market of maize has been an opportunity for many resource-poor family farms out of subsistence farming with better market integration and substantial increase in farm income (Vongvisouk *et al.*, 2016; Hepp *et al.*, 2019; Yu *et al.*, 2013; Zimmer *et al.*, 2018). The growing demand of corn is largely due to its use in the animal feed value chain that itself grows steadily, as the result of the growing meat consumption in the region (Kallio *et al.*, 2019; Erenstein, 2010). Despite these recent market opportunities, farmers are still facing low productivity while uncontrolled intensification based on green revolution principles is increasing risks of environmental impacts (Devkota *et al.*, 2015; Alauddin and Quiggin, 2008; Pretty *et al.*, 2011).

Sustainability for resource-limited farmers is linked primarily to the urge increasing productivity and of reaching greater food security and resilience while natural resources and ecosystems are preserved (Schindler *et al.*, 2015). Resource-limited farmers rely on key biophysical processes occurring in their field at different levels depending on the characteristics of each field. Even at scale of a small agricultural region, a wide variability of biophysical environments and crop managements across locations may result in large variations in environmental impacts as well as in the socio-economic opportunities and constraints that the environment imposes to farmers (Giller *et al.*, 2006).

Assess cropping systems sustainability can be useful to avoid rapid transformations of agriculture ending up in irreversible social and environmental impacts (Stuart *et al.*, 2018;

Tipraqsa *et al.*, 2007). Aiming at the so-called “agroecological transition” (Côte *et al.*, 2019) in industrialized countries, many methods have been developed to assess cropping systems with sustainability indicators (see the review made by Deytieux *et al.* (2016)). Assessments on real cropping systems are often used to identify their strengths and weaknesses with indicator-based approaches (Fumagalli *et al.*, 2011; Pacini *et al.*, 2009) and avoid unsustainable trajectories. Whereas it is common to use data extracted from farmers’ interviews, general statistics, literature or experts, studies less often use the more time-consuming direct measurements to calculate indicators (Pacini *et al.*, 2009; Davis *et al.*, 2012). However, the highly variable cropping systems managed by resource-poor farmers require reliable quantification of the different options for sustainability improvement according to biophysical zones farmers access. Studies seldom use robust quantification of performance variability in farmers' fields managed by farmers, which requires providing estimates of the variability of indicators’ values for each type of cropping systems (see de Barros *et al.* (2009); (Fumagalli *et al.*, 2012) for an analysis of variability).

We studied hybrid maize mono-cropping cultivation in northern Laos as a typical case of rainfed systems with low and highly variable performances and high environmental risks: biodiversity (Castella *et al.*, 2013; Viau *et al.*, 2009), soil fertility degradation (Epper *et al.*, 2020) and high use of herbicide (Shattuck, 2019). Indeed, in the selected region, moto-mechanized maize cropping system emerged a decade ago and crop installation was recently shown to be poorly mastered, which leads, to high herbicide use, erosion risks, low yields, and low resource efficiency, with variations depending on other aspects of crop management and of soil and weather characteristics (Lairez *et al.*, 2020). Continuous monocropping poses by essence severe environmental sustainability issues that can be overcome by mobilizing key agroecological principles such diversification of cultivated species. However, such transition are often complicated for small-scale farmers because of needed changes at field or farm scales and because of the difficulties in creating new markets for the other species. As a first step of agroecological transition, we hypothesize that simply improving the management of currently practiced cropping system may already improve maize production sustainability.

The objectives of the study are threefold: i) assess the agronomic and environmental performances of currently practiced maize cropping systems, ii) identify how the diversity of practices and biophysical situations influences these performances. iii) Evaluate how far a

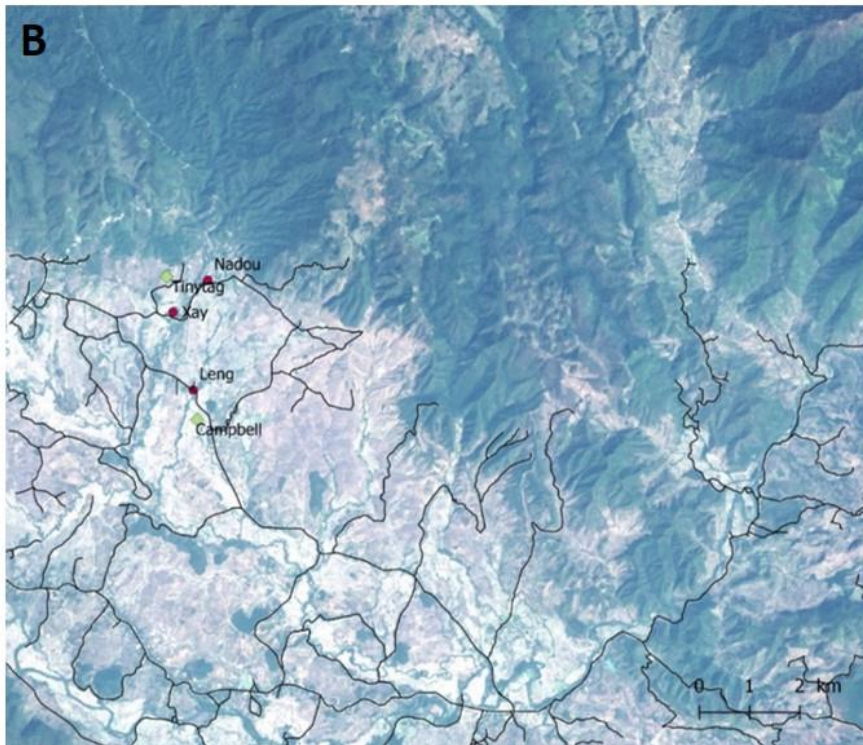
better crop management can improve sustainability at field scale. We defined and used locally relevant indicators representing farmers' socio-economic objectives, risks for the environment and interactions between soil type, crop management and climate.

2 Methods

2.1 Study area and current cropping systems issues

We selected for this study the Kham Basin in Xieng Khouang province located in northern Laos, close to the Vietnamese border (19 °38'N, 103 °33'E; 605 m above sea level) (Figure 10). Over the past two decades, a transition occurred from extensive manually cultivated upland rice systems (slash and burn with fallow) to moto-mechanized cash crop systems with continuous hybrid maize cultivation. Kham Basin is an area of the province with large and relatively flat valleys of moderate elevation (500 to 600 m asl) expected to be suitable for maize cultivation and small mechanization (Figure 11).

Crop management practices are varying depending on the use or not of small machinery for sowing, land preparation method, doses of herbicides and mineral fertilizers. Overall, maize cultivation is currently subject to sustainability concerns: low yields, high costs, risks of water pollution by herbicide and soil erosion (Lairez *et al.*, 2020; Shattuck, 2019). Hybrid maize is cultivated in mono-crop system, with one crop cycle per year during the rainy season (May – October). Cultivation starts in early April with a disk ploughing using tractors and a plough that are generally not owned by farmers but rented on a per hectare service fee. Land is harrowed or not before either being sown manually with two seeds in a hole carved using a stick, or mechanically with a seed drill mounted on a rototiller also used for paddy rice preparation and that is often the property of the farmer (Lairez *et al.*, 2020). Maize yields were found to be strongly lower than potential water-limited yield due to weed infestation favoured by low stand density, itself resulting from a poor mastering of the whole sequence of crop installation operations (Lairez *et al.*, 2020). This technical failure at the beginning of the maize cycle frequently led to herbicide use over recommended doses. Soil erosion exposure and water percolation were also increased and increase the risks of pollutions by some of the herbicides used.



- Legend:
- Village
 - ◆ Weather station
 - Road

Figure 10: A: Aerial view of Kham basin Xieng Khouang province in northern Laos (limits of the basin in red dotted line, and study site in the red circle), source: Google earth. B: map of the study site in Kham Basin.

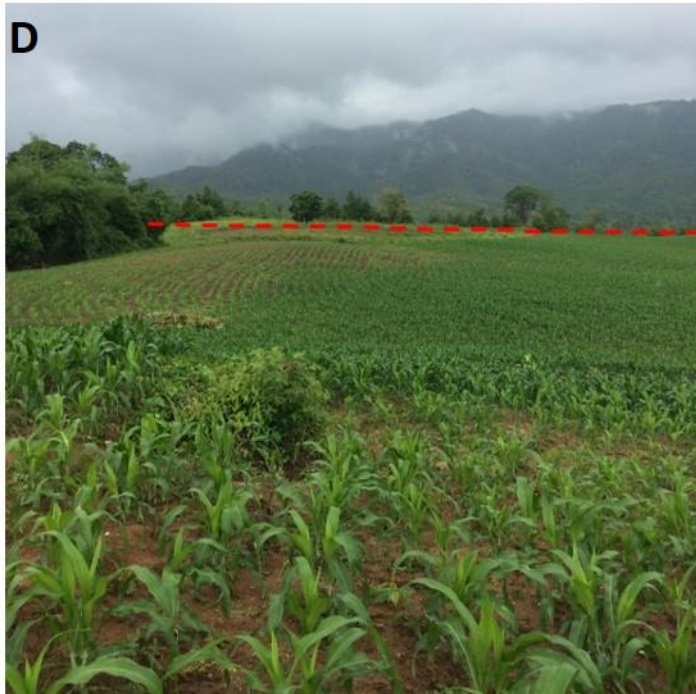


Figure 11: C: view of maize area of Leng Village. D: view of maize area of Xay village.

Here we study how sustainability of such not well mastered monocropping systems could be substantially increased by simply improving the management of currently practiced cropping system. We selected three villages in Kham Basin: Leng, Xay and Nadou because they represented a wide diversity in soils and management practices of maize, with sandy soils in Xay, sandy-loamy and clayey in Nadou and more clayey soils in Leng. Thanks to flatter area in Leng, maize sowing was more often mechanized in that village than in the two others.

2.2 Overview of the Method

The agro-environmental assessment presented below embodied economic and environmental dimensions of sustainability at field level. In a previous study in this region, combining participatory methods and field measurements in a network of farmers' fields, were identified the causes of yield variations and the most relevant sustainability criteria for local farming systems (Lairez et al., 2020). In the present study each of the sustainability criteria at field level was quantified using several indicators. This was done for a number of contrasted crop management types and soil types covering the variability of biophysical zones found in the region.

Figure 12 displays a graphical abstract of the methodology. From the field monitoring network (see part 2.3), climatic variables likely to influence the variability of the indicators were described (part 2.4.1) and types of currently practiced cropping system (Curr-CS) were identified (part 2.4.2).

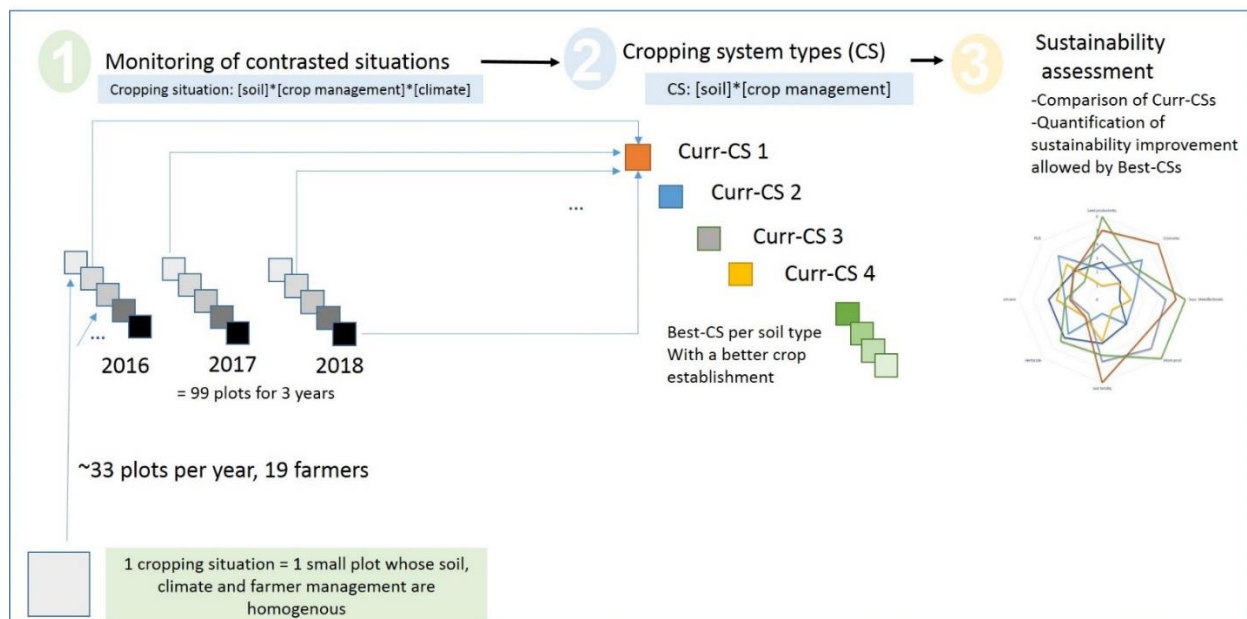


Figure 12: Overview of the method. Curr-CS: current cropping system types, Best-CS: best cropping system with a better crop establishment, yield gap closure and herbicide reduction.

Indicators were computed by combining direct measurements, farmer surveys and simulations with a simple crop model. Then was assessed how far sustainability of Curr-CS may be increased simply by improving crop management (i.e. without changing the cropping system itself) thanks to achieving a better crop establishment. To that end, sustainability indicators relative to Curr-CS types were compared to indicators computed for a hypothetically

improved version of the cropping system type, that we name hereafter “Best-CS” types. Best-CS types were identified one per Curr-CS type, targeting at the same time yield gap and herbicide use reductions based on local recommendations and on best-observed cropping situations in the field-monitoring network (part 2.5).

2.3 Field monitoring network

The elementary unit of assessment was a ‘cropping situation’, defined as a small plot whose soil, climate and management are assumed to be homogenous (Affholder *et al.*, 2003; Jouve, 1984). Hereafter we use ‘plot’ as a synonym for ‘cropping situation’. The size of such plots is a compromise between being small enough to make realistic this assumption of homogeneity, and large enough to allow reliable measurements of plant and soil variables (Affholder *et al.*, 2003). In this study, we used cropping situations containing 4 to 5 maize rows, with a length adjusted so that the area was 16m².

Contrasted cropping situations in farmers' maize fields were monitored over three agricultural seasons (March to October of years 2016 to 2018). Each farmer field contained between 1 and 3 cropping situations depending on the magnitude of spatial variations of soil characteristics within the field. The network was built with the help of farmers, using focus group discussions, field visits and participatory mapping as described in Lairez *et al.*, 2020. The total sample of observations over the 3 years was 99 cropping situations in 19 farmer fields.

Table 7 shows the monitored variables. Weed score was noted every 30 days on every cropping situations, based on a 9 grades scale and linked to a percentage of soil coverage by weeds (Marnotte, 1984; Mathieu and Marnotte, 2000). The number of sowing holes per unit area (‘sowing hole density’) was recorded at emergence and plant density was measured at both emergence and harvest. Every year at harvest, total grain and straw from cropping situations were weighted. Total biomass was weighted at harvest per cropping situation and a sub-sample of straw (~1 kg, precisely weighted) was oven dried at 80 °C for 48 hours to determine the dry weight. Total grains of each cropping situation was weighted at harvest and 100 grains were sampled per cropping situation and dried at 80 °C for 48 hours to determine grain moisture at harvest. Total grains of cropping situations was also weighted after sun drying for 2 weeks to estimate the average moisture of selling maize for economic parameters calculation. Yields were then expressed at 12% moisture. Leaf area index was measured with

a LAI-meter LAI-2200C at flowering stage. Crop management and timing of intervention were monitored monthly with farmer interviews over the three cropping seasons.

Table 7 : list of variables monitored in the field monitoring network used for indicator calculation

	Unit	Timing or frequency of measurement	Source of data
Weed cover			
Weed cover score	Score from 1 to 9	Every month from sowing	Field observation
Yield components			
Plant and sowing hole density	plants (and holes) m ⁻²	At emergence and harvest	Field measurement
Yield	t ha ⁻¹	At harvest	Field measurement
Total aboveground biomass	t ha ⁻¹	At harvest	Field measurement
Weight of 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 liters		
Fertilizer applications (type of product and date)	date		
Fertilizer applications (amount)	kg ha ⁻¹		
Manual weeding (date)	date		
Manual weeding (labour requirement)	Man-days		
Soil			
Soil water holding capacity	mm to maximum rooting depth	Once in 2017 in August for 6 representative pits	Lab analysis
Textural and chemical analysis [0;30 cm]		Once in 2017 before growing season for every plot	Lab analysis
- Cationic exchange capacity	me/100g		
- Soil texture (sand, silt, clay)	%		
- Organic matter	%		
- Total nitrogen	% ₀		
- Total phosphorus	% ₀		
- pH	-		
Soil relief	Score from 1 to 3	Once a year btw ploughing and sowing (years 2017 and 2018)	Field observation
Soil crust	C1: no crust C2: runoff crust covering less area than structural crust C3: runoff crust predominating	Between ploughing and sowing	
Weather data			
Rain	mm	Every 10 minutes	Campbell station + Tinytag
Temperature	°C		
Humidity	%		
Global radiation	kW m ⁻²		
Wind	m s ⁻¹		

Soil was sampled at 30 cm depth for chemical soil analysis in April 2017 on all cropping situation monitored in 2016 and new situations added in 2017 (number of soil samples: 45). A small number of new situations was added in 2018 (n: 5) with no means for additional lab analyses. They were selected for belonging to soil types already sampled (as appraised when

looking at topsoil), and were located close enough to a sampled location to reasonably assume that the soil parameters of the latter were valid for the former. Samples of soils were composite samples (horizon 0-30 cm) of 0.5 kg made of a mix of three sub-samples on a diagonal transect across each cropping situation. At the laboratory, soil variables determined were particle size distribution, pH, organic matter content, total soil nitrogen content, total phosphorus, and exchangeable cations of the saturated extract (Ca^{2+} , Mg^{2+} , K^{+} and Na^{+}). Soil water holding capacity and soil depth were determined in August 2017 by using 6 soil pits dug at 1.5 metres deep and covering a large diversity of soil texture and sensitivity to water stress and water logging. Each plot was assigned with soil water holding parameters of one of the 6 soil pits thanks to its soil type (previously identified) and the farmers' estimate of the soil depth. Soil water holding capacity was determined in the laboratory with non-deformed samples taken from the 6 pits at three depths: 0–10 cm, 10–30 cm and 30–70 cm. Field capacity was determined by depressurization at $\text{pF}=2$ and permanent wilting point was determined by depressurization at $\text{pF}=4.2$, stone volume was determined by the Archimedes buoyancy method in kerosene.

Soil relief was scored, with a visual appraisal, between ploughing and sowing from 1 (no microrelief obstructing water runoff) to 3 (macrorelief >50 cm high). Topsoil crust was observed in 2017 and each plot was classed in the typology of soil crust corresponding to different infiltration and runoff coefficients as established by Casenave and Valentin (1989). Solar radiation, wind velocity, temperature, rain and air moisture were recorded, at a central location of the plot-monitoring network, using an automatic weather station (see Figure 1; Campbell weather station, $19^{\circ}38'34''\text{N}$, $103^{\circ}36'41''\text{E}$, 571 masl), complemented by a second automatic station only recording temperature, air moisture and rain (see Figure 1; Tinytag thermometer/humidity recorder and Tinytag rain gauge, $19^{\circ}39'45''\text{N}$, $103^{\circ}36'17''\text{E}$, 599 masl). This second station was placed at another location at 2.5 km from the principal one, in order to account for spatial variations of these meteorological variables, whereas global solar radiation and wind were expected and assumed less dependent of the location at the scale of Kham Basin. The Tinytag rain gauge logged the rain every 10 minutes allowing to evaluate rainfall intensity that contributes to the erosive power of rainfall events (Mohamadi and Kaviani, 2015; Valentin *et al.*, 2008). Weather data from automatic weather station were available only from July 2016 and were complemented from April to July that year using daily

data from the nearest station of the public weather station network, located 5 km away from our automatic station (Kham District weather station, 19°38'52"N, 103°33'59"E, 604 masl).

2.4 Climate drivers of cropping system sustainability in the local context and typology of cropping systems

2.4.1 Climate drivers that may influence cropping systems performances

In order to avoid making conclusions about results that would be caused by untypical climatic conditions and to verify that the most frequent interactions between climate and crop management were represented in our monitoring design, we compared the rainfall data of the three years of our field study to a historical series of 20-years of daily rainfall records. The records from Kham district weather station constituted a series of 17 years from 1999-2015, that we completed to 20 years using the records from the automatic weather station of the plot network from 2016 to 2018. Year 2016 had a total dataset starting in April only, hampering the use of this year for analyses regarding the onset of the rainy season (see below).

A year with a delayed start of the rainy season may result in a delayed soil tillage with no time for the rain to crush ploughing clods before sowing and may affect the quality of the seedbed (Lairez *et al.*, 2020). We elaborated two climate risk indicators. An indicator of the risk of a late start of the rainy season and an indicator of the risk of failure of May sowing due to a dry period.

The “starting date of the rainy season” was defined with a threshold found in literature expressed in ‘climatological pentad (5-day) mean of precipitation’ (Wang and LinHo, 2002). Each month was divided in six pentads of 5 days each, plus a sixth pentad from day 26 to the end of the month. Wang and LinHo (2002) defined the following rule for Asian monsoon to identify the starting date of the rainy season, starting from May a year *i*:

$[(\text{Average daily pentad precipitation of a year } i) - \text{Local Mean Daily Rainfall in January}] \geq 5 \text{ mm/day.}$

We adapted this indicator to our objective that was the identification of the date from which the ploughing campaign may start. The pentads were analysed from January and not from May. The local mean of daily rainfall in January was calculated on the 19-year series without

year 2016. Years were then ordered by ascending “starting date of the rainy season”. We considered that the rainy season of the year i was delayed, if its starting date was after the third quartile of the distribution of “starting date of the rainy season” on the 19-year series. This date was estimated for each of the three years monitored and the years of the historical dataset.

The indicator of the risk of failing to sow during May due to a dry period was calculated as the percentage of years with five consecutive dry days in May. The threshold of five dry days used to define the risk to fail the sowing was selected from farmers’ interviews who reported having to re-sow in 2017 due to a 5-day dry period during maize emergence.

2.4.2 *Cropping system typology (Curr-CS)*

Once data were collected on the plot monitoring network, the sample of cropping situations was clustered in “cropping system types” (Curr-CS) as a simplified way to account for the diversity of cropping situations (Figure 12). A Curr-CS type crossed “soil types” with “farmer crop management types” and included cropping situations from the three climatic years. The technical parameters of Curr-CS (yields, inputs, costs, etc.) were the average of the cropping situations composing a Curr-CS type.

The typology was expert-based built using a step-by-step comparison approach (Landais, 1998). The objectives of the typology were i) to represent contrasted crop managements leading to contrasted agronomic performances and environmental impacts depending on soil type, ii) to quantify the margins for sustainability improvement allowed by improving crop establishment on different soil types. The rules used to cluster the cropping situations were key management variables leading to the technical failure at crop establishment as identified by (Lairez *et al.*, 2020): land preparation (harrowing/ no harrowing), sowing management (hand sowing/mechanical sowing), soil type (sandy, clayey or Sandy/loamy soils) and herbicide doses (no herbicide/herbicide).

The Curr-CS selected for the sustainability assessment were the clusters with a number of cropping situations above 10 in order to have a sample large enough to estimate the variability within a cluster.

2.5 Identification of local-best maize cropping systems (Best-CS)

Results from a previous study were used to characterize the hypothetical Best-CS as follows. As already said above, maize yield deviations from potential water-limited yield were found in that previous study to be primarily due to weed infestation favoured by low sowing density, caused by inadequate crop establishment (Lairez *et al.*, 2020). Switching from hand sowing to moto-mechanized sowing was intended to increase sowing density up to 7.1 plants/m² but sub-optimum timing of operations from first tillage to sowing and inadequate use of machinery for land preparation as well as sowing prevented the seed driller from operating properly. In the present study, Best-CS were defined as cropping systems with effective moto-mechanized sowing allowed by an optimal land preparation leading to a good crop establishment with a stand density above 5.4 plants/m² and low weed infestation. Best-CS had reduced yield gap, herbicide dose decreased to the local recommended doses, and fertilizer increased to compensate nitrogen uptakes by maize.

The Yield of Best-SC for each soil type was estimated as a range of values. The upper limit was set to the average per soil type of water limited yield, i.e. assuming no weed competition and nutrient limitations, using a plant density of 7.1 plants/m². The water limited yield was estimated using the dynamic, daily-time step model PYE (Potential Yield Estimator, (Affholder *et al.*, 2013)). The lower yield limit was the best yield attained in the set of cropping situations observed on the soil type and having their plant density above 5.4 plant/m² and their weed score keeping below 3.5 all along the crop cycle. These thresholds of plant density and weed infestation were those identified in the previous study as discriminating between effective and failing crop management for most soil types.

2.6 Building relevant sustainability indicators and assessment

2.6.1 Principles for indicators' selection and quantification

We defined criteria for sustainability assessment as issues describing the sustainability of agricultural systems and indicators as the variables quantifying these criteria. The sustainability criteria that were identified as suited to the local context were land productivity, economic performance, labour productivity/work drudgery resource use efficiency, soil fertility, erosion and herbicide risks, susceptibility to weeds and climate variability, and

biodiversity (Lairez et al. 2020). In the present study, we did not assess biodiversity because the cropping systems under comparison did not differ on this criterion.

The choice of indicators to assess the criteria was expert-based. Rules to choose indicators complied with a common approach found in the literature (Bockstaller *et al.*, 2013; Bockstaller *et al.*, 2008; López-Ridaura *et al.*, 2002; Xavier *et al.*, 2020) as follows. First, the indicators were selected for their capacity to discriminate cropping systems sharply for the criteria to be assessed with this indicator: indicators had to be responsive to variations of cropping system components, but also robust, so not too sensitive to small variations. Second, indicators had to go beyond a simple diagnosis of functional properties and, when it was possible, rather had to represent relations and processes at an explanatory level (Pacini *et al.*, 2010). Third, the set of indicators needed to both reflect the farmer's concerns and account for environmental issues that farmers do not necessarily consider but that are at stake for the broader society.

The indicators were estimated for both Curr-CS and Best-CS. For Curr-CS, indicators were calculated for each individual observed cropping situation and then averaged per cropping system type. The indicators values displayed in the result section corresponded to the probability distribution of each indicator per Curr-CS type. The data used to calculate the indicators were direct measurements, outputs from the crop model PYE and farmer estimates obtained in interviews. Each time data was available for Best-CS, indicators' computations were done using observed data of the best situation selected for the lower yield limit of Best-CS. Further details are given in section 2.6.2 when another way of computation was used.

Table 8 gives the source of data for each indicator. Prices and costs of agricultural inputs and outputs were averaged for the 19 farmers of the field-monitoring network. Working calendar, input used and intervention dates, were data collected at field scale in which each cropping situation was located. Every other data were direct measurements on each cropping situation: actual and potential yield, soil parameters, weed score, water stress, runoff and drainage.

Table 8 : Sustainability indicators used to assess maize cropping system (with units in brackets).

Yw: potential water-limited yield, Ya: observed actual yield, GM1: gross margin at current maize price of 171 USD/ton, GM2: gross margin at low maize price of 159 USD/ton, Abs: absolute value, LAIw: Leaf Area Index water limited, LAI0: potential Leaf Area Index, Nmin: Nitrogen mineralized from total soil organic nitrogen (kg ha⁻¹), Nfert: amount of mineral nitrogen applied (kg ha⁻¹), Nuptake: Nitrogen uptake from soil by maize (kg ha⁻¹), NtotSoil: total soil organic nitrogen (kg ha⁻¹), K2: mineralization rate of organic matter, Tmoy: annual temperature (23.4° was taken), %clay: soil clay content, PCA: principal component analysis, CEC: cationic exchange capacity, %OM: soil organic matter content

Sustainability criteria	Sustainability indicators	Calculation	Source of data for indicator computation
Land productivity	Average yield (tons/ha)	Average yield within CS type 12% humidity	Measurement
	Maximum yield (tons/ha)	3 rd quartile of yield distribution within CS type	Measurement
	Relative Yield gap (%)	$(Yw - Ya)/Yw * 100$	Measurement for Ya; PYE model simulation for Yw
	Risk due to very low yield (%)	Probability to have a product at harvest lower than costs Based on yield distribution within CS type	Measurement for yield and farmer surveys for prices/costs
Economic performances	Gross margin (USD) Gross margin max. Yield (USD)	Maize grain yield 12%hum x price sold* - quantities of inputs x input prices	Measurement for yield and farmer surveys for prices/costs
	Return on seasonal investment (USD) Return on seasonal investment max. Yield (USD)	Cash invested/product*	Measurement for yield and farmer surveys for prices/costs
	Cash-inflow needed (USD)	Cash invested at the beginning of cropping season	Farmer survey
	Impact of yield variation on gross margin (%)	$(Abs((average\ Yield - maximum\ yield))/ average\ yield)*100$	
	Impact of maize price variation on gross margin (%)	$[(GM1 - GM2)/GM1]*100$	Measurement for yield and farmer surveys for prices/costs
Weed exposure risks	Season-max weed infestation	Maximum weed score attained along the crop cycle (1 to 9)	Observation
	Early Weed Infestation	Weed score 30 days after sowing (1 to 9)	
Susceptibility to climate variability	Occurrence of water stress (%)	% of cropping situations within CS type for which the ratio (LAI0-LAIw/LAI0)*100 was higher than 10%	PYE model simulation
Labour productivity	Gross margin per man day (USD per man day) Gross margin per man-day (USD per man-day) max. Yield	$[Maize\ grain\ yield\ 12\%hum\ x\ price\ sold* - quantities\ of\ inputs\ x\ input\ prices]/workforce\ needs\ from\ ploughing\ to\ harvest$	Measurement for yield and farmer surveys for prices/costs
	Work drudgery (score)	1: manual weeding and sowing, 2: mechanical sowing and manual weeding, 3: manual sowing and herbicide, 4: herbicide and mechanical sowing	Farmer survey
Soil fertility	Nitrogen balance (kg ha ⁻¹)	Nmin + Nfert - Nuptake With -Nmin=(30/20)*68*[NtotSoil] if pH>7 and -Nmin= (30/20)*0.25*([pH]-3)*68*[NtotSoil] if pH<7 -Nuptake= Ya*21 (21 is N (kg) taken up per ton of maize grain at 12% humidity Standford (1973))	Measurement for NtotSoil, pH and Ya; QUEFTS equations for Nmin (QUEFTS model, Sattari et al. 2014)
	Fertility capital (score)	Indicator 1-acid-base status: score from 1 to 4 given with PCA analysis on variables: CEC, pH, %OM. With 1: acid soils, and 4: basic soils Indicator 2-exportations: [biomass left on soil] / [biomass harvested] Scoring: Fertility Capital=1, if ind1=1 and ind2<0.8 Fertility Capital =2, if ind1= 1 or 2 and ind2>0.8 or ind1>=3 et ind2<0.8 Fertility Capital =3, if ind1>=3 and ind2>=0.8	Measurement for CEC, pH %OM and biomass left and harvested
	Risk of organic matter losses (years)	Number of years, with the cropping system unchanged, to decrease soil organic matter content by half. Mineralisation rate of total organic matter was calculated with the formula: $0,03*(1+0,2*(Tmoy-10))*(1/(1+0,005*[Clay\ Content\ in\ g/kg]))$	Measurement for initial OM content, Tmoy and clay content and formula from Girard et al (2011) to calculate mineralization rate

*: With maize price at 171 USD/tons

Table 8 (continued): Sustainability indicators used to assess maize cropping system (with units in brackets).

Criteria	Sustainability indicators	Calculation	Source of data for indicator computation																				
Herbicide risks	Herbicide treatment risk (score)	<p>$[(\text{applied dose})/(\text{recommended dose} * \text{field area})] * \text{herbicideSolubilityscore} * \text{toxicityscore}$</p> <ul style="list-style-type: none"> - Recommended doses (rec. doses) from local recommendations - Herbicide solubility and toxicity ranked between 1 (low solubility or toxicity) and 4 (high solubility or toxicity) from (PubChem, 2020). Herbicide toxicity estimated with LD50 (median lethal dose on rats) - For the ease of calculation of risk, if paraquat was used, the recommended dose was set to 0.5 even if this herbicide is banned and not recommended by technical services. <table border="1" style="margin-left: auto; margin-right: auto;"> <thead> <tr> <th></th> <th>atrazine</th> <th>glyphosate</th> <th>2.4D</th> <th>paraquat</th> </tr> </thead> <tbody> <tr> <td>Rec. dose</td> <td>1 l/ha</td> <td>1.4 l/ha</td> <td>1 l/ha</td> <td>0.5 l/ha Banned</td> </tr> <tr> <td>solub. score</td> <td>1</td> <td>3</td> <td>2</td> <td>4</td> </tr> <tr> <td>Tox. score</td> <td>2</td> <td>1</td> <td>3</td> <td>4</td> </tr> </tbody> </table>		atrazine	glyphosate	2.4D	paraquat	Rec. dose	1 l/ha	1.4 l/ha	1 l/ha	0.5 l/ha Banned	solub. score	1	3	2	4	Tox. score	2	1	3	4	Farmers survey for applied doses, technician survey for recommended doses
		atrazine	glyphosate	2.4D	paraquat																		
	Rec. dose	1 l/ha	1.4 l/ha	1 l/ha	0.5 l/ha Banned																		
solub. score	1	3	2	4																			
Tox. score	2	1	3	4																			
	Transfer risk due to heavy rainfall (%)	<p>Risk of occurrence of heavy rainfall (>45 mm) the 2 days following herbicide application.</p> <p>Percentage of cropping situations with the risk</p>	Measurement for rainfall																				
	Transfer risk due to soil type (%)	Macro-porosity approximated with soil organic matter content																					
Erosion	Days Plough-sow (score)	Number of days between ploughing and sowing	Farmer survey																				
	Erosive rainfall events (%)	<p>Percentage of fields with bare soil during erosive rainfall events, either already ploughed (1st erosive event in April) or not yet sown (2nd erosive event in May).</p> <p>Erosive events were defined as storm with total rainfall exceeding 12.5 mm and a maximum 10-minutes intensity greater than 25 mm/h (Stocking and Elwell, 1976).</p>	Measurement for rainfall																				
	Runoff risk (%)	% of water runoff on total rainfall (starting from the date of first ploughing and ending at harvest)	Farmer survey for ploughing date, PYE model simulation for runoff and measurement for rainfall																				
	Soil relief (%)	% of situations with macro relief >50 cm	Observation																				
	Slope (score)	1: no slope, 2: medium slope, 3: steep slope	Observation																				
Nitrogen use efficiency	Nitrogen partial productivity (kg maize/Kg N/ha)	Yield 12% Humidity/total N input	Measurement for yield and farmer surveys for N input																				

The model PYE was calibrated against measured values of all cropping situation for LAImax, maize phenology and Yield and yield components. Then, for each cropping situation, we simulated the potential yield (Y0) and water limited yield (YW), PYE being parameterized using the daily weather data of the nearest station and the values measured on the plots for the crop (cultivar), its management (sowing date and plant density), as well as its soil parameters (water holding capacity and soil crust type).

Except for the criteria “susceptibility to water stress” and “nitrogen use efficiency” that were directly assessed each with a single indicator, all the other criteria were assessed with several indicators that were then aggregated to obtain the criteria scores. Explanations on aggregation procedure of indicators are given in section 2.7.

2.6.2 List of sustainability criteria and indicators

Land productivity

Land productivity was assessed with four indicators to be aggregated: average yield, maximum yield, average relative yield gap and risk of very low yield. Average yield was defined as the average yield within a Curr-CS. Maximum yield was defined as the third quartile of yield distribution of cropping situations within a Curr-CS. Relative yield gap between observed yield (Y_a) and water limited potential yield (Y_w) was computed for every cropping situations using PYE. The risk of very low yield was the probability to get a yield below a certain threshold, in the distribution of yields across the cropping situations of the Curr-CS. The yield threshold was set for each cropping system type as the yield below which gross margin becomes negative. In the case of Best-CS, average yield and maximum yield were replaced with the lower and the upper values of the yield range of the Best CS type as defined in section 2.5. The relative yield gap was calculated as the relative difference between these two values.

Economic performance

Economic performance was assessed with seven indicators to be aggregated: gross margin (average and maximum yields), return to seasonal investment (average and maximum yields), cash-flow needed at the beginning of cropping season, impact of yield variation on gross margin and impact of prices variations on gross margin. Gross margin and return to investment indicators were calculated for average yield and maximum yield. The impact of yield variation on gross margin was calculated with the difference between average gross margin and gross margin allowed by the maximum yield in each Curr-CS or Best-CS. This indicator captured the potential, within a cropping system, to increase the gross margin.

Weed exposure risks

Weed exposure risks was assessed with two indicators to be aggregated: (i) Season-max weed infestation (SMWI): the average over cropping situations (within a Curr-CS) of the highest among the weed scores attained along the crop cycle and (ii) Early Weed Infestation (EWI): the average of “weed score 30 days after sowing” (defined in section 2.3).

In the case of Best-CS, SWMI was set to 3.5, and EWI was computed averaging the score at 30 days after sowing over cropping situations whose SWMI was below 3.5.

Susceptibility to climate variability

For both Curr-CS and Best-CS, the susceptibility to climate variability was assessed using the occurrence of water stress expressed as the relative difference ratio $(LAI_0 - LAI_w)/LAI_0$, where LAI_0 and LAI_w are respectively the potential and the water limited values of leaf area index simulated by PYE.

Labour productivity and drudgery

Labour productivity was assessed using the gross margin per man.day worked per hectare for average and maximum yields. Labour productivity was compared to the average value of daily wage for off-farm job on the local labour market.

Work drudgery was assessed with a scoring, depending on whether the sowing was mechanized and if weeds were managed manually.

In the case of Best-CS, the labour and drudgery were set to the values of Curr-CS moto-mechanized (Curr-CS1 and Curr-CS3 in result section).

Soil fertility

Soil fertility was assessed using three complementary indicators to be aggregated: N balance, soil fertility capital and organic matter losses. N balance was calculated using the model Queft (Sattari *et al.*, 2014), yielding the potential quantity of nitrogen left in the soil after maize harvest. The equations of QUEFTS model selected for this study were based on empirical and linear regression equations to estimate the potential soil supplies of available N, based on organic N content and pH. Then maize uptakes of available N were estimated with actual yield per cropping situation.

Soil fertility capital was adapted from the indicator 'Soil acid-base status management' proposed in the method MASC (Sadok *et al.*, 2009). The MASC indicator expresses the impact of pH decrease or increase on long-term soil fertility, soil pH being linked in particular to soil fertility by cation exchange capacity, aluminium toxicity, and soil biological activity decrease. Our version of this indicator was made of two sub-indicators: acid-base status and exportation by crops. Acid-base status was a score from 1 to 4 attributed to cropping situations with a principal component analysis on the following variables: CEC, pH, %OM. Score of 1 meant low acid-base status and score of 4 meant high acid-base status. Exportation by crops was calculated as the ratio $[\text{biomass left on soil}]/[\text{biomass harvested}]$, a ratio below 0.8 was

defined to mean “high exportation”. The two indicators of acid-base status and exportation by crops were aggregated with decision rules based on thresholds, leading to 3 levels of fertility capital (rules and threshold are displayed Table 8).

The organic matter losses were estimated with an empirical equation of total mineralization (Girard *et al.*, 2011) linking clay content and average annual temperature to an estimation of an annual mineralization rate. The number of years to decrease the organic matter stock by half was then estimated from this rate.

Nitrogen balance for Best-CSs were, by construction, equal to zero since fertilization doses were calculated to compensate maize uptakes. Nitrogen mineralization were calculated per soil type and nitrogen uptake calculated targeting the lower limit of yield. Soil fertility capital were calculated with biomass restitution of Best-CS estimated from the observed best cropping situation (selected to determine the lower limit of Best-CS yield) and the average acid-base status of Curr-CS.

Herbicide leaching Risk

Herbicide leaching risk was estimated with three indicators aggregated to obtain a score on the criterion: 1) The herbicide treatment risk calculated as the number of local recommended doses applied multiplied by the herbicide solubility score. 2) The risk of herbicide transfer due to percolation assessed with a score accounting for the presence of a heavy rainfall exceeding 45 mm in 3 hours in the two days following the herbicide application (Tasli *et al.*, 1996). The risk was assessed in 2017 and 2018 for which hourly data of rainfall were available. 3) The risk of herbicide transfer enhanced by the soil type, as herbicide leaching also depends on soil macro-porosity through water infiltration (Siczek *et al.*, 2008). Soil macro-porosity may be created by abiotic factors (e.g. tillage) or biotic factors (soil faunal activity, root growth), we approximated here the macro-porosity using plots’ soil organic matter content because organic matter indirectly increases porosity via increased soil faunal activity (Franzluebbers, 2011).

In the case of Best-CS, the products and doses applied were local recommendations.

Erosion risk

Erosion risk was estimated using five indicators to be aggregated: (i) the average number of days between ploughing and sowing, (ii) the percentage of fields already ploughed but not yet

sown during the period during which erosive rainfall events occur, (iii) the runoff risk, (iv) the slope and (v) the soil micro-relief mitigating erosion between ploughing and sowing.

Adapting from Stocking and Elwell (1976) in order to account for the best time resolution of ten minutes for measuring rainfall intensity, we defined erosive rainfall event as a rainfall greater than 12.5mm when cumulated over the full event, and whose intensity over 10 minutes is greater than 25 mm/h (intensity was measured over 5 minutes in the reference cited above). Erosive rainfall events were only identifiable from July 2016, as the public weather station did not provide the 10-minute time step measurements needed for their identification.

The runoff risk was estimated using PYE model whose runoff module is adapted from Albergel et al. (1991) and accounts for interaction between the time sequence of daily rainfall, soil crust type, and LAI as assumed to decrease the kinetic energy of rain drops when reaching the ground. Since LAI in PYE is influenced by plant density, this latter variable indirectly influenced our estimates of runoff. The runoff risk indicator was computed as the ratio (in %) of simulated runoff over rainfall as cumulated from the date of ploughing to that of harvest.

Nitrogen use efficiency

The nitrogen use efficiency was assessed with N partial productivity, the ratio of maize yield on total nitrogen fertilization applied. Nitrogen fertilization applied of two distinct cropping system types was assumed identical if their confidence intervals overlapped.

2.7 Aggregation of indicators and AMOEBA charts

2.7.1 Comparison of Curr-CS

In order to have a comprehensive and comparative assessment, we used AMOEBA diagrams to graphically integrated indicators on criteria (Ten Brink *et al.*, 1991). AMOEBA stands for 'general method of ecosystem description and assessment' (Wefering *et al.*, 2000). In the AMOEBA approach, a reference system is built with desirable 'sustainable levels' for indicators. Instead of setting arbitrary desirable states, we built our reference system by ranking each indicators' values per Curr-CS. For each indicator, the cropping systems were compared by attributing a score from 1 to 5, with 1 the worst cropping system and 5 the best. When possible, the rank assigned to each Curr-CS for each indicator was not based on the

average value of each indicator but based on the confidence interval around the average from the distribution of cropping situations composing a Curr-CS (80% confidence interval). Different averages but within the same confidence interval resulted in equal scores. Confidence intervals were calculated for the following variables: yield, relative yield gap, gross margin, highest and weed score 30 days, labour productivity, nitrogen balance, days of bare soil.

Then, to obtain a rank at criteria level (criterion score), indicators' scores were averaged (without weighing them) at criteria level using the geometric mean. This method, contrary to arithmetic mean calculation, accounted for antagonism between indicators to be aggregated. The objective was to limit compensation between indicators when averaging indicators to the criterion level. Compensation may have hidden low scores on an indicator by the high score on another indicator.

$$\text{Criterion score} = \sqrt[n]{\prod_i^n \text{indicator } i},$$

with n = the number of elementary "indicator i " to be aggregated for one criterion, and *indicator* the rank attributed to elementary indicators per cropping system.

A first cropping system having a low score on one indicator (ex: 1,4,4,3) will result in an aggregated score to the criteria of 3 with the arithmetic mean and 2.63 with the geometric mean. A second cropping system having medium scores for every indicator (ex: 3,3,3,3) will result in an aggregated score of 3 with both the arithmetic and geometric means. The arithmetic mean ended up with equal ranks for the two cropping systems whereas the geometric mean classified the first system lower than the second due to its bad performance on one indicator.

2.7.2 Sustainability improvement allowed by Best-CS

Ratios were calculated for each indicator to quantify the relative performance of Best-CS compared to its corresponding Curr-CS (see below). Then indicator ratios composing each criterion were averaged with the geometric mean to obtain improvement scores allowed by Best-CS at the criteria level. If the Best-CS brought an improvement on indicator i compared to Curr-CS, the ratio for indicator i was:

$$\text{Ratio } i = (\text{Performance on indicator } i \text{ with Best-CS}) / (\text{Performance on indicator } i \text{ with Curr-CS})$$

If the Best-CS decreased the performance on indicator i , the ratio was:

Ratio $i = (\text{Performance on indicator } i \text{ with Curr-CS}) / (\text{Performance on indicator } i \text{ with Best-CS})$

Improvement score on criteria $j = \sqrt[n]{\prod_i^n \text{Ratio } i}$,

No improvement with Best-CS for criteria j will score 1, a deterioration of criteria j will score below 1 and an improvement above one.

Overall sustainability improvement = $\sqrt[9]{\prod_j^9 \text{Improvement score criteria } j}$

The geometric mean of improvement scores assessed the overall sustainability improvement allowed by each Best-CS. The number 9 was the number of criteria assessed. If the mean was above 1, the cropping system sustainability was improved “overall” by best-CS. We assumed limited compensations between sustainability criteria to assess sustainability overall: cropping systems with a decreased performance on a criterion and high improvement on others will score lower than another cropping system with medium improvement on each criterion.

3 Results

3.1 Climate drivers that may influence cropping systems performances

On the historical dataset, the average total annual rainfall was 1273 mm and the average cropping season rainfall (May-September) was 895 mm. The average starting date of the rainy season was 22 March. The threshold date, from which a year was identified as having a delayed rainy season, was found to be the 9th of April. Seven years on 19 had a period of five consecutive dry days in May. The risk of sowing failure in May was therefore 36.8%.

The three years of our on-farm plot monitoring were found to correctly represent the historical rainfall variability. Years 2016 and 2017 belonged to the first quartile of “total cropping season rainfall” distribution and 2018 to the last quartile. Year 2017 was a dry year with a late start of the rainy season and a 14-days dry period in May (total rainfall: 875 mm, cropping season rainfall: 549 mm, starting date for the rainy season: April 13). The year 2018 was an extra wet year with a late start of the rainy season and no dry day period in May (total rainfall of 1570 mm, cropping season rainfall: 1251 mm, starting date for the rainy season: 15 April). Available data for 2016 showed two periods of six consecutive dry days in May.

3.2 Current cropping systems typology and Best-CS determination

From the 99 initial cropping situations monitored, 89 situations were clustered successfully in five clusters with a number of cropping situations above 10. The five Curr-CS types retained for the sustainability assessment were three Curr-CS with moto-mechanized sowing and two Curr-CS with manual sowing. They are described hereafter, with confidence intervals at 80% given between brackets for plant density, nitrogen fertilization and period between ploughing and sowing.

Curr-CS1: 'mechanical sowing, no harrowing, sandy soils, herbicide use' (number of cropping situations: 10) are mechanical sowing cropping situations on poor sandy soils. No harrowing is performed. Ploughing is done once, in April and soil clods are left to be crushed by rain until sowing 29.5 (± 5) days after ploughing. The plant density reached 4.5 (± 0.6) plants/m². Low doses of mineral fertilizer were used (10 (± 3) kg N/ha) and farmers relied exclusively on herbicide to manage weeds.

Curr-CS2: 'mechanical sowing, harrowing, sandy-Loamy soils, no herbicide' (number of cropping situations: 15) are mechanical sowing cropping situations on sandy-loamy soils. Consistently with the soil texture which makes less likely than in sandy soil for rains to crush clods, farmers harrowed before sowing with a disc harrow. Low period between ploughing and sowing (23 (± 3) days) makes more difficult the clods to crush compared to Curr-CS3 (see below). The plant density reached 3.7 (± 0.2) plants/m². They exclusively used hand weeding for weed management and an amount of nitrogen fertilization of 12.4 (± 3) kg N/ha.

Curr-CS3: 'mechanical sowing, harrowing, clayey and loamy-clayey soils, herbicide' (number of cropping situations: 32) contains mechanically sown cropping situations with harrowing before sowing on clayey soils with a long period between ploughing and sowing (mean of 38 (± 5) days). Weeds are managed by a combined use of chemical and mechanical destruction. The harrowing mechanically destructs weed plantlets, which emerged during the period between ploughing and sowing. Weeds that germinate after maize emergence are then sprayed with herbicide. The plant density reached 4.8 (± 0.26) plants/m². Farmers used 15.5 (± 3) kg N/ha of nitrogen fertilization in average.

Curr-CS4: 'hand sowing, no harrowing, sandy-clayey soils, low sowing hole density, herbicide' (number of cropping situations: 20) contains hand sown cropping situations on sloping land

with no harrowing before sowing on sandy-clayey soils. Ploughing is done once, in late April and soil clods are left to be crushed by rain until sowing (22 (\pm 2) days on average). Maize was sown manually with two seeds per hole made with a digging stick, resulting in a low hole density (mean 2.5 (\pm 0.2) holes/m²) and large space (and light for weeds) between holes even if plant density averaged 4.6 (\pm 0.5) plants/m². Low doses of mineral fertilizer were used (mean 8.7 (\pm 4) kg/ha). They used manual and herbicide control to manage weeds infestation.

Curr-CS5: 'hand sowing, no harrowing, loamy-clayey soils, no fertilizer' (number of cropping situations: 12), contains hand sown cropping situations on fertile loamy–clayey soils. They had a short period between ploughing and sowing (mean 13.3 (\pm 3) days). The difference between hole and plant densities was not significant compared to the difference found for Curr-CS4. Sowing hole density reached 3.8 (\pm 0.4) holes/m² and plant density 4.3 (\pm 0.4) plants/m². Herbicide was used but no mineral fertilizer was applied.

Best-CS1 to Best-CS5 were defined, each corresponding to Curr-CS1 to Curr-CS5. From the analysis of climate drivers (section 3.1.) it was concluded that all these Best-CS would have a ploughing beginning from mid-April with the objective to target a moto-mechanized sowing in early June, May being identified as a risky month for sowing in the analysis of climate variability. In every Best-CS, soils are let 1-1.5 months bare after ploughing to let weed plantlets emerge. They are then harrowed, even for sandy soils, just before sowing with a cultivator, instead of a small disc harrow currently used. This practice intends to create a good seedbed facilitating mechanical seedler operation. Weeds plantlets are also mechanically destroyed by harrowing to reduce weed infestation at maize emergence. Just after harrowing, mechanical sowing is done early June with a seedler well mounted and set to reach the maximal plant density of 7.14 plants/m² allowed by the seedler. Herbicides are used to the recommended doses only if the mechanical destruction of weeds had not succeeded. Best-CS 1 to 5 differed by the fertilization amounts that resulted from the objective of having a nitrogen balance equal to zero and accounting for the organic nitrogen content and mineralization rates of the different soil types. These fertilization rates were 80, 60, 67, 75 and 22 kg N/ha for respectively Best-CS1, Best-CS2, Best-CS3, Best-CS4, Best-CS5.

3.3 Sustainability assessment of current maize cropping systems (Curr-CS)

Land productivity

Land productivity was highly variable across and within Curr-CSs (Table 9). The worst systems for land productivity criterion were the manual maize with low sowing hole density Curr-CS4 and the moto-mechanized systems Curr-CS1 and Curr-CS2 (Figure 13). Their yields averaged respectively 2.2, 2.9 and 2.9 tons/ha. The best systems on land productivity criterion were Curr-CS3 and Curr-CS5 reaching 3.7 and 3.8 tons/ha for average yield respectively. Yield thresholds leading to a risk of negative gross margins were for Curr-CS1 to CS5: 1, 1.3, 1.5, 1.1 and 1 tons/ha. This risk was the highest for Curr-CS4 due to high proportion of plots below 1.1 tons/ha (14%).

Economic performance

The best Curr-CS for economic performance criteria was manual maize Curr-CS5 and the worst manual maize Curr-CS4. Curr-CS5 had the highest gross margin (473 USD/ha) due to low cash-flow needed and its high yield. Moto-mechanized Curr-CS3 had the highest cash-flow needs but nevertheless ended up with the second-best gross margin alongside Curr-CS1. Curr-CS4 had the lowest gross margin, on the same level than Curr-CS1 and Curr-CS2 (considering confidence intervals). But Curr-CS4 performed also the lowest on other indicators contrarily to Curr-CS1 and Curr-CS2. Moto-mechanized Curr-CS1 had the lowest cash-flow needs (after Curr-CS5), resulting in a good return to seasonal investment despite its low yield. Curr-CS2 (mechanical sowing, harrowing, no herbicide) had the greatest potential for increasing its gross margin by reaching the maximum yield (see impact on gross margin indicator). Curr-CS2 may be able to increase its gross margin by 45.3% when yielding at maximum yield compared to average yield.

Weed exposure risks

The lowest risks of exposure to weed infestation were observed for manual maize Curr-CS5 and Curr-CS3 and the highest were observed for Curr-CS2 (no herbicide) and Curr-CS4.

Susceptibility to climate variability

Moto-mechanized Curr-CS2 and hand sown Curr-CS4 situations were the most affected by water stress with respectively 27% and 40% of situations having a water stress ratio above 10%. Water stress occurred mostly in 2017 (77% of water stress situations) and was caused by

a too early sowing, before the date from which there was no period of five consecutive days without rain (June 3rd for Year 2017).

Table 9: Sustainability indicator results for 5 current maize cropping systems. Confidence intervals at 80% in brackets. Curr-CS1: mechanical sowing, no harrowing on poor sandy soils, herbicide; Curr-CS2: mechanical sowing, harrowing on sandy-loamy soils, no herbicide; Curr-CS3: mechanical sowing, harrowing on clayey-loamy soils, herbicide; Curr-CS4: hand sowing, low sowing hole density, herbicide; Curr-CS5: hand sowing, fertile soils, no fertilizer.

	Curr-CS1	Curr-CS2	Curr-CS3	Curr-CS4	Curr-CS5
Land productivity					
Average yield (tons/ha)	2.9 (0.4)	2.9 (0.3)	3.7 (0.2)	2.2 (0.3)	3.8 (0.4)
Maximum yield (tons/ha)	3.5	3.6	4.2	2.7	4.4
Relative Yield gap (%)	56.9 (9)	57.7 (5)	47 (4)	66 (5)	48 (6)
Risk due to very low yield (%)	10	6	6	14	0
Economic performances*					
Gross margin average yield (USD/ha)	313 (78)	264 (54)	379 (39)	206 (46)	473 (61)
Gross margin maximum yield (USD/ha)	423	384	465	276	583
Return on seasonal investment average yield (USD)	1.8	1.1	1.5	1.1	2.8
Return on seasonal investment maximum yield (USD)	2.4	1.6	1.8	1.5	3.5
Cash-inflow needed (USD)	175.9	232	253.6	186	169
Impact of yield variation on gross margin (%)	+34.9	+45.3	+22.6	+34	+23.4
Impact of prices variations on gross margin (%)	-11	-13.3	-11.8	-17.5	-8
Weed exposure risks					
Season-max weed infestation (score)	5.6 (0.8)	6.9 (0.6)	4.6 (0.4)	6 (0.4)	4.2 (0.4)
Early Weed Infestation (score)	4.1 (0.9)	3.9 (0.6)	2.8 (0.2)	3.4 (0.4)	2.7 (0.5)
Susceptibility to climate variability					
Occurrence of water stress (%)	0	27	0	40	8
Labour productivity and drudgery					
Gross margin average yield per man day (USD per man day per ha)	6.1 (1.5)	4.3 (0.9)	7.4 (0.8)	2.8 (0.6)	6.5 (0.8)
Gross margin maximum yield per man day (USD per man day per ha)	8.3	6.3	9.1	3.8	8
Work drudgery (score)	4	2	4	3	3
Soil fertility					
Nitrogen balance (kg ha ⁻¹)	-26 (11.3)	-2 (13)	-20 (7.7)	0 (7.7)	9 (14.2)
Soil fertility capital aggregated score	1.8	1.8	2.1	1.7	2.3
Organic matter losses (in years to decrease half of the stock)	9.2	13.8	14	11.9	12.8
Herbicide risk					
Herbicide treatment risk (score)	17(7)	0	24(9)	13(5)	30(7)
Transfer risk due to heavy rainfall (%)	0	0	13	10	8
Transfer risk due to soil type (%)	1.8	2.5	2.5	2	2.5
Erosion risks					
Days plough-sow (number of days)	29.5(5)	23.3(3)	38.4(5)	22.2(2)	13.3(3)
Bare soil during the 2 erosive events (%)	50.2	50	84	60	50
Runoff risks (%)	7.6	4.8	4.4	4.6	7.5
Slope (score)	1.3	1.5	1.3	2.8	2.0
Soil relief (%)	7	20	9	6	50
Nitrogen use efficiency					
N partial productivity (kg Maize/KgN/ha)	256.8	184.9	204.8	238.1	-

* with maize price at 171 USD/tons

Labour productivity

Gross margin per man day were the highest for Curr-CS3, Curr-CS5 and Curr-CS1. The labour productivity criterion was the highest for moto-mechanized system Curr-CS3 and the lowest for manual maize curr-CS4. At average yield the labour productivity of Curr-CS3 was 7.4 USD/man day/ha for Curr-CS3, which was significantly above Curr-CS2 and Curr-CS4. The daily income in Kham District for off-farm jobs was 7.3 USD/days. Only Curr-CS3 was markedly above the daily off-farm income, and even at their maximum yield, Curr-CS2 and Curr-CS4 remained below the off-farm daily income. The systems with the lowest work drudgery were Curr-CS1 and Curr-CS3, due to moto-mechanized sowing and herbicide spraying instead of hand weeding.

Soil Fertility

Impacts of maize on soil fertility varied greatly depending on the soil type, the worst system being the Curr-CS1 on sandy soils with a negative nitrogen balance of -26kg N/ha, a soil fertility capital of 1.8 and an organic matter stock that may be decreased by half in 9 years. The best system for soil fertility was Curr-CS5 with a positive nitrogen balance (+9 kg N/ha), a soil fertility capital of 2.3 and an organic matter stock that may be decreased by half in 13 years.

Herbicide Risk

Every Curr-CSs applied herbicide higher than the recommended dose except for Curr-CS2 (no use of herbicide). Herbicide treatment risk was the highest for Curr-CS5 (8.9 (± 1.5) times the recommended doses and a risk indicator of 30 (± 7)). Other cropping systems using herbicide were also above recommended doses: Curr-CS1 (7.4 (± 2.6) times the recommended dose, and risk of 17 (± 7)), Curr-CS3 (3.8 (± 0.5) times the recommended dose and risk of 24 (± 9)), Curr-CS4 (3.8 (± 0.9) times the recommended dose and a risk of 13 (± 5)).

In 2018, the year for which drainage was the highest, drainage first occurred from 19 July. Drainage risk was extremely high in 2018 with 45.3-43.9 % of rainfall drained from ploughing to harvest. Drainage occurred mostly at the beginning of the cropping season, starting from mid-July for years 2017 and 2018. A late application of herbicide implied more risks for herbicide leaching. Such fields with late application were identified for Curr-CS3 and Curr-CS4. Moreover, these Curr-CSs contained situations that were sprayed and followed by a heavy rainfall (>45 mm) in the 2-day period after application.

Erosion Risk

None of the systems performed well on erosion indicators. Curr-CS3 had a long period between ploughing and sowing (38 days) and had its soils more frequently exposed to erosive rainfalls but cropping situations were more frequently flat. The runoff risk indicator did not vary much between systems, but a higher risk was identified for year 2017. During ploughing and sowing, heavy rainfalls may increase the risk of erosion and drainage. In 2017, two erosive rainfall events occurred during the most common period between ploughing and sowing, on the 23rd of April and the 12th of May. The events had respectively maximum rainfall intensities of 32.9 mm/h and 61.18 mm/h. Afterward during the cropping season in 2017, eight other erosive rainfall events occurred between 14th of July and 10th of October, with an average intensity of 54 mm/hours. In 2018, two erosive rainfall events occurred on the 18th of April and the 11th of May with respectively maximum rainfall intensities of 44.7 and 76.5 mm/h. Afterward, 13 erosive rainfall events occurred from 2nd of June to 22nd October, with an average intensity of 55.1 mm/h.

Hand sown situations were more frequent on sloping land (score of 2.8 and 2 for respectively Curr-CS4 and Curr-CS5) which may favour erosion risks despite shorter period of bare soil on average (22 and 13 days for respectively Curr-CS4 and Curr-CS5). For Curr-CS5, the presence of soil micro/macro reliefs after ploughing may however mitigate erosion.

Nitrogen use efficiency

Curr-CS5 was ranked better on nitrogen use efficiency, which was not surprising since no fertilizer is applied on this system. No clear difference was found between the other Curr-CSs (same dose of 12 kg N/ha kept for the calculation), except for Curr-CS3 having a higher Nitrogen partial productivity due to its higher yield.

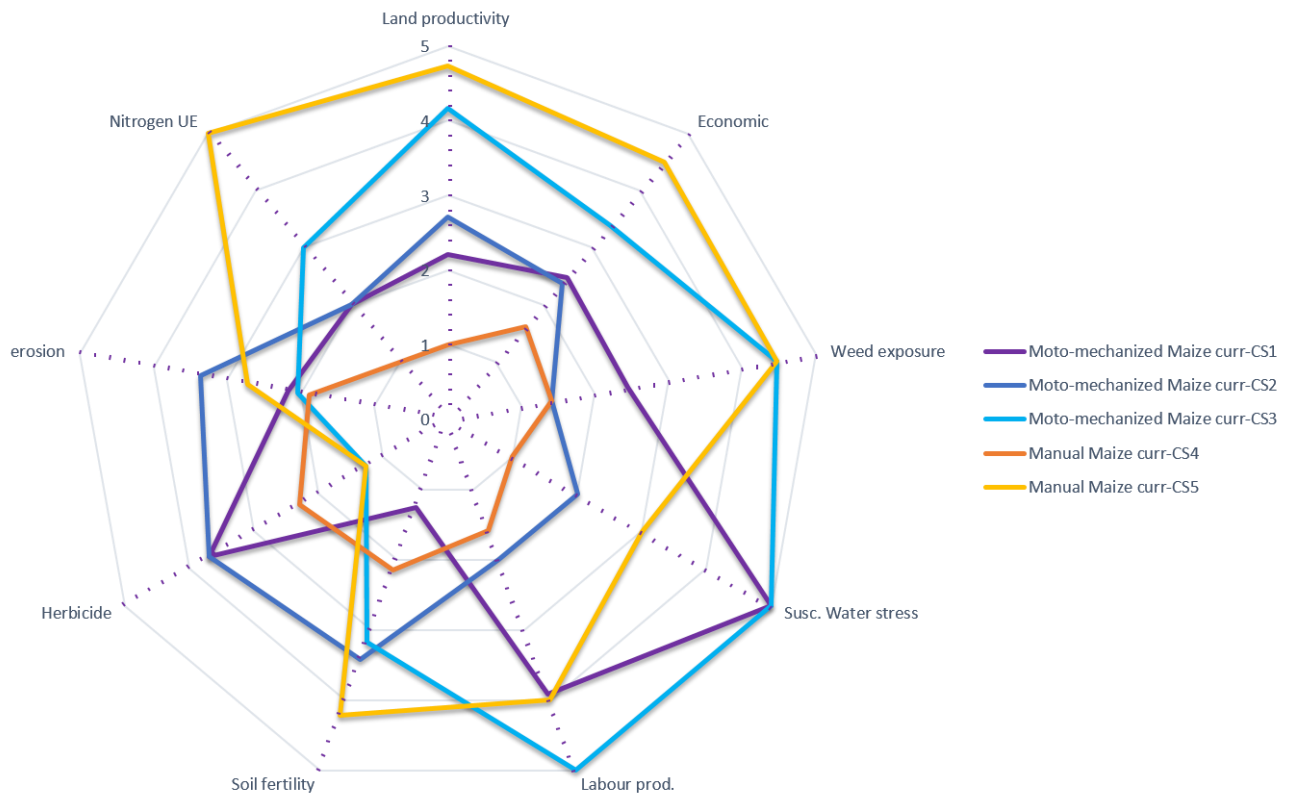


Figure 13 : AMOEBA diagram of sustainability criteria for the 5 maize cropping systems. The cropping systems were ranked by attributing a score from 1 to 5 on every indicator that composed a criterion, with 1 the worst system and 5 the best. Then ranks were averaged to the criterion level with the geometric mean. A smaller area on the diagram means a lower overall sustainability performance. Nitrogen UE: Nitrogen use efficiency, Susc. Water stress: susceptibility to water stress, Labour prod.: labour productivity

To sum up (Figure 13), the more sustainable cropping systems with the largest area on the AMOEBA diagram were manual Curr-CS5 and moto-mechanized Curr-CS3. Curr-CS3 performed best, compared to Curr-CS5 on susceptibility to water stress and labour productivity criteria. Curr-CS5 performed best, compared to Curr-CS3, on land productivity, economic performances, soil fertility and nitrogen use efficiency criteria. Curr-CS5 better sustainability is largely due to the fact that it is cultivated on more fertile soils. The less sustainable cropping system with the smallest area on the AMOEBA diagram was manual curr-CS4. Curr-SC4 performed the lowest on every criterion except for soil fertility and herbicide criteria for which Curr-CS4 was ranked second worst for soil fertility and second best for herbicide.

It is worth noting that there was virtually no fertility management in every Curr-CSs. If combined with important soil nutrient drainage, as it was the case in 2018, it may lead to soil fertility depletion over the long-term. Erosion and herbicide risks were a critical issue for every Curr-CS. The only system that did not use herbicide was moto-mechanized Curr-CS2, but this

system was among the worsts on every other sustainability criteria except for erosion and soil fertility.

3.4 Sustainability improvement allowed by Best-CS

When comparing best-CS4 with the less sustainable system that is Curr-CS4, yield is multiplied by 2.5, gross margin by 2.7, labour productivity by 3.9 and herbicide criterion is improved by 4.3 (Table 10). The downside of Best-CS4 was the high cash inflow needed and erosion risk increased. In the case of the already best performing systems regarding land productivity and economic criteria (Curr-CS3 and Curr-CS5) applying Best-CS would also improve their gross margin, but at a lower rate of 1.6. On herbicide criteria, these systems had the highest improvements allowed by Best-CS (improved by 8 or 10) (Table 10). However, Best-CS5 resulted in an erosion performance divided by 2 compared to Curr-CS5.

The gross margin allowed by Best-CSs ranged between 545 and 742 USD/ha. Applying Best-CS more than doubled gross margins of Curr-CS2 and Curr-CS4. If we consider that a family is composed of six persons and maize area averaged 2 ha per farm, cultivating a Best-CS will allow, at least an income of 0.5 USD/day/person and at best of 0.7 USD/day/person. Whereas this daily income ranged only from 0.15 to 0.48 USD/day/family member with current cropping systems (confidence interval considered). Every Best-CSs were competitive with off-farm opportunities of revenue since labour productivity was between 10.7 and 14.6 USD/worked days while a day worked off-farm was paid 7.3 USD.

Table 10: Comparison ratios of Best-CS (maize cropping system targeting yield gap and herbicide reduction) to their corresponding Curr-CS. A ratio below 1 means a lower performance of the Best-CS compared to Curr-CS.

		Best-CS1	Best-CS2	Best-CS3	Best-CS4	Best-CS5
Land productivity	Average yield	1.9	2	1.6	2.5	1.5
	Maximum yield	1.8	1.8	1.5	2.3	1.5
	Relative Yield gap	1.9	2	1.6	2.4	1.5
	Risk due to very low yield	1.1	1.1	1.1	1.2	1
Economic performance	Gross margin average yield	2	2.3	1.6	2.7	1.6
	Gross margin maximum yield	1.7	1.9	1.5	2.5	1.6
	Return to seasonal investment average yield	1	1.5	1.1	1.3	1.3
	Return to seasonal investment maximum yield	0.7	1	0.9	1	1.1
	Cash-inflow needed	0.5	0.6	0.7	0.5	0.8
	Impact of yield variation on gross margin	2	2.8	1.5	1.6	0.9
	Impact of prices variations on gross margin	1	1.2	1	1.7	1.7
Weed exposure risks	Season-max weed infestation	2	2.7	5.3	2.7	1.1
	Early Weed Infestation	1.3	1.1	1.3	1.1	1
Susceptibility to climate variability	Water Stress	1	1.4	1	1.2	1.1
Labour productivity and drudgery	Gross margin average yield per man day	2	2.8	1.6	3.9	2.2
	Gross margin maximum yield per man day	1.4	1.9	1.3	3	2
	work drudgery	1	2	1	1.3	1.3
Soil fertility	Potential Nitrogen balance	1.3	1	1.2	1.2	1.2
	Soil fertility capital aggregated score	1.1	1.1	1.4	1.2	1.3
	Number of years to reach half of OM stock	1	1	1	1	1
Herbicide risk	herbicide treatment risk	5.7	0.9	8	4.3	10
	transfer risk due to rainfall	1	1	1.1	1.1	1.1
	transfer risk due to soil type	1	1	1	1	1
Erosion risk	Days plough-sow	0.7	0.6	0.9	0.5	0.3
	Bare soil during the 2 erosive events	0.6	0.6	1	0.7	0.6
	Runoff risks	1	0.9	0.7	1	0.7
	Slope	1	1	1	1	1
	Soil relief	1	1	1	1	0.3
N ressource UE	N ressource UE	0.3	0.5	0.4	0.3	0.1

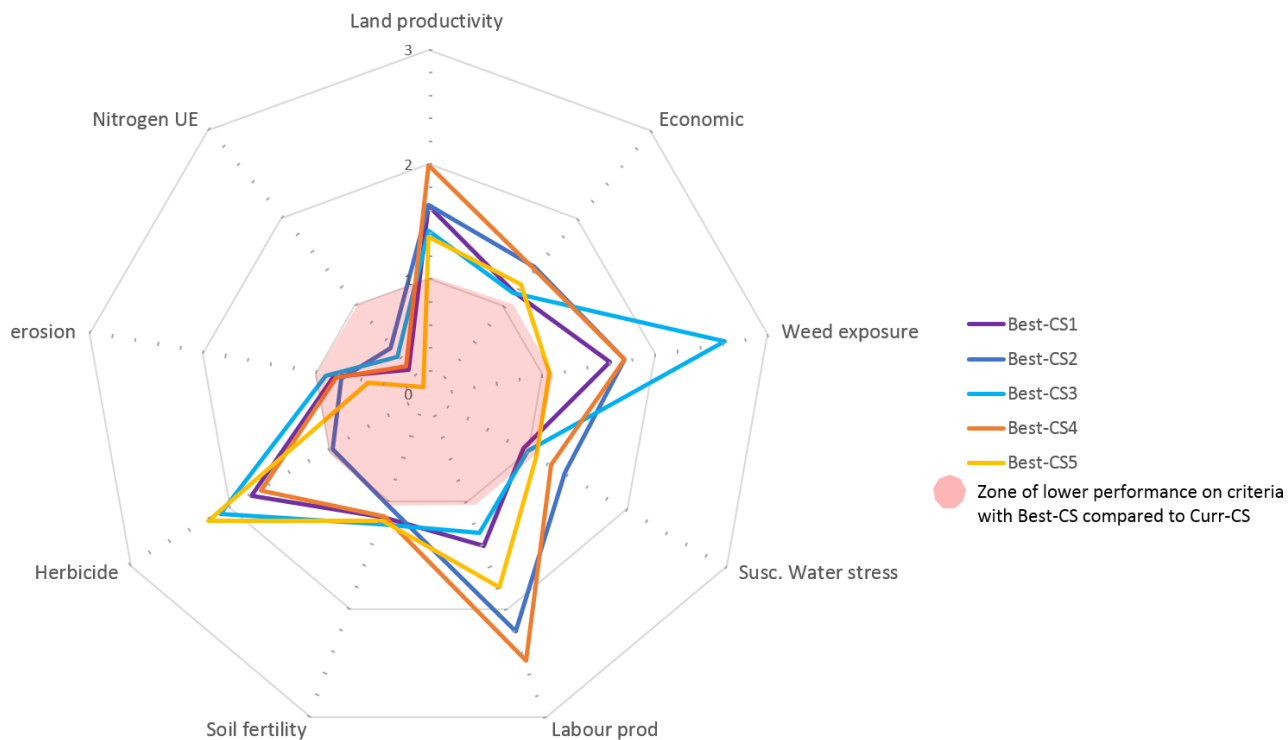


Figure 14 : Spidergram of sustainability improvement allowed with Best-CS.

A score on a criterion corresponds to the geometric mean of the ratios of indicators composing a criterion (ratio = Best-CS/Curr-CS if improvement with Best-CS and Curr-CS/Best-CS if there is a decreased performance with Best-CS). On the spidergram, a score of 1 means no change with the Best-CS and a negative score means a decreased performance on the criteria overall with Best-CS. Nitrogen UE: Nitrogen use efficiency, Susc. Water stress: susceptibility to water stress, Work prod.: work productivity

To sum up (Figure 14), Best-CSs improved all Curr-CS performances on the following criteria: land productivity, susceptibility to weed and water stress, and labour productivity. In Curr-CSs using herbicide, Best-CSs allowed to multiply by 4 (at least) the performance on herbicide criteria. However, Best-CSs decreased the performances of all Curr-CSs on nitrogen use efficiency and erosion and have limited effect on soil fertility (Figure 14). Sustainability was increased overall by Best-CS for every Curr-CS except for Curr-CS5. The improvement allowed by Best-CS5 on the herbicide criterion did not compensate for the reduced performance on nitrogen use efficiency and erosion.

4 Discussion

Our assessment used a diversified set of indicators in order to assess the different dimensions of maize cropping systems sustainability in farmers' fields of northern Laos and identified possibilities of improvement allowed by "best managed cropping systems" alongside these indicators. There is limited empirical evidence to quantify environmental degradation issues

due to maize monocropping in Laos (Lestrelin, 2010). This study is the first detailed integrated and in-farmer field assessment of maize cropping systems sustainability in Southeast Asia. When imagining solutions to the dilemma of improving productivity while limiting the environmental impact, rural development stakeholder may be tempted to get rid of maize, a crop usually blamed for its low sustainability (Viau *et al.*, 2009; Shattuck, 2019). Especially on steep and thus vulnerable slopes of mountainous Southeast Asia where maize could be unsustainably grown as a response to a growing market for animal feed (Zimmer *et al.*, 2018). However, in Southeast Asia there are also many wide plains and plateaus within the mountains, where it is more opportune to look closely at the sustainability of maize cropping before deciding that it should be replaced by something else. It is in this context that our study looked at how far a simple improvement of crop management had the potential to improve sustainability.

4.1 Are current maize cropping systems of the region sustainable and under what conditions?

Maize yield was found to be below the national average of 5.4 tons/ha for years 2016-2018 (FAOSTAT, 2018) for every maize cropping systems. Our results appeared to be more similar to a quantified study made in Vientiane province that found an average yield of 2.3 tons/ha and a maximum yield of 4.9 tons/ha (Asai and Soisouvanh, 2017). In addition to low yields, herbicide sprayed could reach up to 8 times the recommended dose while some transfer risks have been identified enhancing the risk of leaching to groundwater and runoff to surface water: heavy rainfall just after spraying, high drainage risk in 2018, and the use herbicides with high solubility.

Our findings provide insights into the debate on mechanization and sustainability. Several studies highlighted the importance of small mechanization appropriate to smallholders to enhance sustainability of cropping systems (Baudron *et al.*, 2015; Sims and Kienzle, 2016). Small mechanization may address key sustainability issues such as reducing work drudgery and relaxing peak-season labour constraints, and improving labour productivity and timeliness of field operations (Mutyasira *et al.*, 2018; Laing *et al.*, 2018; Aryal *et al.*, 2019). However, our results indicate that depending on soil types, a poorly mastered sowing mechanization is not necessarily more sustainable than manual sowing. In the current state of low and highly variable economic performances and land productivity, it is probably not profitable for

farmers to invest in the costly moto-mechanization if they have fertile loamy-clayey soils, highly available workforce, an efficient crop management and higher labour productivity than with off-farm activity. By contrast, if they access to poor sandy soils, moto-mechanization can more than double the land productivity, economic performances and the labour productivity. More off-farm work opportunities may appear in the region entailing structural changes in the sources of rural household incomes and transforming farmers from 'peasants into post-peasants' (Rigg, 2006a). If at the same time local maize price decreases, as it has been observed in the neighbouring province of Houaphan (Kallio *et al.*, 2019), farmers practicing low-performing cropping systems (Curr-CS1, CS2 and CS4) may start abandoning maize cultivation. At such low labour productivity (2.8 USD/man day for Curr-CS4), maize may also be replaced by other farm activities like improved pasture and livestock system highly promoted by successive political plans at the province scale (Nampanya *et al.*, 2017; Millar and Photakoun, 2008). Such transformation for the low-performing maize cropping systems may improve sustainability overall. Farmers would shift away from mono-cropping with a diversification of their activities. Some weaknesses of the current maize-based systems, especially weed management and soil fertility, may be thus addressed by rotations with improved pasture (Pravia *et al.*, 2019; Cardina *et al.*, 2017). However, since 2003, maize price globally increased in the international market (from 107.2 USD/Metric ton in June 2003 to 123.2 USD/metric ton in June 2018) (WFP, 2018). In the near future, grain production will be essential to feed the sub-region and the planet (Chen and Lu, 2019). This plain could have a comparative advantage in making grain rather than raising livestock, an activity usually suited to steeper environments where cultivating crop is more difficult.

4.2 How far a better mastering of crop management can improve sustainability?

Given these trends, it was worth taking a closer look at whether improved control of mechanisation, even for the least efficient systems, can significantly improve the different dimensions of sustainability. The possibility to increase sustainability with a better mastering of crop installation differed from one cropping system to another. Improvements depends on current farmer technical mastery of the technic to be improved (here, the crop installation) and their soil types. This finding is in accordance with the recommendation made by (Daum and Birner, 2020) that future research on mechanization needs to question which type of

mechanization is best for farmers and the environment depending on the farming system, agro-ecological zone and soil types.

Best-CSs are far from perfect on every sustainability criteria but they have the virtue of addressing the issues of land productivity and herbicide use. There remains potential for improvement on criteria like resource use efficiency, erosion, soil fertility and biodiversity (not measured in this study). Future climate change in northern Laos calls for a climate-smart transition of cropping systems. Future projections in IPCC AR5 scenario predicted a warmer climate, more frequent extreme climatic events and more intense precipitations (Hijioka *et al.*, 2014). The current trend of shifting to commercial agriculture based on grain markets may lead to an increase in harvest index of crops in the future. Therefore, while the climatic risks will rise in the future, the crops will be more climate-sensitive, with more risks of crop water stress and climatic events impacting the grain filling. Cropping systems with low density and long period between ploughing and sowing will have their environmental risks (water percolation, runoff, erosion) accentuated. A more sustainable cropping system for the region will have to increase the sizes of the canopy and the rooting zone, as well as the duration for which these sizes are large. Solving crop installation issues is a relevant first step of climate-smart transition but future research will have to go further to solve erosion, resource use efficiency and biodiversity issues.

4.3 Challenges for in-farmer field assessment of the performance of mechanized systems

Making a quantitative comparison of current cropping systems with best-managed cropping systems was very informative on how far sustainability may be increased by simply solving technical issues that farmers may experience during rapid intensification processes. As already enhanced by several authors, cropping systems sustainability assessment needs to consider closely the variability of biophysical environment that farms have access to (Meylan *et al.*, 2013; Blazy *et al.*, 2009; Bernet *et al.*, 2001). It is especially true for rainfed family farms whose livelihood is highly dependent on environment and climate. Farmer's flexibility to implement more sustainable options is constrained by their biophysical environment, highly variable across farms and even within a farm (Giller *et al.*, 2006). The agro-environmental assessment presented here considers the variability of the results in time, space and across farmers' managements in interaction with the climate. Other studies also considered variability of cropping systems for sustainability assessment, albeit in different ways by building typologies

from farmer interviews (Fumagalli *et al.*, 2011; Colomb *et al.*, 2013), or from expert-based knowledge (Vasileiadis *et al.*, 2013). Compared to these approaches based on interviews, estimating the variability of cropping systems in a region from an in-farmer field monitoring, seems more robust since we were able to display indicator's results with their associated variance.

Indicators used in the assessment were selected for their capacity to discriminate cropping systems for the selected criteria, to be genuinely predictive of their effects on both long-term and short-term sustainability and to reflect part of the farmers' perspective. Maize cropping systems were effectively discriminated for all criteria except on runoff risk indicator. Runoff risk calculation was not based on crop model simulations of real situations but on simulations of potential water-limited situations. Drainage and erosion risks may have been underestimated and the difference on indicator results between cropping systems may have been smoothed. A solution would have been to build an ad-hoc crop model considering, in addition to water stress, weeds and nutrients daily dynamics and constraints (Colbach *et al.*, 2014). We rather decided to keep the crop model simple according to available data. Quantifying sustainability in farmers' fields and not in experimental facilities is a challenge because the monitoring time is often short and the data collected does not allow using such complex models.

In our study, the organic matter losses and the risk of low yield leading to negative gross margins accounted for long-term sustainability of cropping systems. In the neighbouring Thailand, low yields were shown to trap farmers in long-term debt cycle with the consequence of more vulnerability to shocks (Chichaibelu and Waibel, 2017; Bruun *et al.*, 2017). Our finding on organic matter stocks indicates that they will decrease by half at worst in 9 years for sandy soils. We, however, did not identify a threshold of organic matter content from which maize cultivation would not be possible anymore. The soil fertility indicators used remained simple, we did not assess for example the effect of soil tillage types on key soil ecological functions (herbicide degradation, pathogens control and nutrient cycling) as Roger-Estrade *et al.* (2010) suggested. Moreover, it is important to note that the empirical equation used to assess organic matter loss was not validated for the soils of the region. A solution was to assume that the observable differences between cropping system types on the parameters of this model (clay and initial organic matter contents) were high enough to keep the indicator able to

classify accurately the cropping systems. Especially because soil texture was used as a key variable to cluster plots in the typology.

In this study, farmers did not select directly the indicators neither their reference values representing a desirable state of sustainability. It was rather the set of criteria selected from a previous study that reflected farmer preference about cropping system sustainability (Lairez *et al.*, 2020). Xavier *et al.* (2020) used farmer valuation to estimate the reference values representing desirable state of sustainability. However, farmers may have no awareness on some indicators considered by researchers as essential for sustainability. Moreover, defining a desirable state implies to know which cropping system management, or state of the ecosystem provides guarantees for a future sustainability, which is a tricky question even for researchers. Indicators' level, informing about the present state under which future sustainability will be guaranteed, are hardly predictable by science. For soil fertility for example, it is hard to predict from what threshold of soil fertility soils will be depleted to an irreversible state (Rockström *et al.*, 2009; Ludwig *et al.*, 2018).

5 Conclusion

This study evaluated how far sustainability at field scale can be improved by a better crop management for contrasted maize cropping systems of northern-Laos. The sustainability of maize cropping systems was assessed in farmers' fields with locally relevant indicators for contrasted crop management and soil types covering the variability of biophysical zones found in the study region.

Results showed high concerns on herbicide use, erosion, resource use efficiency and soil fertility for all the cropping systems. Land/labour productivity and economic performances were also found to be at critical thresholds for some systems. Moto-mechanization compared to manual systems was no panacea on every sustainability criteria if the technique was poorly mastered. A more sustainable pathway for moto-mechanized cropping systems could be followed by unlocking the crop establishment technical failure. Improving crop establishment will probably facilitate the needed transition toward probably costlier and labour demanding alternatives able to enhance soil fertility and resource use efficiency and to decrease erosion and herbicide risks under future climate change.

Contrary to industrialized farming context, knowledge on performances and impacts of mechanisation remains limited in the Global South. Quantitative results presented here contributed to informing priority-setting for institutional development and agricultural policies in the region: we suggest that policy makers should consider the lever of a successful small mechanization appropriate to maize farmers to foster a sustainable transition. Future work at farm scale will integrate other farming system components (lowland rice, livestock systems) driving maize-based farm sustainability.

Chapitre 4 : Evaluation intégrée de la durabilité des fermes

Ce chapitre présente la troisième étape de la démarche : l'évaluation intégrée de la durabilité pour différents types de fermes contrastés par leur structure et les objectifs des agriculteurs.

Un modèle de ferme est utilisé pour mettre en perspective les résultats d'évaluation à l'échelle du système de culture, obtenus au chapitre 3, par rapport à l'échelle de la ferme.

Cette étape a les objectifs suivants :

- 1) Evaluer la durabilité actuelle des fermes compte tenu de leur diversité dans une région d'étude.
- 2) Evaluer l'attractivité économique de scénarios alternatifs basés sur une meilleure gestion des systèmes de culture maïs.
- 3) Evaluer les effets de ces scénarios sur la durabilité de fermes contrastées.

Les références et les annexes de l'article sont données à la fin du manuscrit.

Farm sustainability assessment accounting for farmers' goals in small farms of the developing world. A case with mechanized maize mono-cropping.

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1 Introduction

In past two decades, South-East Asia witnessed a rapid market integration of subsistence farming systems with subsequent adoption of intensive cash crops like cassava or maize (Kong *et al.*, 2019; De Koninck, 2003; Mahanty and Milne, 2016; Ornetsmüller *et al.*, 2018; Zimmer *et al.*, 2018). Cropping systems have intensified adopting mostly technologies of conventional intensification (including herbicides, improved seeds, and mechanization). These technologies are new for poor farmers and not well mastered. Often, the resulting cropping systems do not perform as well as expected, do not generate sufficient income to lift people out of poverty, and have strong environmental or social impacts (Kyeyune and Turner, 2016; Shattuck, 2019).

In response to the concerns raised by such rapid conventional intensification of agriculture, a wide range of initiatives intend to promote sustainable intensification and avoid the excessive use of external inputs (Pannel, 2013; Godfray *et al.*, 2010; Tiftonell, 2014). In this sub-humid tropical environment, the objective of maximizing sustainability applying the principles of agroecology, would likely lead to design production systems with integrated fertility management thanks to optimized nutrient fluxes between livestock and crop activities, with multi specific cropping systems based on spatial and temporal arrangements of crops and use of their residues as soil cover, so that nutrient and water fluxes out of the soil-plant system are minimized and light conversion into biomass is maximized (Affholder *et al.*, 2014). However sustainable intensification technologies with proven positive impacts on the environment compared to conventional intensification techniques, are rarely adopted by resource-limited farmers (Jambo *et al.*, 2019; Andersson and D'Souza, 2014; Giller *et al.*, 2009). Their low-adoption rate may be due to their negative impact on farm income on the

short term (Shiferaw and Holden, 1998; Affholder *et al.*, 2010; Affholder *et al.*, 2014) or to the lack of evidence of a positive impact on productivity and income on the longer term (Pittelkow *et al.*, 2015). Even after market integration, farmers whose income remains close to the poverty line of two dollar a day per capita, continue to undergo subsistence issues. These farmers face trade-offs in their decision-making between the short-term socio-economic dimensions (e.g. income, food security) and the long-term environmental dimension of sustainability (e.g. soil and water quality conservation). Numerous other factors may prevent farmers to adopt sustainable intensification technologies, such as the lack of effective market channels for inputs and outputs, cash constraints, or limited workforce availability on farms (Pannell *et al.*, 2014). Overall, for truly agroecological transition to take place, strong investments in public policy are needed to facilitate the emergence of new institutional, economic and financial arrangements that could improve farmer access to a fair market and to technologies, and moreover to resolve the tensions between short-term constraints of producers and environmental issues (Affholder *et al.*, 2014; Côte *et al.*, 2019).

Here, we hypothesise that whereas such policy investments will probably take decades to be done and even more to make effect, a substantial room for improvement in sustainability exists in these farming systems and is more at reach, based on improving the current management of their conventionally intensified cropping systems.

Multicriteria assessment of farm sustainability are needed to identify strengths and weaknesses of current farming systems but also to find alternative, more sustainable pathways, by comparing the benefits and constraints of different options. Abundant literature exists on multicriteria assessment for farm sustainability (Alary *et al.*, 2020; Wei *et al.*, 2009; Schader *et al.*, 2014; López-Ridaura *et al.*, 2002; Iocola *et al.*, 2020; Schindler *et al.*, 2015; Chopin *et al.*, 2016). Common economic indicators used for the comparison of options in multicriteria assessment methods are gross margins of crop and livestock systems or net farm income (Sadok *et al.*, 2009; Vasileiadis *et al.*, 2013; Hani *et al.*, 2003). However, these indicators are usually not sufficient to deduce potential adoption of alternative pathways in complex farms with several activities that are as much sources of income and interact one with another in harnessing farm resources in land, labour and cash. In such farms, the gross margin of a certain activity may increase at the expense of another activity's income so that overall farm income decreases. Alary *et al.* (2016) defined "the economic attractiveness of an

innovative cropping system” as the expected increase of net household total income at farm level that would be achieved by adopting that cropping system, while satisfying farm constraints relative to cash, labour and land availability over time, and as compared to the current system. This economic attractiveness can grasp possible farm dynamics through the identification of necessary conditions that an alternative cropping system has to fulfil to be adopted by farmers.

Farm sustainability is multidimensional and often shows synergies and trade-offs between different goals (Kanter *et al.*, 2018; Klapwijk *et al.*, 2014). Sustainability is also a matter of perspective and is highly dependent of a context (Reed *et al.*, 2006; Lele and Norgaard, 1996). It is thus crucial to consider farmers’ goals achievement when assessing the progress in sustainability that different alternatives would achieve. Klapwijk *et al.* (2014) called for more integrated approaches combining participatory and optimization methods to quantify the trade-offs between goals.

Here, we develop a household-level approach to analyse how improvement in the management at cropping system level may lead to more sustainability at farm level. The objectives of the study are to assess: i) the sustainability of currently observed maize-based farming systems, accounting for their diversity in a study region and ii) the economic attractiveness of improved crop management and its effects on sustainability and farmers’ goals fulfilment.

2 Method

2.1 Study area

We selected for this study Kham Basin in Xieng Khouang province located in northern Laos, close to the Vietnamese border (19°38’N, 103°33E). Kham basin is a typical example of fast market integration of subsistence farms. Over 20 years, the cropping system components of the mixed crop – livestock farming systems have switched from extensive manually cultivated upland rice systems to cash crop systems with hybrid maize cultivation combined with the use of moto-mechanization, herbicides and mineral fertilizers. This rapid switch to maize cultivation was favoured by the increase in maize price and maize demand for the thriving livestock feed industry in Vietnam in the 2000s. This agricultural transformation provoked a

short-term increase in farm income and helped avoiding the severe agrarian crisis that would likely have occurred otherwise, since the productivity of the subsistence-oriented systems that prevailed before would hardly have increased sufficiently to match the population growth. However, this transformation poses strong threats on the long-term sustainability of farming systems, notably with rising risks of soil erosion and of overuse of herbicides (Lairez *et al.*, 2020; Shattuck, 2019). It was previously established that maize cropping systems sustainability may be improved at field level by improving crop management, especially at crop installation stage, with a resulting decrease of both yield gap and herbicide use (Lairez *et al.*, in prep).

Kham basin has soils ranging from sandy to clayey-loam types with relatively flat valleys of moderate elevation (500 to 600 m asl.). Maize is cultivated on non-irrigated land during the rainy season from May to November. After maize harvest, cattle freely graze maize residues. During the rainy season, some farmers cultivate *Brachiaria ruziziensis* on non-irrigated land for cattle feeding. Rice straw and natural pastures complement the cattle's feed ration. In the lowland areas, paddy rice is cultivated for household consumption and the possible surplus is sold. During the dry season, these lowland fields are also dedicated to watermelon, garlic and onion where water is available for irrigation. In most households, off-farm activities provide a substantial contribution to the income. The most frequent of these activities is women weaving, followed with other small business such as shops selling basic commodities or agricultural service renting for ploughing or herbicide spraying, and many off-farm daily jobs during the dry season.

2.2 General approach

A large body of literature exists on bio-economic farm models (e.g. see the review from Janssen and van Ittersum, 2007) to *ex ante* assess evolutions of farms induced by changes in their economic environment or in the technologies available (Blazy *et al.*, 2010; Bartolini *et al.*, 2007; White *et al.*, 2005; Dogliotti *et al.*, 2005). Here we developed and used a bio-economic farm model to perform an *ex ante* assessment at farm level of hypothesized changes in the agronomic performances of cropping systems and to provide insights on trade-offs and synergies between sustainability indicators.

The model simulated the strategic decisions of farmers, by optimizing farm activities under multiple constraints and toward a single farmer strategic objective of maximizing farm

income. In order to account for the current diversity of maize farm systems (MFS) of Kham Basin, we modelled several contrasted farms. In-depth farm surveys and agronomic monitoring were used to provide the modelling with data. Then, the model was used to perform simulations with currently practiced cropping systems (Curr-CS) as the sole set of options available to simulated farmers. These 'baseline simulations' were used to calibrate and evaluate the capacity of the model to represent current decisions of farmers regarding their farm plan, and to assess the sustainability of currently observed MFS. Scenario simulations were then used, in which improved management of maize cropping systems (Best-CS) was added to the set of options available to the simulated farms. These scenario simulations helped identifying the necessary conditions under which better managed maize cropping systems (Best-CS) with reduced yield gap and herbicide use could be a sustainable option for the diversity of MFS of the study region. Finally, potentials for sustainability improvement were discussed according to farm types and depending on the magnitude of trade-offs between farmer goals possibly differing from the sole objective of maximizing farm income.

2.3 Characterizing the diversity of farms (structure and farmers' goals)

To build the model we selected a sample of 16 farms from two topologies. One is a 'structural typology', i.e. a typology based on the endowment of farms in resources and the composition of the family. The second is a typology of farmers' goals. The 16 farms were selected from a sample of 120 farms to cover the more frequent combinations of 'structural types' and 'goal profiles' in six villages of the Kham Basin (Dokham, Laeng, Lé, Houat, Xay and Nadou). The villages were contrasted in terms of their agro-ecological characteristics, road accessibility, and village size. The 120 households were randomly selected from a 2016 exhaustive census (Lestrelin and Kiewvongphachan, 2017).

First, the structural farm typology was built based on 120 farm household interviews about farm household characteristics and activities: land area, family size, household workforce, cattle herd size, assets, share of maize on total area, and off- and on-farm incomes. The typology was based on a hierarchical clustering on principal components using the R package FactoMineR (Lê *et al.*, 2008).

Second, the typology of farmer’s goals (Jourdain et al., submitted) clustered the 120 farm households in different “goal profiles”. These goal profiles were the results from a Best-Worst Scaling (BWS) experiment (Finn and Louviere, 1992) on the 120 farmers (Jourdain et al., submitted). We provide here a summary of the method and the results obtained in Jourdain et al., (submitted). From a card game previously carried out to identify farm-level sustainability criteria (Lairez *et al.*, 2020), Jourdain et al., (submitted) selected 7 “farm strategic goals” to be presented to farmers for the BWS experiment (Table 11).

Table 11 : Average ranking of farmer goals on the total sample of 120 farmers elicited with the Best-Worst scaling experiment and goal profiles defined by relative weight of goals as defined by (Jourdain et al., submitted).

*B: the number of times the goal was mentioned as the most important, W: the number of times it was mentioned as the least important, SS: the standard score= (B-W)/(N*3) (where N is the number of surveys, and 3 reflects the fact that each objective is presented three times to respondents), : ABW: the analytical best-worst: $ABW = \text{Log}(1 + SS)/\text{Log}(1 - SS)$ (Marley et al., 2016), GP: Farmer goal profile identified in (Jourdain et al., submitted).*

Goals	Average rankings of farmer goals on the total sample				Goal profiles (GP) as defined by the relative weight of individual goals (the sum of each column is 100)			
	B	W	SS	ABW	GP1	GP2	GP3	GP4
Self-sufficient rice production	220	44	0.49	1.07	38	30	26	13
Viable farm to transfer to children	199	49	0.42	0.89	25	41	19	16
Regular income	113	113	0.00	0.00	10	8	4	37
Reduce risk by diversifying	89	139	-0.14	-0.28	8	3	11	15
High income (even if irregular)	71	124	-0.15	-0.30	6	6	22	6
Low Labour requirements	75	172	-0.27	-0.55	9	4	7	7
Low cash requirements	73	199	-0.35	-0.73	4	8	12	4

During the BWS, farmers were presented with 7 sets of 3 goals and, for each set, were asked to choose the most important and the least important goal guiding their farming household decisions for the coming five years (choice of activities, technical choices, investments, etc.). BWS average ranking of farmer goals showed that farmers ranked high the goals of “self-sufficient rice production” and “Viable farm to transfer to children” (Table 11). Another important goal expressed by farmers was the development of activities that could provide income regularly for a steady influx of cash to the household. Most farmers gave relatively low importance to the goals of reducing labour and cash requirements. The description of the typology of goal profiles from which the 16 farms were sampled is displayed Table 11 (GP1 to GP4).

2.4 Characterizing farm activities

To collect data on farm technical coefficients and parameters, an in-depth survey on the subsample of 16 farms was conducted during the 2018 dry season. A 4-5-hour-long interview was carried out to collect detailed data on assets (motorised equipment for agricultural activities and for people transport), farm productions, management and seasonality of work, input/output prices (farm gate for products sold, market for products bought, input prices, and daily wages from off-farm work) and seasonality of family expenses and treasury. Each interview was followed with a farm visit to crosscheck and deepen farmers' answers on areas, distances, cattle herd size and land types.

2.5 Characterizing cropping systems

Data describing maize cropping systems (technical management, prices, working calendar and yield variability per soil type) were generated with a 3-years monitoring design from 2016 to 2018 thoroughly described in Lairez *et al.* (2020). The analysis included 35 maize plots of 16 m² in farmer fields for the three years and covered the diversity of technical management and soil characteristics of Kham Basin. Lairez *et al.* (in prep) made a typology of maize cropping systems from which technical parameters (maize yields, workload and costs) were extracted to be used in the farm model. Five currently practiced maize cropping systems types (Curr-CSs) were considered, two on sandy soils, one on sandy-loamy soils and two on loamy clayey soils (Table 12). Additionally to soil types Curr-CSs differed by their sowing technique (moto-mechanical vs. manual), external input use and soil preparation type.

As possibly more sustainable variants of Curr-CS we considered a set of hypothetically improved maize cropping systems (Best-CS) per soil type. Compared to Curr-CS, in Best-CS soil preparation and sowing were considered effective, resulting in an optimal stand density, a low dose of herbicide applied and a moderate yield gap. The parameters of Best-CSs are described in details in Lairez *et al.* (in prep.) and are summarized in Table 12. In the case of moto-mechanized cropping systems, a depreciation cost of the seed drill was accounted in costs calculation.

All other agronomic data (rice, dry season crops, improved pasture with *Brachiaria ruziziensis* and cattle performance) were collected through farmer surveys and in some cases completed with yield measurements in additional specific plots.

Table 12 : Maize cropping systems description and parameters. Curr-CS1: moto-mechanized maize on poor sandy soils, curr-CS2: moto-mechanized maize on sandy-loamy soils, curr-CS3: moto-mechanized maize on loamy-clayey soils, curr-CS4: manual maize on sandy soils, curr-CS5: manual maize on loamy-clayey soils. Best-CS: optimized moto-mechanized maize cropping systems targeting yield gap closure and herbicide use reduction on different soil types.

Soil type	Sandy soil			sandy-loamy soils		Loamy-clayey		
Maize cropping systems	Curr-CS1	Curr-CS4	Best-CS1 and CS4	Curr-CS2	Best-CS2	Curr-CS3	Curr-CS5	Best-CS3 and Best-CS5
Land type	Flat sandy soils	Flat or sloping Sandy soils	Flat sandy soils	Flat sandy-loamy soils	Flat sandy-loamy soils	Flat loamy-clayey soils	Flat or sloping loamy-clayey soils	Flat or sloping loamy-clayey soils
Selling Yield (ton/ha 12% humidity)	2.9	2.2	5.56	2.9	5.8	3.7	3.8	5.8
Work (man-day/ha)	51	72.75	51	51	51	51	72.75	51
Cost (USD/ha)*	228	192	scen1: 415 scen2: 465 scen3: 515 scen4: 565 scen5: 615	234	scen1: 367 scen2: 417 scen3: 467 scen4: 517 scen5: 567	265	207	Scen1: 385 Scen2: 435 Scen3: 485 Scen4: 535 Scen5: 585
Gross margin (USD/ha)	267.9	184	Scen1: 570 Scen2: 520 Scen3: 470 Scen4: 420 Scen5: 370	261.9	Scen1: 625 Scen2: 575 Scen3: 525 Scen4: 475 Scen5: 425	367.7	443	Scen1: 607 Scen2: 557 Scen3: 507 Scen4: 457 Scen5: 407
Labour productivity (USD/man-day/ha)	5.2	2.3	Scen1: 11.2 Scen2: 10.2 Scen3: 9.2 Scen4: 8.2 Scen5: 7.2	5.1	Scen1: 12.3 Scen2: 11.3 Scen3: 10.3 Scen4: 9.3 Scen5: 8.3	7.2	5.9	Scen1: 12 Scen2: 11 Scen3: 10 Scen4: 9 Scen5: 8

2.6 Farm modelling

An overview of the model is shown in Figure 15. A bio-economic farm model was built using the “optimization under multiple constraints” approach based on mathematical programming with GAMS software (version 22.5). The full set of mathematical equations and the corresponding GAMS code are given as supplementary material (Appendix 6). The model used the single goal of maximizing farm income, considering the contrasted types of farm structure without accounting for the contrasted farmer’s goal profiles. These goal profiles were used afterwards to discuss the trade-offs that individual farms may have, when simulated adopting Best-CS, according to their specific goal profiles.

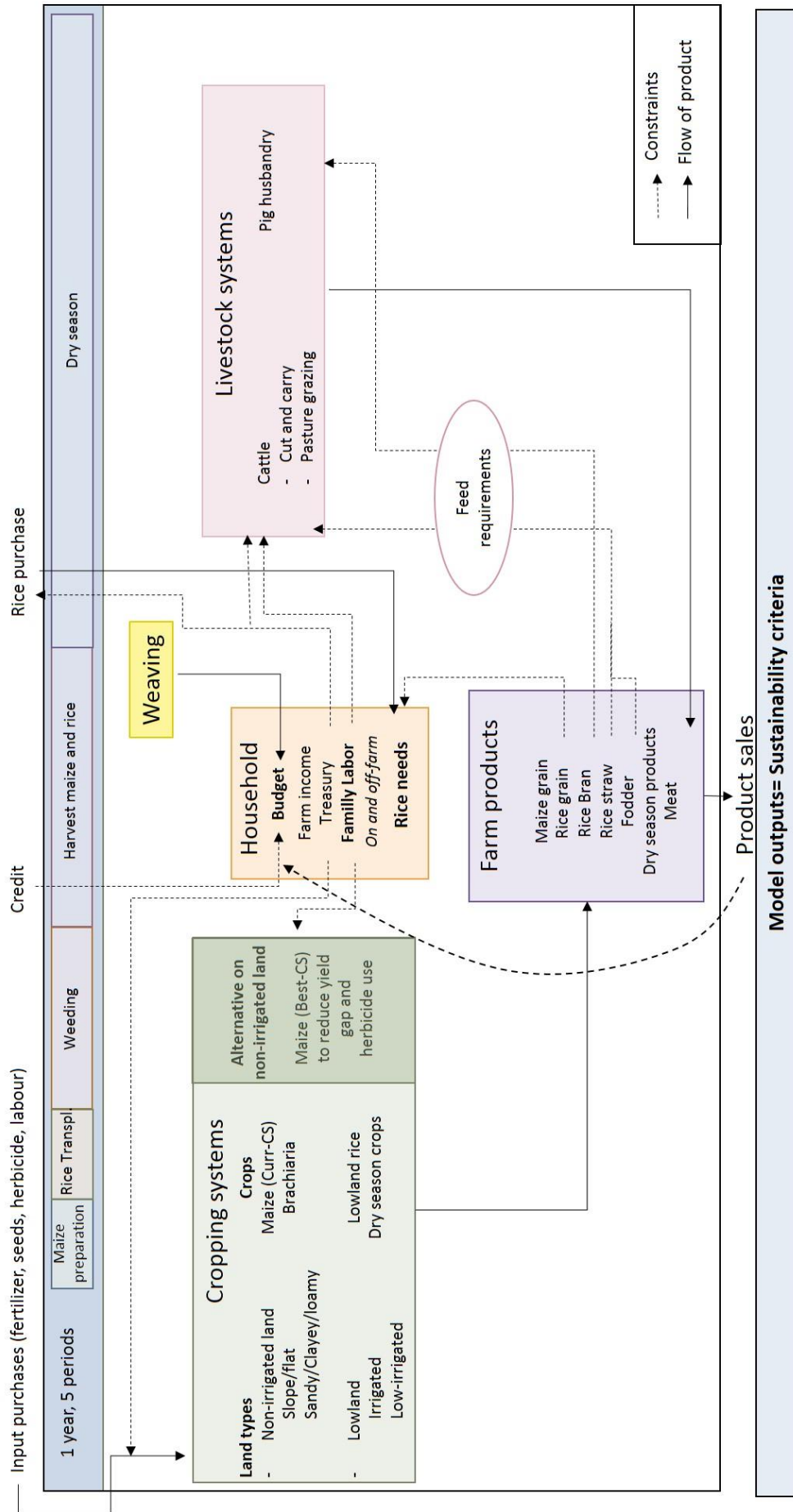
Each farm was characterised by its household composition (mouths to feed, working labour, rice needs), initial cash and rice and area of land type where different cropping systems can be cultivated with specific performances and impacts. Hereafter, a land type is defined by a

degree of slope (irrigated or low irrigated lowland, sloping/flat non-irrigated land) and the soil type (sandy, clayey-Loamy, sandy-loamy).

The year was divided in five periods for which are computed the main balances of resources (mainly cash, labour, and food balances) that are constrained to positive values. The periods were 1) maize preparation, 2) rice transplanting, 3) weeding of rice and maize fields, 4) maize and rice harvests, 5) dry season crops.

To represent workload peaks and the constraint that certain activities must be completed rapidly within a short time span, the different periods did not have the same duration. Periods from 1 to 5 lasted respectively 30, 30, 61, 106 and 138 days.

The total labour needed for crop, livestock and off-farm activities could not exceed farm labour availability plus the labour hired during a given period. The maximum family labour allowed for off-farm was the maximum observed on the observed farm under simulation. This choice was done to represent a realistic off-farm labour market. Similarly to the labour balance, the farm activities implemented during a period cannot cost more than the available cash during this period. Cash available during a period t was the supplementary cash at the end of period $t-1$ (or initial treasury for period 1) minus the cash needed in period t for family expenses for food and education. Family expenses were calculated based on observed farm data, with a coefficient varying per farm, according to the composition of the family (age and cash needs for education and food except rice). A cash maintenance equation rebuilt the initial cash given in period 1 to each farm. Influx of cash may come at every period from off-farm jobs, cattle/pig and rice sales, and at period 4 and 5 also from sales of other crops products. A credit market was available to all farms at 12% rate with an upper limit set to the maximum observed of 1160 USD.



Farm income & diversity, land productivity, cash and maize price dependency, farm transmissibility, workload, farmer autonomy, soil fertility, herbicide, erosion, rice self-sufficiency, crop-cattle integration

Figure 15: Overview of the farm model. Curr-CS are current maize cropping systems on different land types. Best-CS are alternatives to curr-CS to target reduced yield gap and herbicide use (inspired from a model representation by (Alary et al., 2016))

A set of constraints described the availability of farm land in each land type: 1) irrigated lowland, 2) Low-irrigated lowland, 3) flat non-irrigated land with loamy-clayey soil, 4) slopping non-irrigated land with loamy-clayey soil, 3) flat non-irrigated land with sandy-loamy soil, 4) slopping non-irrigated land with sandy soils, 5) flat non-irrigated land with sandy soils. Maize and forage were cultivable only on non-irrigated land and paddy rice and dry season crops on lowland (irrigated for dry season crops). Maize hand sowing was possible on every non-irrigated land types and maize moto-mechanized sowing was only feasible on flat and moderately sloping non-irrigated land types.

Each livestock activity was described by sales cash and labour/costs requirements. Livestock activities integrated in the model were cattle raising or pig husbandry. The model simulated “cattle units”, 1 unit representing 1 female cow older than 3 years-old with 2.7 young cows: one of 2-year-old, one of 1-year-old and 0.7 representing the born cow of the year under simulation. Cattle raising is by essence an activity whose production takes several years to yield. To represent well cattle systems in our model despite its time horizon of only one year, and following a relatively common approach to do this (Norton and Hazell, 1986), we added a cost corresponding to past costs of raising a female cow for 3 years. Cattle freely grazed on village territory during periods 5 and 1, we thus set only periods from 2 to 4 as constraining periods for cattle feeding with fodder. Forage needs per cattle unit were obtained from observed data on the farm sample.

We considered 2 types of cattle systems with specific work and forage needs and each limited by a specific maximum herd size based on observed data on the 16 farms sample. 1) *cut-and-carry cattle system*: during rainy season (periods 2, 3 and 4) farmer cuts and carries *brachiaria* and natural grass to cows parked in a small plot. Cows are also supplemented with rice straw, and during periods 5 and 1 they freely roam on village territory. The maximum herd size limit for cut-and-carry system was set to 6 cattle units. 2) *Pasture-grazing cattle system*: during the rainy season (periods 2, 3 and 4), cows are kept in fenced pastures for grazing and complemented with rice straw. During the periods 5 and 1 they freely roam on village territory. The maximum herd size limit for pasture grazing system was set to 12 cattle units.

Pig husbandry was represented by “pig units” (1 female sow with her 5 piglets). The model only simulated traditional pig husbandry feed system with rice bran with a maximum of 2

units, the maximum size observed on our 16 farms surveyed. In the model, only farms producing rice can fatten pigs with rice bran, as observed in our sample.

A constraint of rice self-sufficiency of the household at every period of the year was imposed. The model allowed to use as rice consumed either rice produced on the farm or purchased on the market, considering a purchase price higher than the selling price, their ratio defining a transaction cost coefficient for rice purchase. Based on real farm data, each farm was provided with an initial rice stock at the beginning of the simulation. The energy content of paddy rice and the human energy need according to age and gender categories were computed using (Leung, 1972) tables, see sup material appendix 7.

2.7 Calibration of model and quality of the model predictions

Eight farms were used for model calibration, and eight for an independent evaluation of model's performance simulating the observed farm plan. The parameters to be calibrated were transactions costs for rice purchases and hired labour. The calibration of these two costs was done to be valid for 8 farms by paying attention to the capacity of the model to predict the areas under maize for differing farm types. The model was then used to simulate the eight other farms, and check the consistency between simulated and observed farm plans on non-irrigated land (for pasture and maize) and lowland (for rice and dry season crops) using quality indicators. The quality of the model was assessed, following the approach used by Affholder *et al.* (2010) as derived from Norton and Hazell (1986), using three indicators on cultivated areas: mean absolute deviation (MAD), Theil index and model efficiency:

$$MAD = \frac{1}{N} \sum_{i=1}^N |XP_i - X OBS_i|$$

$$\text{Theil index} = \frac{\left[\frac{1}{N} \sum_{i=1}^N (XP_i - X OBS_i)^2 \right]^{0.5}}{\left[\frac{1}{N} \sum_{i=1}^N XP_i^2 \right]^{0.5} + \left[\frac{1}{N} \sum_{i=1}^N X OBS_i^2 \right]^{0.5}}$$

$$\text{Model efficiency} = 1 - \frac{\sum_{i=1}^N (XP_i - X OBS_i)^2}{\sum_{i=1}^N (XP_i - \widehat{X obs})^2}$$

With XP_i the predicted area of a cropping activity, $X OBS_i$ the observed area of a cropping activity, N is the number of pairs of cropping activity compared (N=48), $\widehat{X obs}$ is the mean value of the N observed areas.

All the three indicators measure the ability of the model to fit to actual cultivated areas. MAD indicator quantifies the absolute deviations of predictions. Theil index provides an estimation of the deviations of predictions relatively to a combination of the means of areas simulated and observed. The closer MAD and Theil indexes to zero the better. Model efficiency quantifies the ability of the model to predict land allocation even when there is a large distribution of observations around the mean. The closer the model efficiency is to one the better.

2.8 Use of the farm model for scenarios and sustainability assessment

2.8.1 Assessment of economic attractiveness of Best-CSs

A scenario analysis was used to assess the economic attractiveness of the Best-CSs *i.e* the necessary conditions that Best-CSs, assumed to improve sustainability at farm level, had to fulfil to be adopted by simulated farms.

Baseline. The baseline represented the reference situation simulating current cropping and livestock systems, with Best-CSs not included in the list of cropping system options available to the simulated farmers.

In all other scenarios, Best-CSs were included in the list of cropping system options available to the simulated farmers, as follows:

Scenario 1 (SCEN1). In SCEN1 the production costs of Best-CS were set between 367 and 415 USD/ha depending on soil type, as identified in Lairez et al. (in prep), calculated as the sum of the variable costs (land preparation, seeds, herbicide and fertilizer) and the depreciation cost of the seedrill (Table 12).

Scenarios 2 to 5 (SCEN2 to SCEN5). In order to assess the sensitivity to the production costs of the economic attractiveness of Best-CSs, these production costs of Best-CSs were incremented by 50 USD from one scenario to the next (Table 12).

Here, we defined economic attractiveness of Best-CS for a farm as the simulated conversion rate of land from Curr-CS (in the baseline) to Best-CS (adapted from (Alary *et al.*, 2016)). For a given farm simulated in a scenario, if this conversion rate was above 50%, Best-CS was defined “economically attractive” for the farm and the scenario.

The cost variation of Best-CSs across the different scenarios allowed detecting a threshold per farm from which the model simulates Best-CS rejection. This threshold represented the maximum cost affordable by the farmer for converting to Best-CS. If in SCEN5 a farm was still simulated adopting Best-CS, additional simulations of increased cost were done to estimate the maximum cost affordable. The consequences on income, workload, labour productivity and cash needs were also calculated for SCEN1 and SCEN2 in comparison to the baseline.

2.8.2 Sustainability assessment of farms

The sustainability assessment was done on four farms (representing each a farm type) for baseline and SCEN1 using the model outputs transformed in sustainability indicators.

Sustainability criteria are themes relating to the state of sustainability of agricultural systems (van Cauwenbergh *et al.*, 2007). We identified these criteria for the specific context of our case study, at farm and field levels in a previous work combining the perspectives of both scientists and farmers (Lairez *et al.*, 2020). This consisted of a set of 11 criteria (Table 13).

Table 13 : Criteria and indicators of farm sustainability quantified by the farm model, units in brackets.

Sustainability criteria	Sustainability indicators	Description
Farm income	Total farm income (USD)	Gross value from livestock and crop total sales plus income generated from off-farm activities minus the sum of all expenses for crop, livestock, hired labor, rice bought, fixed costs and loan interest rate if farmer had borrowed in period 1.
	Farm income/household Member per day (USD/member)	To be compared to the 1.9 USD/day poverty line
	Income diversity (score)	Assessed with a score counting the number of activities generating income (from 2 to 6)
	Cash inflow regularity (score)	Assessed with a score counting the number of periods with income (from 1 to 5)
Land productivity	Gross margin from farm activities per hectare (USD/ha)	Gross margin from livestock and crop total sales plus the value of rice produced and consumed.
	Income dependency on maize price fluctuation (%)	Estimated by decreasing by 20% maize selling price and by calculating, with a fixed farm plan, the ratio: ((product from maize selling with current price)-[product from maize selling with price decreased])/total farm income
Cash and maize price dependency	Cash outflow needed at the beginning of the cropping season (USD/ha)	Total expenses needed in first period for crop, livestock, hired labour, rice bought and fixed costs.
	Asset/child**	Only farming equipment (milling machine, rototiller, truck, etc.) and motorbikes/car are counted.
	Cattle unit/child**	
Transmissibility	Land/child**	
	Rice production self-sufficiency (-)	Total land cultivated Rice produced/total rice needs for family consumption
Work and drudgery	Workload peak	Workload peak was estimated per period summing the total labour force available on farm minus the work needed for farm and off-farm activities. A peak is reached when more than 95% of total labour force available on farm is used.
	Labour productivity and labour productivity per hectare (USD/man-day and USD/man-day/ha)	Estimated dividing the total farm income by the total labour provided (on-farm and off-farm)
	Percentage of rice bought (%)	Treasury at the end of period 3 minus the expenses in period 4. Representing maize harvest sale rush due to cash constraints in period 4. It represented farmer ability to choose marketing timing and price at harvest in period 4. A low treasury leads the farmer to sell rapidly the harvest.
Farmer autonomy and constraints	Selling constraints (USD)	
	Lowland constraint to higher income (USD/ha of lowland)	Marginal increase of income per additional unit (hectare) of lowland area
	Non-irrigated land constraint to higher income (USD/ha)	Marginal increase of income per additional unit (hectare) of non-irrigated area
	Labour constraint to higher income (USD/day)	Marginal increase of income per additional labour unit (man.day) available during labour peak periods.
Herbicide	Indebtedness (%)	Loan/total income (%)
	Herbicide score	Indicator calculated for maize fields only (see chapter 2/(Lairez et al., in prep.))* Depending on transfer risk due to heavy rainfall after application, herbicide treatment risk (number of recommended doses applied, toxicity and solubility) and soil type
	Soil fertility score	Indicator calculated for maize fields only (see chapter 2/(Lairez et al., in prep.))* Depending on nutrient balance, soil fertility capital and organic matter losses.
Livestock-crop integration	Livestock-crop integration score	1: no cows, 1.5: pasture-grazing system, 2: Cut and carry system
	Erosion risk score	Indicator calculated for maize fields only (see chapter 2/(Lairez et al., in prep.))* Depending on the number of days of bare soil, erosive rainfall events, runoff risks, micro-relief, and slope.

* The score in Lairez et al., in prep. was calculated per hectare between 1 (worst) and 6 (best). If the farm grew different maize cropping systems, the score was averaged on total land allocated to maize. ** The number of children is the total number of children, counting also the ones not living in the house at the time of the survey

In addition to the comparative assessment of sustainability across farms, indicators and criteria were used to quantify the degree of achievement, in baseline and SCEN1, of the seven farmers' goals as elicited in the BWS experiment. To this end, we established a correspondence between these farmers' goals and our sustainability indicators or criteria, displayed Table 14.

Table 14 : Indicators or criteria assumed to correspond to farmers' goals. A star (*) indicates a criterion. Criteria and indicators computations are described table 13.

Goals	Sustainability criteria or indicator
Self-sufficient rice production	Rice production self-sufficiency*
Viable farm to transfer to children	Transmissibility*
Regular income	Cash inflow regularity
Reduce risk by diversifying	Income diversity
High income (even if irregular)	Total farm income
Low Labour requirements	Work and drudgery*
Low cash requirements	Cash outflow needed at the beginning of the cropping season

We used normalization and AMOEBA diagrams to graphically integrate indicators on criteria (Ten Brink *et al.*, 1991). AMOEBA stands for 'general method of ecosystem description and assessment' (Wefering *et al.*, 2000). In the AMOEBA approach, a reference system is built using desirable 'sustainable levels' of indicators. Instead of setting arbitrary desirable states, we built our reference system using "internal normalization" (Pollesch and Dale, 2016), normalizing indicator values according to distribution of indicators performances of the 16 farms modelled in baseline and SCEN1.

This normalization followed equation 1 below for the case of an indicator *i* whose increase means an increase [Eq. 1a] or a decrease [Eq. 1b] in sustainability:

Equation 1:

Eq. 1a:

$$\text{Normalized Indicator Score } i = \frac{\text{Indicator value } i - \{\text{Min}_j\}}{\{\text{Max}_j\} - \{\text{Min}_j\}}$$

Eq. 1b:

$$\text{Normalized Indicator Score } i = 1 - \frac{\text{Indicator value } i - \{\text{Min}_j\}}{\{\text{Max}_j\} - \{\text{Min}_j\}}$$

Where $\{\text{Min}_j\}$ and $\{\text{Max}_j\}$ are respectively the minimum and maximum values of the indicator over the $j=32$ simulations corresponding to 16 farms under scenario baseline and SCEN1.

This normalization results in dimensionless values ranging from 0 to 1 and are aggregated at criteria level on a 100 grades scale using a geometric mean following equation 2 below:

Equation 2:

$$\text{Criterion score} = 100 * \sqrt[n]{\prod_i^n (1 + \text{Normalized indicator score } i)} - 100$$

Contrarily to a classic arithmetic mean approach, the geometric mean avoids low indicator scores to be compensated by high scores on other indicators when averaging their scores (Pollesch and Dale, 2016; Lairez *et al.*, 2016).

AMOEBAs diagrams were used to compare performances of the four farms for baseline and SCEN1 on the 11 sustainability criteria. When assessing degree of achievement of farmers' goals, the weighted sum of criteria/indicators deviations to the maximum performance (here 100) was used as synthetic indicator (Equation 3).

Equation 3:

$$\text{Overall farmer goal achievement} = 100 - \frac{\sum_i^n W_i (100 - \text{criterion/indicator score}_i)}{100}$$

With n the number of criteria used to assess farmer goals and W_i the weight (between 1 and 100) of the criterion i extracted from the BWS experiment (Table 11).

3 Results

The farm typology is presented and followed by an explanation of the farm sample selected to build the model (section 3.1). Then results on the quality of model's predictions for the baseline are reported (section 3.2). Section 3.3. presents the results of the economic attractiveness of Best-CSs, the maize cropping systems targeting at yield gap and herbicide use reductions. Eventually, the sustainability assessment of 4 farms selected from the typology is presented in section 3.4.

3.1 Typology and farm selection

The detailed results of PCA and hierarchical clustering are given in supplementary material (appendix 8). We obtained three farm types, displayed in Table 15. Type 1 "small maize farms" was divided into type 1a (small maize farm without paddy land, 8% of farms of type 1) and type 1b (small maize farms with small paddy land) to represent the poorest farms highly

constrained on rice self-production. Type 2 were medium maize farms and type 3 large maize farms. The goal profiles per structural type and the number of farms selected per type to build the farm model are displayed Table 15.

Table 15 : Farm structural types identified from the hierarchical clustering on 120 farms and number of farms selected from each type to build the farm model. A star (*) indicates values significantly different from the overall mean (χ^2 -test, p value < 0.05).

	Type 1 small maize farms (47% of farms) Type 1a no paddy (8%) Type 1b small paddy (39%)	Type 2 medium maize farm (47% of farms)	Type 3 large maize farm (6% of farms)
Number of farms per type selected to build the model	Type 1a: 2 Type 1b: 6	6	2
Total area (ha)	2.6* (1)	4.3 (1.2)	9.1(3.13)
Paddy rice area (ha)	0.8* (0.6)	1.4*(0.6)	2.2*(0.8)
Maize area (ha)	1.6 *(0.7)	2.6*(0.9)	4.6*(0.7)
Family size (number of people living in the house)	4.2* (1.1)	6.4*(1.6)	6
Mouths to feed per worker	1.8	1.7	1.4
Cattle (units)	1*(1)	2.7*(1.9)	6.7*(3.2)
Assets (number)	3.4*(1.5)	5*(1.3)	7.5*(2.5)
Proportion of goal profiles on 120 farms per structural type	55% GP1 10 % GP2 21% GP3 14% GP4	38% GP1 18 % GP2 20% GP3 24% GP4	56% GP1 33 % GP2 20% GP3 0% GP4

3.2 Assessment of the model quality

The total model efficiency was 0.67 (Table 16). The model represented accurately land allocation for lowland rice but overestimated slightly land allocation of dry season crops (Table 16 and Figure 16). The simulated number of cattle units was above the corresponding observed values for farm type 1 and 3 and the model slightly overestimated land allocated to maize compared to observed values (Table 17). The efficiencies to predict allocation of manual and moto-mechanized maize area were 0.9 and 0.65 respectively (Table 16).

Table 16 : Assessment of the quality of the land allocation predictions by the model for 8 farms used for validation

MAD *	0.14
Theil Index*	0.24
Model efficiency (all crops)**	0.67
Manual maize	0.9
Mechanized maize	0.65
Paddy rice	1

*: The closer to zero the better the prediction quality is, **: the closer to 1 the better the prediction quality is.

Table 17 : Maize areas and cattle units observed and simulated for the 16 farms modelled in the baseline and comparison to observed values of the total sample of 120 farms

Farm type 1		
Simulated	Observed	Observed
Average maize area per farm in the 16 farms (ha)		Average maize area in the full sample of 120 farms
1.1	0.9	1.6
Cattle units cut for carry system in the 16 farms		
4.5	1.9	1
Cattle units for pasture grazing system in the 16 farms		
0	0	0
Farm type 2		
Simulated	Observed	Observed
Average maize area per farm in the 16 farms (ha)		
1.25	1.1	2.6
Cattle units cut & carry system in the 16 farms		
6	6	6
Cattle units pasture grazing system in the 16 farms		
0	0	0
Farm type 3		
Simulated	Observed	Observed
Average maize area per farm in the 16 farms (ha)		
4.4	3.8	4.6
Cattle units cut for carry system in the 16 farms		
0	0	4.5
Cattle units for pasture grazing system in the 16 farms		
12	8	12

In the baseline, one farm was simulated with mechanical maize instead of manual maize (Figure 16). In the village to which this farm belongs, none of the farmers had heard of the existence of the mechanical seedler, which probably prevented them to grow moto-mechanized maize whereas it might have been a sound strategy to do so. Oppositely, two farms were simulated with manual maize instead of the mechanized maize they grew in the real world. A possible explanation for this discrepancy is that we may have wrongly classified the soils of these farms into categories with very low performances of mechanized maize, based on limited information, from interviews with farmers only whereas for most other farms soil characterization was less uncertain.

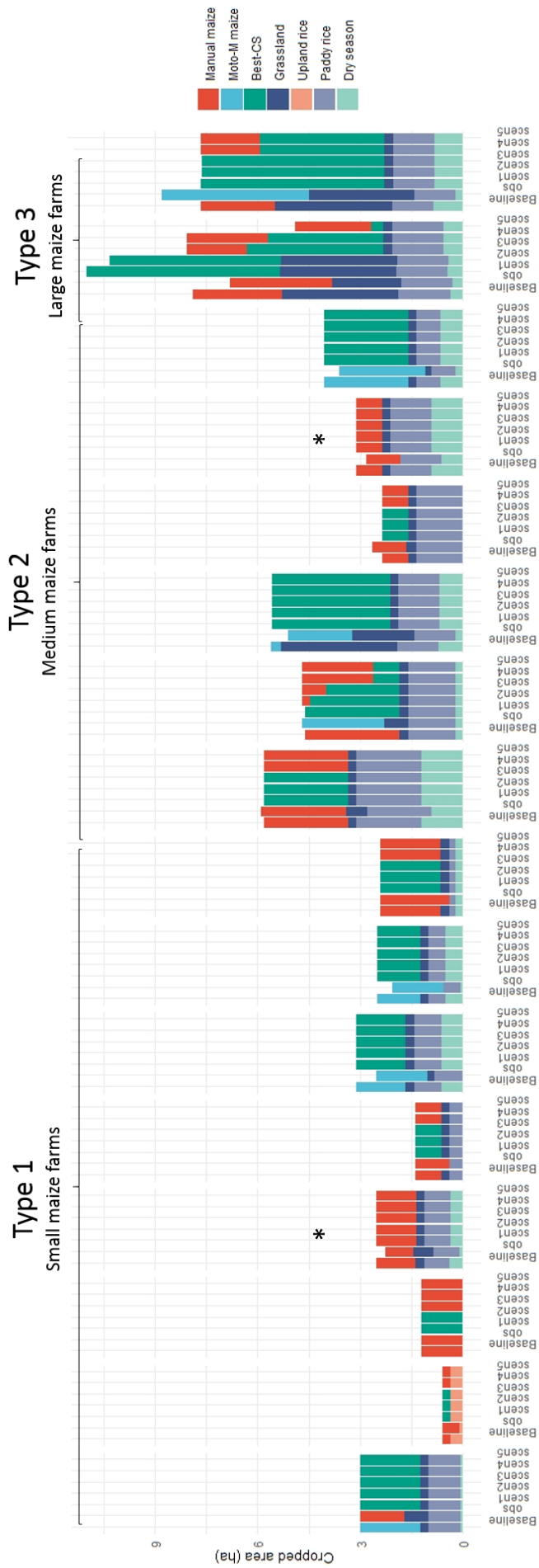


Figure 16 : Land allocation observed and simulated for the 16 farms used to build the model. Farms indicated with a star are farms with sloping land. Scenarios (scen1 to scen5) are simulations with Best-CS to reduce herbicide and yield gap. Baseline: current farm optimized for income maximization under constraints, obs: Observed farm plan, scen1-5: scenarios 1 to 5 with best-CS at a cost gradually increased by 50 USD.

3.3 Economic attractiveness of Best-CS

Up to SCEN3, only farms having sloping land exclusively did not adopt Best-CS in the simulations (Figure 16). From SCEN4, 44% of the simulated farms still adopted Best-CS (Table 18). These farms had sandy and loamy sandy soil types. This was not surprising given the low gross margin of Curr-CSs on these soil types compared to their corresponding Best-CS (Table 12). In 37.5% of the farms, even with the very high production costs associated with SCEN5, Best-CS was still simulated adopted. Additional simulations for these farms showed an average threshold of production cost, above which Best-CS was rejected, of 625 USD/ha, i.e an additional cost of 210-258 USD/ha compared to the value estimated for Best-CS in SCEN1 and of 397-433 USD/ha compared to the costs of Curr-CS (depending on soil type).

Table 18 : Simulated conversion rate of Best-CSs (cropping systems with reduced yield gap and herbicide use) with SCEN1 to SCEN5. A maize area converted above 100% means that additional land was converted to best-CS compared to land allocated to curr-CS in the baseline. A farm was classified as “adopting the Best-CS” when the conversion rate was above 50% of area allocated to curr-CS (current maize cropping system) in the baseline scenario.

Scenarios	%farm adopting Best-CS (%)	Average conversion rate of curr-CS to Best-CS compared to baseline (%)
SCEN1: Average 16 farms	87.5	
Farm Type 1	85.7	100
Farm Type 2	83	322
Farm Type 3	100	231
SCEN2: Average 16 farms	87.5	
Farm type 1	85.7	100
Farm type 2	83	320
Farm type 3	100	219
SCEN3: Average 16 farms	81.5	
Farm type 1	75	100
Farm type 2	83	281
Farm type 3	100	200
SCEN4: Average 16 farms	43.7	
Farm type 1	37.5	100
Farm type 2	33	446
Farm type 3	100	149
SCEN5: Average 16 farms	37.5	
Farm type 1	25	100
Farm type 2	33	446
Farm type 3	50	90

In 56% of the farms, the model predicted rejection of Best-CS starting in SCEN4. These farms had all loamy-clayey soils that resulted in relatively high gross margin for curr-CS3 and curr-CS5 compared to their corresponding Best-CS in SCEN4 (Table 12). This corresponded to a maximum affordable production cost of Best-CS of 485 USD/ha for these farms. The economic

attractiveness of Best-CS was the highest for farm type 3 and the lowest for farm type 1a (Table 18 and Figure 16).

SCEN1 changed land allocation compared to the baseline for two farms raising livestock in pasture grazing feeding system: the simulated farms in SCEN1 shifted to the less land consuming cut-and-carry cattle system and increased the area allocated to maize. As a consequence of changing the cattle system simulated, the herd size was decreased from 12 to 6 cattle units.

The benefit brought by Best-CS in SCEN1 and SCEN2 varied across farm types (Table 19). In large maize farms (type 3) income increased by 15% while it increased by 7-8% only for small and medium maize farms in SCEN1 or SCEN2, compared to baseline simulations. The highest decrease in workload was recorded for farm type 1 (-11%) leading to a 15% increase in its labour productivity in SCEN1 relatively to baseline. The highest proportion of areas in hand sowing maize compared to mechanical sowing in this farm type explained this highest decrease in workload. The workload remained unchanged for type 2 and type 3 farms in SCEN1 compared to baseline, due to an increase in their total maize area or because maize was already mechanized.

Table 19 : Benefits brought by Best-CSs in SCEN1 and SCEN2 compared to the baseline for the different farm types for farm income, labour and cash requirements and labour productivity, per farm type.

Name scenario	Variation of labour requirement (%)	Variation of labour productivity (%)	Variation of cash requirement (%)
SCEN 1: Average 16 farms			
Farm Type 1	-11	+15	+29
Farm Type 2	-1.5	+10	+36
Farm Type 3	-3.5	+14	+23
SCEN2: Average 16 farms			
Farm type 1	-11	+11	+34
Farm type 2	-0.6	+9	+42
Farm type 3	-1.3	+11.5	+37

3.4 Sustainability assessment of 4 farms

Figure 17 shows a graphical representation of the 4 farms that were selected for this in-depth sustainability assessment. Farm sustainability results are displayed on AMOEBA diagrams (Figure 18) representing the performance of each of these 4 farms regarding 11 sustainability criteria. Figure 18 also contains spider-graphs representing the degree of achievement of the

7 farmer goals. Table 20 gives detailed data on the raw indicators before their aggregation into the criteria level.

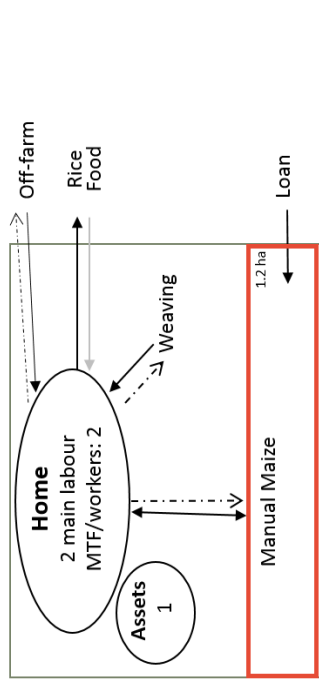
3.4.1 Small maize farm rice constrained (type 1a)

This farm had the goal profile 1 with the two most important goals of rice self-sufficient production and having a viable farm to transfer to the next generation. However, this farm did not access to lowland and had a high share of income dedicated to rice purchases. The farm was 4 times below the poverty line of 1.9 USD per day and family member. The farm also had a very low performance on the criterion of transmissibility, for either land, assets or livestock indicators. In the baseline, the balance of household income was made with 44.5% of off-farm activities and the land productivity from farming activities was the lowest of the 16 farms sampled to build the model (347 USD/ha).

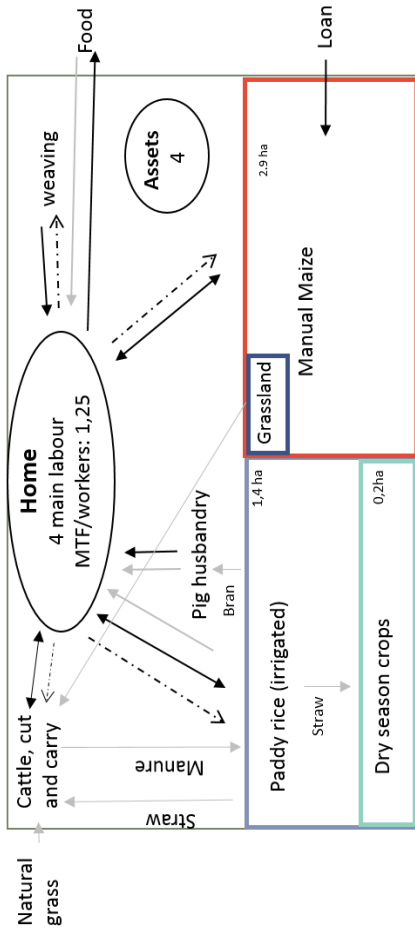
When included in the optimization the possibility to grow Best-CS, the income increased by 30% but indebtedness rate increased by 70% and the maize became heavily reliant on credit (53.3% of farm income). The high shadow price of lowland area indicated that one more hectare of lowland to produce paddy rice would multiply the farm income by 9. An increase of 1 ha of non-irrigated land would increase by 1.7 the income in SCEN1, not even allowing reaching the poverty line of 1.9 USD/day. SCEN1 markedly increased the performance on the criterion of work productivity (48% increase) and drudgery due to the decrease by 30% of work needs on-farm (sowing mechanization). SCEN1 increased slightly the farm transmissibility by adding a mechanical seed drill to the assets already possessed. SCEN1 multiplied by 6 and 1.2 the performances on herbicide and soil fertility criteria respectively.

The better management of maize as represented by the shift from Curr-CS to Best-CS markedly increases income, but not sufficiently to lift this strongly rice-constrained farm of type 1 out of extreme poverty. This is especially because this farm grew Curr-CS5 with a gross margin already at 73% of the gross margin of Best-CS5 (Table 12). More generally, even if Best-SC was adopted by the simulated farm, SCEN1 did not significantly increase the already low overall achievement of farmer goals (baseline: 11.65% of the overall target achieved and SCEN1: 13.47%).

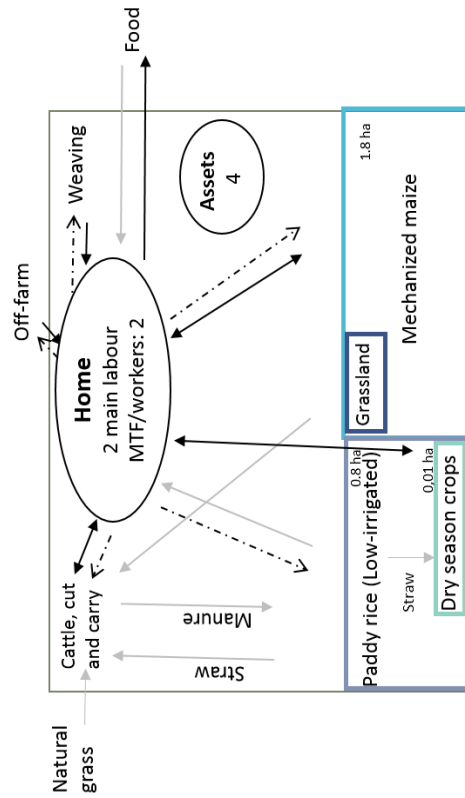
Farm 1: Small maize farm/ rice constrained (type 1.a)



Farm 3: Medium maize farm (type 2)



Farm 2: Small maize farm (type 1.b)



Farm 4: Large maize farm (type 3)

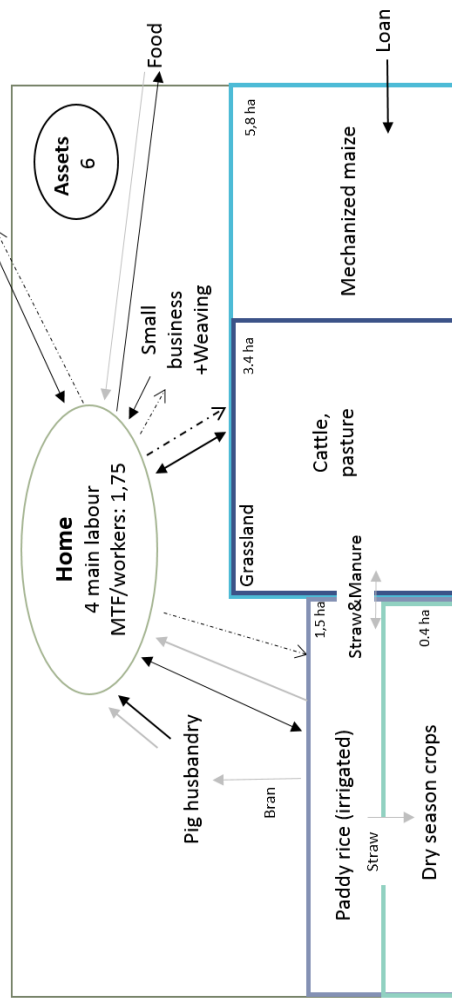


Figure 17 : Four contrasted farms selected from the typology. Arrows represent flows (cash, nutrients or labour). MTF: mouths to feed



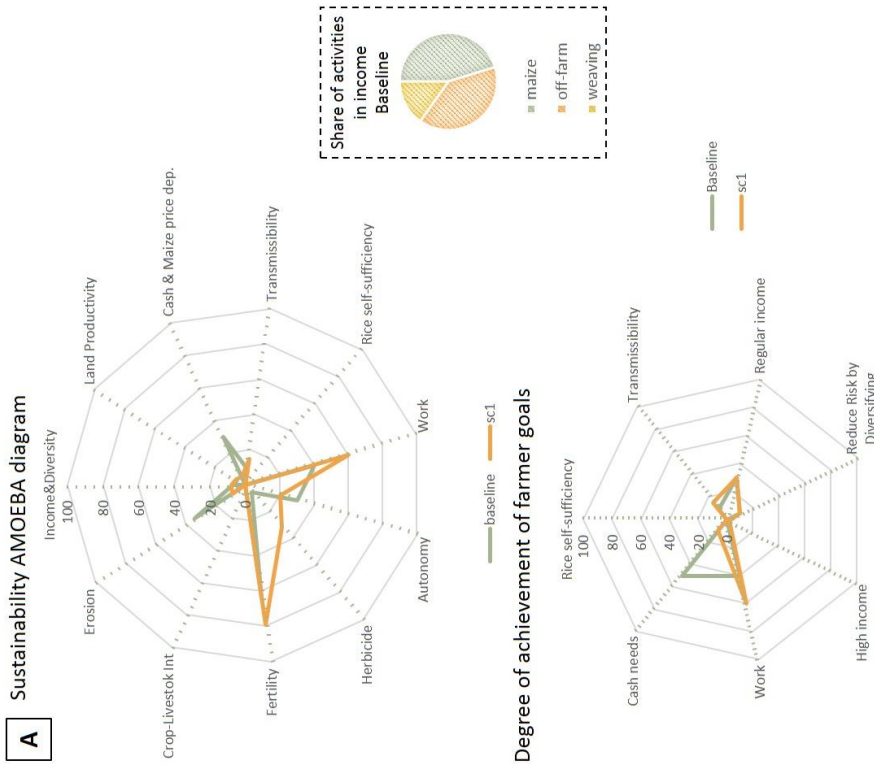
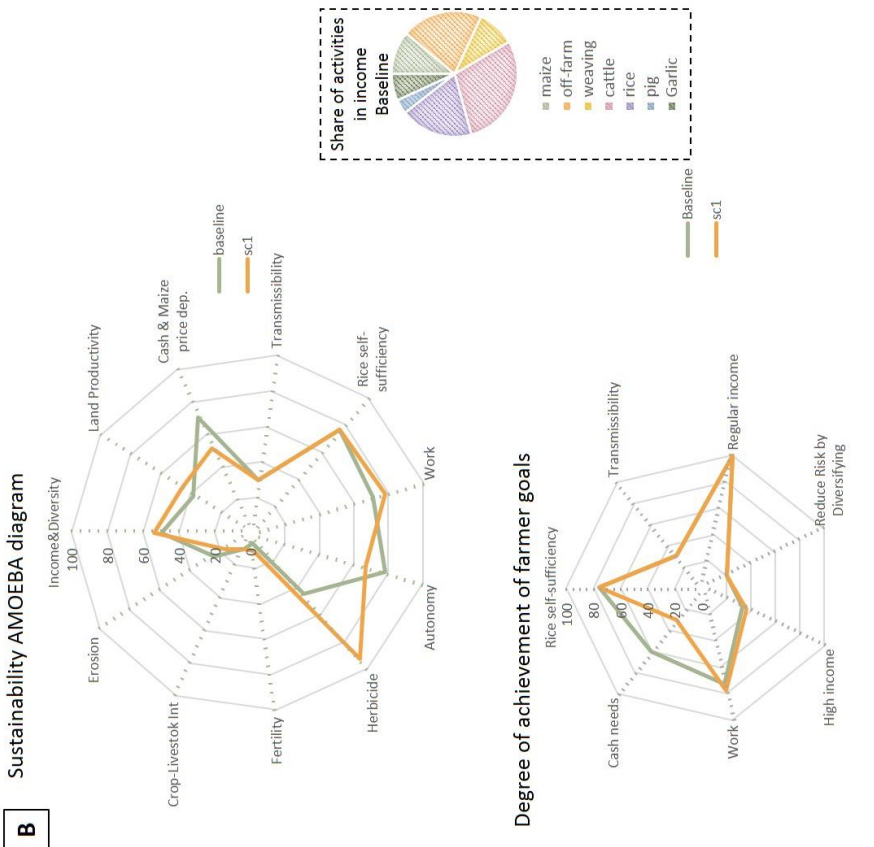


Figure 18 : Sustainability performances of 4 contrasted farms and degree of achievement of farmer goal. A: small maize farm/ice constrained (type 1a). B: small maize farm (type 1b).

Table 20 : Indicator values for 4 farms selected for in-depth sustainability analysis, for simulated scenarios baseline and SCEN1. In baseline scenario, only currently practiced cropping systems (Curr-CS) can be chosen by simulated farms, whereas in SCEN1 improved management aiming at reducing yield gap and herbicide use (Best-CS) are added to the list of options available to simulated farmers. Indicators marked with a star (*) are the ones used to assess the sustainability criteria in the AMOEBAs diagrams displayed figure 4. Curr-CS1: moto-mechanized maize on poor sandy soils, curr-CS2: moto-mechanized maize on sandy-loamy soils, curr-CS3: moto-mechanized maize on loamy-clayey soils, curr-CS4: manual maize on sandy soils, curr-CS5: manual maize on loamy-clayey soils, T1: period 1 of maize preparation (ploughing and sowing), T5: period 5 of dry season crops.

	Farms	Type 1.a Small maize farm Rice constrained		Type 1.b Small maize farm		Type 2 Medium maize farm		Type 3 Large maize farm	
		Curr-CSs simulated in farms' plan in the baseline:		Curr-CS1		Curr-CS4 and CSS		Curr-CS1,2 and 3	
CRITERIA	Scenarios Indicators	Baseline	SCEN1	Baseline	SCEN1	Baseline	SCEN1	Baseline	SCEN1
		Farm income & diversity	*Total farm income (USD)	535	688	3486	3772	4559	5453
*Farm income/household Member per day (USD/member)	0.5		0.6	2.4	2.6	2.5	3	3.2	3.8
*Cash-flow regularity (score)	3		3	5	5	5	5	5	5
*Income diversity (score)	3		3	4	4	6	6	7	7
Off-farm income plus weaving (USD)	622		622	739	739	708	708	2469	2469
Ratio of off-farm income over total gross income (%)	44.5		34	12.1	10.6	9.2	7.8	16.6	15.4
Land productivity	* Gross margin from farm activities per hectare (USD/ha)	347	474	1100	1242	1111	1222	577	693
Cash and maize price dependency	* Cash outflow needed at the beginning of the cropping season (USD/ha)	280	456	225.5	344.5	186	293	209.5	264.5
	*Income dependency on maize price fluctuation (%)	21	25	3.6	6.7	4.8	7.6	6.2	8.5
Farm transmissibility	*Asset/child	0.5	1	1	1	0.7	1	2.7	2.7
	*Cattle unit/child	0	0	1.5	1.5	1.5	1.5	2.4	2.4
	*Land/child	0.6	0.6	0.7	0.7	0.9	0.9	1.7	1.7
Rice production self-sufficiency	*Rice production self-sufficiency (-)	0	0	3.8	3.8	4.8	4.8	4	4
Work productivity and drudgery	*Workload peak	-	-	-	-	-	-	T1 and T5	T1 and T5
	*Labour productivity/ha (USD/man-day/ha)	2.3	3.4	2.5	2.7	1	1.3	0.7	0.8
	*Labour productivity (USD/man-day)	2.7	4	7.4	8	5.1	6.6	6.6	8
	Required on-farm (man-day per ha)	87	61	371	371	688	626	821	739
	Required work off-farm + weaving (man-day per ha)	109	109	102	102	204	204	433	455
Farmer autonomy and constraints	*Percentage of rice bought (%)	100	100	0	0	0	0	0	0
	*selling constraints (USD)	-244	-244	227	227	159	159	814	814
	*Lowland constraint to higher income (USD/ha)	4400	4400	1281	1281	1281	1281	1262	1210
	*Non-irrigated land constraint to higher income (USD/ha)	922.4	738	191	429	257	452	34	0
	*Labour constraint to higher income (USD)	-	-	-	-	-	-	T1: 7 T5: 4.4	T1: 7 T5: 4.4
	*Indebtedness (%)	30.8	53.3	0	9.46	11.6	18.3	7.4	12.1
Crop-livestock integration	*Crop-livestock integration score	1	1	2	2	2	2	1.5	1.5
Herbicide	*Herbicide score	1.3	2.9	3.7	6.6	1.5	3	2.1	3.8
Soil fertility	*Soil fertility score	4.2	5	1.3	1.5	3.6	4.1	2.9	3.4
Erosion	*Erosion risk score	2.7	1.4	2.2	1.85	2.5	1.45	2.27	2

3.4.2 *Small maize farm (type 1b)*

This other small maize farm of type 1 illustrated an example of the gain of sustainability allowed by acceding to 0.7 ha of lowland, as compared to farms with no lowland area at all of type 1a. The goal profile of this farm was 'profile 3-constrained optimizer' with balanced goals. Compared to the preceding farm of type 1a, the presence of lowland increased the degree of rice production self-sufficiency but also the crop-livestock integration criterion since cattle raising was possible. Dry season crops also brought an additional income during the dry season period making the source of income more diversified compared to type 1a (Table 20).

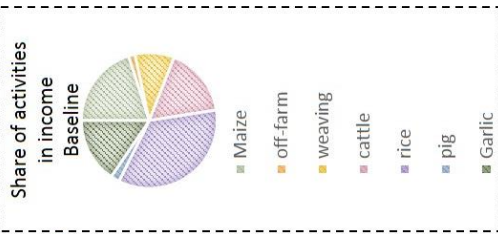
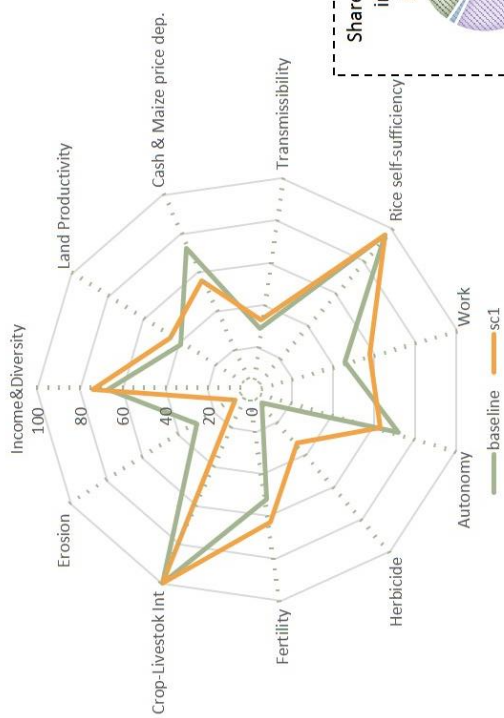
When comparing SCEN1 with baseline for this farm, performances on herbicide criterion was multiplied by 2, the income by 1.08 and the land productivity by 1.13. The counterpart of these improvements was the reduced performance on the criteria of autonomy, erosion and "cash and maize price dependency". Even if the model simulated an adoption of Best-CS, SCEN1 decreased slightly the overall farmer goal achievement for this farm (50.8% of the overall target reached vs. 52% with the baseline) because the income improvement did not compensate the decreased performance on cash need. To obtain a greater overall goal achievement with SCEN1, this farm would need to multiply the farm income by at least 1.25 (other criteria unchanged) to offset the low performance on cash needs at 1.42 times the cash needed in the baseline.

3.4.3 *Medium maize farm (type 2)*

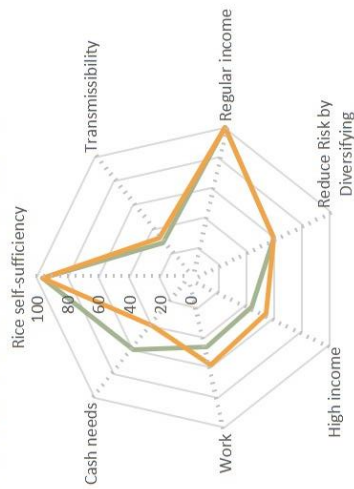
The goal profile of this farm was 'profile 3-constrained optimizer' with balanced goals. SCEN1 increased significantly the performance on criteria of soil fertility, herbicide and work, compared to baseline. To a lesser extent, the farm income was also increased (+21%). The improvement of income was limited mostly because this farm grew already the manual cropping system with the best gross margin (Curr-CS5 on fertile soils with high use of herbicide). For this farm, the main downside of SCEN1 was a lower performance on the criteria of cash and maize price dependency and autonomy. SCEN1 slightly improved the overall achievement of farmer goals (61.6% of the overall target reached vs. 60.17% with the baseline). From the farmer perspective, the lower performance on cash needs criterion of SCEN1 would be compensated by the better performance on income, transmissibility and work.

C

Sustainability AMOEBA diagram

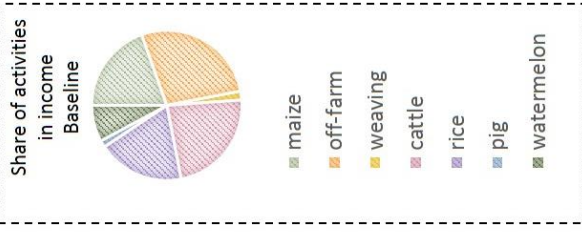


Degree of achievement of farmer goals



D

Sustainability AMOEBA diagram



Degree of achievement of farmer goals

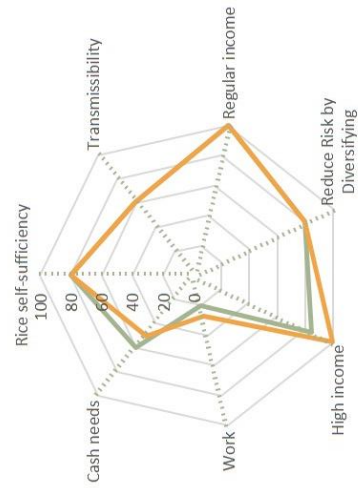


Figure 18 (continued): Sustainability performances of 4 contrasted farms and degree of achievement of farmer goal. C: medium maize farm (type 2). D: large maize farm (type 3)

3.4.4 *Large maize farm (type 3)*

Despite its high rice production, the goal profile of this farm was the goal profile 1 with the two most important goals of rice self-sufficient production and having a viable farm to transfer to the next generation. After adopting Best-CS, in the simulations this farm improved by 17% and 20% its income and land productivity respectively. SCEN1 also significantly increased the performance on work, soil fertility and herbicide criteria. The counterpart of these improvements was the reduced performance on the criteria of autonomy and cash and maize price dependency. SCEN1 slightly improved the overall achievement of farmer goals (71.3% of the overall target reached vs. 72.3% with the baseline).

4 Discussion

4.1 Space for sustainability improvement in maize farms of northern Laos

The use of a farm model for the sustainability assessment of different maize-based farming systems (MFS) brought interesting insights on the diversity in farm potential to improve their sustainability. The simulation of scenarios with improved management of maize cropping systems illustrated the trade-offs between sustainability criteria and farmers' goals that are associated with changes in cropping systems aiming at improving sustainability, even when such changes are relatively modest compared to those required by the so-called agroecological transition. As already shown at field level in Lairez et al. (in prep), across all farm types, the environmental sustainability was always improved with improved crop management except for the erosion criterion. Farm income increased for all farm types on the condition that cash was available for increased expenditure at the beginning of the growing season. However, improved crop management favoured more the already wealthiest large maize farms and had limited income improvements for the most rice-constrained farms in our simulations. Our results indicate that farms may be more constrained by land and cash than by labour availability except for the large maize farm where the latter might become a constraint for the sustainable intensification of maize production. For the two most cash and rice constrained farms, SCEN1 reduced or only slightly increased the overall degree of achievement of farmer goals: benefits on income, work or transmissibility criteria did not compensate enough for the additional high cash needed. This simulated result is in line with the recurrent results from surveys finding financial constraints as a reason for low adoption of

sustainable intensification technologies (Jambo *et al.*, 2019; Ajayi *et al.*, 2003). Our results also indicated that land productivity was fundamental for sustainability but not always sufficient to let the poorest farmers move out of poverty. A growing body of literature already showed that narrowing yield gap is not always sufficient to escape poverty (Ollenburger *et al.*, 2018; Harris and Orr, 2014; Kyeyune and Turner, 2016). Some farms are definitely too small and too highly constrained to get out of poverty only by reducing yield gap. This is consistent with results found in other mountainous areas of South-East Asia (e.g., Jourdain *et al.* (2014)).

We identified in other studies that soil fertility mattered for farmers at crop level (Lairez *et al.*, 2020; Jourdain *et al.*, 2020) even if this criterion was not ranked by farmers in the best-worst scaling experiment of strategic goal at farm level. Policy-makers will certainly want to support a more sustainable transition, beyond the improved maize cropping systems proposed in this study. For any costlier transition to happen the poorest farmers will probably need to be incentivized and/or rural policy will have to enable farmers to access to irrigation more easily (e.g. conversion of non-irrigable land into irrigable land). In the current conditions of poor irrigable lowland accessibility, we estimated that the poorest farmers would need an increase of at least 3.9 times their current income to cross over the poverty line.

For medium and large maize farms, an appropriate mechanization for land preparation and sowing may increase significantly their income and work productivity while decreasing herbicide use. However, the degree of appropriateness of mechanization options depends on farm type. Mottaleb *et al.* (2016) highlighted that few farms in developing countries can afford to invest in agricultural machinery and rather access to machinery through fee-per-service systems. Today, custom-hire service providers are available in Kham Basin but not in a way that farmers have the leeway to operate timely on limited intervention windows. We showed that for farms with sandy and loamy-clayey soil types, Best-CS may be worth for the largest farms to invest in their own tractor for timely field operations. Indeed, the threshold cost of non-adoption was 625 USD/ha. This cost, minus all the costs except land preparation costs (seeds, fertilizer herbicide) multiplied by the maize area of the largest farm of 5.4 ha on 15 years may reach an amount similar to the cost of purchasing a tractor (40 000 USD).

Provincial plans for livestock development (Millar and Photakoun, 2008) may encourage a shift away from the least-performing maize cropping systems to livestock raising on improved pasture. This would to some extent relieve pressure on tractor availability and provide space

for sustainability improvement for other farmers still having maize as a key component of their production system. However, the model suggested that for the farms having pasture grazing cattle systems on large area, in SCEN1 it would be more economically attractive to allocate land to Best-CSs and switch to a cut-and-carry system on smaller forage area. This simulated result suggests a high economic-attractiveness of Best-CSs compared to current farming systems transitioning to pasture-grazing systems by converting more maize land to forage.

4.2 Knowledge gained for multicriteria assessment of cropping systems

Our study pinpoints the necessity to upscale cropping systems sustainability assessments to the farm-level. A conventional approach to measure the benefits that a farm can get from an alternative cropping system is usually to compare performances at field level and seldom to upscale the results to the farm level (Harris and Orr, 2014). A simple analysis at cropping system level would have accentuated the economic benefits potentially brought by Best-CSs. For example, for the poorest farm (type 1a), gross margin from farm activities may increase by 37% by adopting Best-CS but the total farm income increased less compared to baseline (29%) and led to a high indebtedness rate of 53%.

Assessing farm sustainability necessarily leads to a reflection on the trade-offs and synergies between the numerous dimensions defining this concept (Kanter *et al.*, 2018; Giller *et al.*, 2011). Integration of farmers' objectives in the evaluation is required to assess the extent of trade-offs in the light of what matters to them. Especially because sustainability is a subjective concept (Reed *et al.*, 2006). However, Kanter *et al.* (2018) noted that the step of defining the context and what is economically and ecologically desirable from stakeholder perspectives is often skipped in trade-off analyses. Like (Ditzler *et al.*, 2019) found in the neighboring Vietnam, we noticed that the extent of synergies or trade-offs between sustainability criteria depended deeply on farm structure and the multiple, often contrasting, farmer's goals. We recognized that our approach represents too simply the multitude of factors that drive a farmer's decision. Their objectives are only integrated into the trade-off analysis after optimization in the model. Another approach would have been to identify Pareto-efficiency frontiers (Tittonell *et al.*, 2007; Cavender-Bares *et al.*, 2015) or apply multi-objective optimization aggregating farmer goals in the objective function (Li *et al.*, 2020; Ditzler *et al.*, 2019). For a given farm structure, different objective functions may have been tested and an 'acceptable solution' (Dogliotti *et al.*, 2005) or a 'solution space' (Ditzler *et al.*, 2019; Groot *et*

al., 2012; Timler *et al.*, 2020) could have been found after iterative rounds successively maximizing (or minimizing) different goals.

Although adoption of Best-CS has been simulated for most farms, it is important to note that this does not necessarily mean that it will actually be adopted. This study is a first step to identify the most striking constraints preventing farm transitions: working calendar, cash constraints, rice self-sufficiency and land resources. This approach aimed to identify the farm constraints preventing sustainability improvement and to delineate the necessary socio-economic conditions under which a more environmental-friendly innovation at crop level might be adopted (Affholder *et al.*, 2010). Our objective was not to represent realistically farmer decision but rather “optimized farms” with sustainability results at their optimum. In this perspective, farmer risk aversion was not considered and an economic rationality of farmers was assumed. As it stands today, the model has been able to represent accurately farming activities of very contrasting farms. The results generated by the model can be used in model improvement loops through discussion with farmers. In addition, to identify sufficient conditions of transition, further analyses will consider farmer risk aversion, the variability of input/output prices and look into how to aggregate farmers’ goals in the optimization function.

5 Conclusion

Our case in Laos is an example of region seeming biophysically favorable to cereal production, where poor farmers recently got out of economically unsustainable subsistence farming, but do not properly master the moto-mechanized cropping systems they adopted, which leads to new threats to sustainability.

We have shown that combining a farm model with a multicriteria assessment balanced with an analysis of farmer goals achievement was relevant for assessing the leeway for improving farm sustainability. The simulations suggested that relatively modest improvements in the currently poorly managed moto-mechanized cropping systems would improve significantly farm sustainability in both its economic and environmental dimensions. However, even if improved management was simulated to be adopted by the poorest farms, the high amount of cash required for purchasing inputs and pay for soil tillage makes unlikely that adoption by

the poorest farmers actually takes place in the real world, unless policies are developed to financially support them.

Further enhancing sustainability in this context would require a stronger mobilization of the principles of agroecology. Our methodological approach combining a farm model and a multicriteria assessment would be relevant to use as well, if sound data are available to estimate the agronomic and environmental performances of agroecological cropping systems designed to this end. It is broadly recognized that a truly agroecological transition will need strong investments in public policy. In the developing world, it is thus likely to take decades before this is fully implemented and makes effect. Our study shows a case, that may be of some global relevance given the observed trend in moto-mechanization of maize in small scale farms in emerging countries, where exists on a shorter term a path to improved sustainability through better crop management.

Chapitre 5 : Discussion générale

Ce chapitre présente une discussion générale de la thèse. La thèse a mobilisé de nombreuses méthodes et approches pour répondre aux enjeux de l'évaluation intégrée dans des contextes où l'accès aux données est limité. Ce chapitre présente les apports de notre méthodologie pour réduire les incertitudes sur l'évaluation de la durabilité des systèmes de culture et des fermes. Ensuite, nous présentons les pistes de recherche à approfondir pour réduire les incertitudes qui subsistent. Enfin, des recommandations pour le développement et la recherche local sont réalisées et une dernière partie ouvre sur la portée globale de l'étude.

1 Sources d'incertitude liées à la méthodologie

1.1 Robustesse des conclusions portées par le diagnostic agronomique

La méthodologie du diagnostic agronomique dans les parcelles d'agriculteurs a été adaptée et utilisée de deux manières dans cette thèse. En premier lieu pour diagnostiquer les causes de la variabilité du rendement et identifier des critères de durabilité (chapitre 2) et dans un second temps pour réaliser un diagnostic agroenvironnemental (chapitre 3).

Nos résultats majeurs issus de ce diagnostic agronomique adapté sont rappelés ci-dessous :

- Les rendements du maïs sont faibles par rapport au potentiel permis par le climat, et très variables.
- Le plus faible écart au rendement potentiel limité par l'eau est obtenu lorsque le score d'infestation des adventices ne dépasse pas 3.5 sur une échelle de 9 points, à aucune des 5 dates d'évaluation du score distribuées tout au long du cycle.
- Si la densité de poquets est supérieure à 5.4 poquets/m² ce score d'infestation ne dépasse pas 3.5.
- La moyenne des densités de poquets obtenue est faible (4.1 poquets/m²) et ne permettrait pas d'atteindre le potentiel de production des cultivars même s'il n'y avait aucun autre facteur limitant
- Le semoir moto-mécanisé devrait augmenter significativement la densité par rapport au semis manuel, mais seulement 4% des agriculteurs utilisant un semoir réussissent à obtenir la densité de poquets permise théoriquement par le semoir (7.1 poquets/m²).
- A cause de ces faibles densités de peuplement et d'une gestion mécanique des adventices inappropriée, les adventices envahissent les champs et les agriculteurs utilisent beaucoup d'herbicide pour tenter de les maîtriser.

A partir de ces résultats, nous avons expliqué la variabilité des rendements ainsi :

- Les faibles rendements sont en premier lieu causés par les adventices dont l'infestation est elle-même causée par une gestion technique inappropriée.
- Les faibles densités de poquets seraient expliquées différemment suivant que le semis est manuel ou mécanisé. Pour le semis manuel elles seraient expliquées par le semis de 2 graines par poquet relativement espacés les uns des autres pour gagner du temps. Pour le semis moto-mécanisé, elles seraient expliquées par une mauvaise maîtrise technique, en interaction avec le climat, de la séquence d'interventions pour les différentes préparations du sol et le semis. Nos observations suggèrent que

l'hétérogénéité du sol au moment du semis empêcherait le semoir d'assurer une distribution optimale des graines, car celle-ci se fait par friction d'une roue crantée à la surface du sol. L'hétérogénéité du sol empêcherait donc la roue crantée de tourner régulièrement et de distribuer les graines au bon moment (Figure 19).



Figure 19 : Le semis moto-mécanisé dans des états de surface hétérogènes

- Les mauvais états de surface du sol pourraient être dus à des outils inadaptés pour préparer le sol et/ou à des conditions suboptimales d'humidité entre le labour et le semis.

Pour comprendre la variabilité des performances et impacts chez les agriculteurs, le diagnostic agronomique est le seul moyen que nous avons, car la portée des enquêtes d'agriculteurs est limitée que cela soit pour déterminer les facteurs explicatifs du rendement (Lobell *et al.*, 2019) ou pour diagnostiquer la durabilité des systèmes de culture pratiqués. En effet, l'annexe 4 présente un état des lieux des enjeux de durabilité tels qu'identifiés par des enquêtes d'agriculteurs et par l'analyse de la littérature locale pour la zone d'étude et nous constatons que les problèmes de densité de peuplement ne sont pas évoqués. De plus, une analyse plus

approfondie des perceptions des agriculteurs avec la Q-méthodologie (chapitre 2) a révélé qu'ils étaient plutôt en désaccord avec la phrase « Les faibles densités sont la cause principale des faibles rendements en comparaison à la fertilité du sol ». Van Asten *et al.* (2009) a montré que les agriculteurs pouvaient avoir des difficultés à identifier les contraintes limitant le rendement lorsque celles-ci étaient uniformes dans le temps et l'espace comme c'est probablement le cas pour les faibles densités et les mauvaises herbes. Les connaissances scientifiques issues du diagnostic ont donc permis d'expliquer et de comprendre les processus biophysiques à l'œuvre.

Les incertitudes menaçant la robustesse de nos conclusions nous apparaissent donc relativement limitées par rapport aux conclusions que l'on aurait eues par simples enquêtes d'agriculteurs ou l'analyse de la bibliographie. Même si les sources d'incertitude sont réduites, il convient tout de même d'estimer les incertitudes que nous avons eues en mobilisant le diagnostic agronomique et de proposer des pistes pour les limiter. Ces incertitudes peuvent être liées à l'incomplétude des variables explicatives que nous avons considérées dans notre analyse ou à des erreurs de mesure :

- *Les erreurs de mesure*

Les incertitudes peuvent être liées à des erreurs de mesure et d'estimation des paramètres du modèle de culture. Les instruments de mesure tels que le Licor utilisé pour mesurer l'indice de surface foliaire (LAI) ou les balances pour peser les biomasses et les rendements peuvent générer des incertitudes. Pour les balances ces erreurs sont connues, elles dépendent de leur précision. Elles ont été les mêmes pour toutes les situations culturales ce qui ne change pas la hiérarchie des causes expliquant la variabilité du rendement. Pour l'estimation du LAI avec le Licor, le risque d'erreur pourrait être plus élevé pour des densités de peuplement faibles et hétérogènes (Affholder, 2001). Cette erreur de mesure aurait pu être estimée en répétant la mesure un grand nombre de fois sur des situations contrastées afin d'estimer les interactions entre types de situation culturale et qualité de la mesure. Des incertitudes sont également à prévoir sur les paramètres du modèle de culture tels que la réserve utile, les stades phénologiques et les composantes du rendement. Pour estimer l'effet de l'erreur sur la

réserve utile, il convient par exemple de faire une étude de sensibilité de notre analyse aux variations de réserve utile de l'ordre de 20% par exemple (Annexe 9).

Notre but dans le chapitre 2 était de pouvoir conclure sur les liens entre les variables explicatives, et non d'identifier statistiquement le système de culture le plus performant. Dans le chapitre 3 nous avons tout de même été en mesure de regrouper des situations culturales en types de systèmes de culture (les « Curr-CS ») ayant un même type de sol et les mêmes pratiques clefs sur l'itinéraire technique : travail du sol, semis, herbicide et fertilisation. Nous avons pu produire des barres d'erreur autour de certains points mesurés (rendement, score d'infestation par les mauvaises herbes, risques d'érosion et d'herbicide) grâce à ces échantillons constitués de plusieurs situations culturales où seuls le climat et les dates d'intervention variaient.

- *L'incomplétude des variables explicatives*

La situation culturale est l'unité élémentaire sur laquelle l'ensemble du raisonnement pour hiérarchiser les variables explicatives de la variabilité du rendement a été construit. Par définition, une situation culturale est homogène sur les variables explicatives suivantes : le type de sol, les pratiques et le climat. Le raisonnement s'est bâti sur l'analyse des écarts de rendement de ces situations culturales aux rendements potentiels limités par l'eau. Ces situations au potentiel ont uniquement le stress hydrique comme contrainte limitant le rendement par rapport au potentiel permis par le rayonnement disponible et les températures. Comparer les situations culturales en termes d'écart au potentiel et non uniquement leurs rendements observés, permet de s'affranchir, dans l'analyse de la variabilité, des effets de la variable « stress hydrique » ainsi que des interactions que le stress hydrique peut avoir avec la densité de peuplement. Lorsqu'on fait des comparaisons entre les situations culturales pour établir la hiérarchie des facteurs à l'origine de la variabilité des rendements, toute différence d'écart au potentiel qui ne serait pas due aux erreurs de mesure doit pouvoir s'expliquer par une différence dans les variables explicatives du sol et des pratiques.

1.2 Robustesse des conclusions issues des interactions avec les agriculteurs

En complément du diagnostic agronomique pour identifier les critères de durabilité, les perspectives des agriculteurs ont également été essentielles pour comprendre leurs perceptions, objectifs et préoccupations. Notre résultat majeur issu de l'utilisation des jeux sérieux est le suivant (chapitre 2) :

- Ces agriculteurs, au seuil de pauvreté, ont en priorité des objectifs socio-économiques de court-terme (autosuffisance en riz, revenu) mais ils expriment aussi des préoccupations à long terme comme les risques liés aux herbicide, la transmissibilité de la ferme et la fertilité du sol.

Les interactions directes avec les agriculteurs par enquêtes ou « focus group » peuvent être source d'incertitudes à cause du biais de désirabilité et de surinterprétation des dires d'agriculteurs. Le biais de désirabilité peut pousser les agriculteurs à répondre de telle manière à être perçus favorablement par l'enquêteur. La surinterprétation des dires des agriculteurs peut arriver lorsque des concepts subjectifs sont discutés comme la durabilité, la fertilité ou la transmissibilité.

Dans notre étude, l'utilisation de jeux sérieux et de la Q-méthodologie a permis de réduire ces biais (Wheeler *et al.*, 2019; Lusk and Norwood, 2010). Grâce au caractère indirect des jeux sérieux, le biais de désirabilité a été minimisé par rapport aux enquêtes directes où l'on demanderait à l'agriculteur s'il considère la fertilité comme importante ou s'il souhaite réduire son usage d'herbicides. Nous avons également limité le risque de surinterprétation des résultats des jeux sérieux par l'utilisation de la Q-méthodologie. Le jeu Takit (chapitre 2) a donné la fertilité comme un critère de durabilité important pour les agriculteurs. Ce résultat pouvait exprimer une inquiétude des agriculteurs sur les faibles performances du maïs plutôt qu'une réelle préoccupation sur la qualité du sol. La Q-méthodologie a démontré que la perception des agriculteurs sur la fertilité était bien plus complexe qu'une considération unique du rendement. Nous avons identifié des groupes contrastés d'opinion sur la fertilité. Un groupe par exemple était préoccupé par le « capital fertilité » laissé aux générations futures et liait la fertilité à l'utilisation de légumineuses et à la couleur noire du sol. Un autre groupe avait attaché de l'importance à la structure du sol après le labour pour définir si un sol était fertile ou non. La fertilité n'était pas forcément équivalente à de forts rendements pour ce groupe.

Afin de limiter davantage les incertitudes, tout comme pour le concept de fertilité, si l'étude était à approfondir, il serait intéressant de réaliser une enquête Q-méthodologie pour un autre concept subjectif tel que la transmissibilité de la ferme. De plus nombreux retours et discussions avec les agriculteurs permettraient également de limiter les biais de surinterprétation sur ces concepts subjectifs traduits en langue locale (ex. Okoba and Sterk (2006)).

1.3 Robustesse des conclusions sur la durabilité des fermes et systèmes de culture

Nos résultats majeurs issus de l'évaluation de la durabilité sont rappelés ci-dessous :

À l'échelle du système de culture (chapitre 3),

- Les systèmes évalués montrent de forts risques de pollution à l'herbicide (doses, molécules actives et risques liés au climat), une faible productivité du travail rendant certains systèmes moins compétitifs que le revenu tiré des activités extra-agricoles, des risques sur la fertilité du sol et sur l'érosion accentués par des pluies à fort risque érosif en début de saison culturale.
- Cinq systèmes de culture alternatifs avec une mise en culture réussie ont été inférés à partir de situations réelles suivant le type de sol. Ces systèmes pourraient améliorer sensiblement les performances sur les critères de durabilité suivants : risque herbicide, productivité de la terre et du travail, sensibilité aux mauvaises herbes et au stress hydrique. Toutefois, une meilleure mise en culture réduit les performances en matière d'érosion et d'efficacité de l'azote.
- Pour quatre des systèmes de culture alternatifs, la moyenne géométrique des 9 critères de durabilité est supérieure à 1 indiquant qu'ils amélioreraient la durabilité dans l'ensemble. Le cinquième système alternatif sur le sol le plus fertile est le seul dont la moyenne géométrique des 9 critères est inférieure à 1. Les meilleures performances sur les critères « risques herbicide » et « productivité du travail » ne compensent pas suffisamment la détérioration des critères « risques sur l'érosion » et « efficacité de l'azote ».

À l'échelle de la ferme (chapitre 4),

- Les simulations avec le modèle de ferme suggèrent que les systèmes de culture alternatifs pourraient être attractifs économiquement pour tous les types de fermes simulées, même les plus contraintes.
- Mais c'est pour les fermes déjà les mieux dotées en capitaux que ces systèmes apparaissent les plus bénéfiques pour la durabilité à l'échelle des fermes. Dans nos simulations, ils permettent de réduire significativement l'utilisation d'herbicide et augmentent le revenu total des fermes.
- La principale contrainte des systèmes alternatifs est le coût augmenté en début de saison culturale ce qui limiterait dans la réalité probablement l'adoption de ces systèmes par les fermes les plus contraintes en trésorerie.

Les incertitudes liées aux indicateurs et critères utilisés pour évaluer la durabilité peuvent être de trois sortes : i) l'oubli d'un enjeu de durabilité pourtant primordial à considérer dans le contexte et pour la finalité d'évaluation, ii) une mauvaise prédiction des impacts et performances par les indicateurs utilisés, iii) une perte de robustesse et d'information à cause de l'agrégation des indicateurs en critères.

- Les incertitudes liées à l'oubli d'un enjeu de durabilité

Notre démarche de contextualisation des critères de durabilité réduit les risques d'incertitudes liés à l'oubli d'enjeux de durabilité par rapport à si nous avons appliqué une méthode d'évaluation multicritère générique avec un jeu de critères prédéterminé. En effet, la plupart des méthodes existantes ont été développées dans un contexte d'agriculture industrialisée où l'évaluation est généralement utilisée pour améliorer les systèmes agricoles subventionnés et basés sur des intrants chimiques dans des systèmes alimentaires mondialisés. Dans ce cas, l'évaluation de la durabilité vise principalement à limiter les impacts environnementaux de systèmes de culture dont le rendement est déjà à 70-80 % du rendement potentiel (par exemple Carberry *et al.* (2013); (van Wart *et al.*, 2013)). En revanche, les points de départ des évaluations de la durabilité dans notre contexte sont des exploitations à faible revenu et non subventionnées qui s'efforcent encore d'augmenter leur revenu agricole pour sortir de la pauvreté, principalement en intensifiant progressivement leurs systèmes de culture (Pasuquin *et al.*, 2014).

Afin de contextualiser les critères et indicateurs de durabilité, certaines méthodes construisent l'ensemble de leur démarche avec une approche participative incluant des acteurs d'une filière ou d'un territoire (Rey-Valette *et al.*, 2008; Howlett *et al.*, 2000). La difficulté dans ce type d'approche est de concilier les points de vue contradictoires de différents acteurs (Munda *et al.*, 1994), car même un groupe d'experts de la même thématique peut se trouver en désaccord sur les questions de durabilité (de Olde *et al.*, 2017). Nous avons donc plutôt choisi d'avoir une approche quantifiée (par une approche dérivée du diagnostic agronomique) pour s'abstraire autant que possible des présupposés sur la durabilité dans ce contexte où les données sont rares et les agriculteurs pauvres, et pour comprendre les causes de la variabilité du rendement cruciale au revenu de ces agriculteurs.

Puis nous avons complété l'analyse par les perspectives des agriculteurs, car dans ce contexte d'agriculture pauvre non subventionnée, l'agriculteur est l'acteur très fortement impacté par les performances et impacts du système de culture mis en place. Les agriculteurs n'ont en revanche pas directement participé à la sélection des indicateurs utilisés pour l'évaluation. Notre approche pourrait sans doute être améliorée en faisant valider les indicateurs et les critères puis les résultats par les agriculteurs (Reed *et al.*, 2006).

La dimension sociale dans les évaluations multicritères fait souvent défaut (Macombe *et al.*, 2013). Certains auteurs évaluent la dimension sociale en tenant compte de la capacité organisationnelle des agriculteurs ou de l'équité sociale des systèmes de production (Binder *et al.*, 2012; Rodrigues *et al.*, 2010; Valdez-Vazquez *et al.*, 2017). Dans notre étude nous avons choisi d'intégrer à la dimension sociale uniquement l'autonomie des fermes, la transmissibilité et la pénibilité du travail, car les indicateurs et critères sélectionnés devaient discriminer les différentes fermes et systèmes de culture évalués. Il serait cependant pertinent de mieux représenter la pénibilité du travail, par exemple à l'aide d'enquêtes auprès des agriculteurs pour identifier les tâches qu'ils considèrent comme pénibles.

- Les incertitudes liées à la prédiction des impacts et performances avec des indicateurs

Par construction, les indicateurs sont une simplification de la réalité et sont utilisés dans cette étude comme outils de classification relativement robuste des systèmes de culture. Leur rôle n'était pas de quantifier précisément les impacts réels des flux d'herbicide ou l'impact d'un système de culture sur la fertilité d'un sol (chapitre 3) mais plutôt de faciliter les comparaisons de systèmes de culture sur les enjeux de durabilité. Ces indicateurs ont été des compromis entre complexités, pour permettre un diagnostic et expliquer les processus en tenant compte des nombreuses interactions à l'œuvre, et simplicité, pour obtenir des résultats dans un temps limité dans ces contextes de transition rapide. L'enjeu était de ne pas être trop simpliste, au risque de se tromper dans les conclusions, mais de ne pas non plus être trop complexe au risque de faire des erreurs dans les mécanismes modélisés à cause d'imprécisions sur le trop grand nombre de paramètres à estimer.

Les indicateurs devaient avoir la capacité d'identifier des variations clefs des processus biophysiques à l'origine des impacts et performances des systèmes de culture, mais ils

devaient également être assez robustes pour ne pas être trop sensibles à de petites variations dans ces processus. La complexité des indicateurs mobilisés dépend aussi de la disponibilité des données souvent rares dans ces contextes tropicaux et soulève la question du type de données à acquérir pour faire converger les contraintes de ces terrains avec les exigences de l'évaluation quantifiée de la durabilité. Il n'est pas toujours possible de réaliser des mesures directes des impacts réels des systèmes de culture et nous pensons que cela ne devrait pas être un objectif en soi pour les évaluations dont la finalité est identique à la nôtre. En effet, mesurer seulement les impacts finaux comme la quantité de terre érodée ou la biodiversité piscicole impactée par la percolation des herbicides dans les eaux souterraines, ne permet pas de remonter facilement aux causes de ces impacts contrairement à des indicateurs ou des modèles prédictifs qui intégreraient les processus et auraient une plus grande puissance explicative. Or ce sont bien les causes que nous souhaitons expliquer puisque la finalité de notre évaluation est de comprendre les facteurs bloquant ces systèmes de culture dans des trajectoires non durables et d'identifier de meilleures trajectoires.

À la lumière de ce constat, comment faire converger les contraintes de ces terrains avec des enjeux de quantification robuste ? Les pratiques agricoles, suivant la sensibilité du milieu, peuvent générer des émissions qui à leur tour, suivant les conditions de transfert génèrent des changements d'état puis des impacts réels (Lairez *et al.*, 2016). Plutôt que de partir d'un modèle complexe avec de nombreux paramètres à estimer qui risquerait d'être inutilisable, une solution pour la quantification est de décomposer les liens de causalité des pratiques (ex. : doses d'herbicide appliquées par l'agriculteur) aux impacts réels (ex. : diminution de la biodiversité piscicole) et d'identifier les variables clefs à mesurer qui prédiront assez finement les impacts finaux de ces pratiques. A la place de mesurer finement l'impact réel qui a peu de puissance explicative, l'effort de mesure doit donc s'orienter sur le développement d'indicateurs ou de modèles opérationnels capables de quantifier les impacts potentiels (Freyer *et al.*, 2000). L'enjeu sera alors de paramétrer ces indicateurs et modèles opérationnels avec des données de la région étudiée et de s'assurer qu'ils répondent effectivement à l'objectif qui leur est attribué, à savoir de discriminer des systèmes sur leur durabilité lorsque des paramètres clefs atteignent certains seuils à définir localement.

En ce qui concerne la sensibilité des classements obtenus vis-à-vis de la durabilité que cela soit des fermes ou des systèmes de culture, notre étude nous apparaît assez robuste. En premier lieu, car la robustesse des conclusions au niveau des systèmes de culture ou des fermes tient au fait qu'une modification du système évalué doit être mise en évidence par un changement de valeur des indicateurs, mais si cette modification est dans la gamme de variabilité du système évalué cela ne doit pas changer le classement. En effet, pour le classement des systèmes de culture, nous avons tenu compte des intervalles de confiance des indicateurs de durabilité : au lieu d'évaluer un système « moyen », l'ensemble des situations culturelles définissant un type de système de culture a permis d'estimer des barres d'erreurs sur certains indicateurs et de tirer des conclusions dans la gamme de variabilité des systèmes évalués. Ensuite, au niveau de la ferme au lieu de considérer un unique système de culture de maïs dont la durabilité devait être améliorée, nous en avons analysé plusieurs représentant la variabilité actuelle, afin de discuter des marges de durabilité de manière plus pertinente pour ces agriculteurs très dépendants de la variabilité de leur milieu biophysique. En second lieu, une évaluation est qualifiée de robuste si un autre évaluateur applique la même démarche méthodologique, par exemple une autre année sur un réseau de placettes différent, et qu'il obtient les mêmes conclusions. La manière dont a été construit le dispositif de façon à maximiser la variabilité des placettes dans des fermes et villages contrastés sur plusieurs années nous permet d'être assez confiants sur ce dernier point.

Au chapitre 3, pour réaliser l'évaluation des systèmes alternatifs (les « Best-CSs »), nous ne possédions ni d'observations de situations culturelles à la fois performantes sur la productivité et sur les critères environnementaux, ni d'un modèle de culture capable de modéliser finement les interactions du climat et des pratiques avec les performances et impacts pour ces Best-CSs. Il a fallu construire un raisonnement agronomique en combinant les résultats issus des arbres de classification (CART du chapitre 2) à la modélisation d'un système de culture au potentiel limité par l'eau. Pour aller plus loin dans l'estimation des performances et impacts de ces systèmes alternatifs pourtant bien moins différents des systèmes actuellement observables que ne le seraient des alternatives plus franchement agroécologiques, des progrès sont à réaliser sur la modélisation du système de culture. La

section 2 de ce chapitre présente une analyse des limites des modèles existants pour l'évaluation que cela soit des systèmes actuels ou agroécologiques.

- Les incertitudes liées à l'agrégation des indicateurs au niveau des critères

Dans les évaluations multicritères, la durabilité se décompose le plus souvent en enjeux, critères et indicateurs. Les indicateurs, les unités élémentaires de l'évaluation, sont agrégés pour évaluer les critères puis porter un jugement sur la durabilité d'un système de culture ou d'une ferme. L'agrégation s'accompagne donc de transformations des indicateurs sur une échelle commune et de pondérations éventuelles qui déterminent l'importance relative des indicateurs les uns par rapport aux autres (Lairez *et al.*, 2017). L'agrégation peut influencer les résultats de l'évaluation suivant les choix réalisés. La plupart des méthodes génériques d'évaluation manquent de transparence dans ces choix et ne donnent pas de résultats désagrégés.

Dans notre étude, nous avons réalisé la transformation des indicateurs sur une échelle commune en utilisant la normalisation ou le classement interne plutôt que des valeurs de référence externes et nous avons choisi d'utiliser la moyenne géométrique pour agréger les indicateurs au niveau des critères plutôt que la moyenne arithmétique communément utilisée. Notre approche tient compte des erreurs sur les incertitudes des indicateurs et la moyenne géométrique réduit les éventuelles compensations entre indicateurs (un mauvais score sur un indicateur est plus difficilement compensable par un bon score sur un autre). Enfin, les résultats des indicateurs avant agrégation sont donnés pour plus de transparence dans les conclusions sur la durabilité des systèmes évalués.

2 Quels fronts de recherche investir pour réduire les incertitudes de l'évaluation

2.1 La modélisation des systèmes de culture

L'évaluation de systèmes de culture dans les parcelles des agriculteurs est fondamentale pour comprendre la variabilité de leurs performances et de leurs effets sur la durabilité des exploitations agricoles. Étant donné la complexité d'envisager l'évaluation *in situ* d'une multitude de champs cultivés, il semble plus judicieux de cibler la mesure sur les processus

biophysiques clefs pour être en mesure d'extrapoler, à l'aide de la modélisation, les résultats dans des milieux et climats contrastés. Dans l'état actuel des modèles disponibles, à la condition de réaliser un effort de paramétrage conséquent, il est possible de modéliser relativement bien les processus biophysiques à l'origine des flux d'azote et d'eau dans les systèmes de culture et leurs effets sur les performances et impacts (Falconnier *et al.*, 2020). En revanche, les recherches sur la modélisation des effets des adventices sur les performances agronomiques sont moins avancées et nous sommes encore plus démunis lorsqu'il s'agit de modéliser des systèmes agroécologiques plurispécifiques.

En effet, les études sur la modélisation des interactions des adventices avec les performances des systèmes de culture sont encore peu nombreuses et partielles dans les agricultures industrialisées où sont développés la plupart des modèles de culture (Freckleton and Stephens, 2009; Chauhan *et al.*, 2017). Jusqu'à présent, l'effet négatif des adventices sur les performances agronomiques était traité par l'usage d'herbicides, mais aujourd'hui les nouveaux objectifs de réduction des herbicides et la suppression progressive de nombreux produits phytopharmaceutiques amènent la recherche ainsi que les professionnels du domaine à réorienter leurs travaux vers des approches intégrées pouvant faire intervenir une combinaison de leviers (rotations/interculture, mécanique, thermique, etc.). Dans la plupart des grands modèles génériques, les interactions avec les adventices ne sont pas représentées. Une solution pourrait être de les assimiler à une culture associée pour les intégrer dans les modèles, en présumant une simplification de la communauté d'adventices. Cette simplification ne serait pas forcément limitante pour tirer des conclusions sur les interactions des adventices avec les performances du système de culture sauf si les communautés sont très diverses d'une situation culturale à une autre. Le modèle Florsys (Munier-Jolain *et al.*, 2013) considère de manière plus fine les adventices en représentant les différentes espèces que l'on peut rencontrer dans ces communautés et leurs effets sur le rendement ou d'autres variables comme la biodiversité (Colbach *et al.*, 2017) ou le lessivage de l'azote (Moreau *et al.*, 2020). Cependant, ces modèles ont été construits pour des milieux tempérés et peuvent nécessiter des adaptations pour être transposés aux contextes tropicaux. En effet, les facteurs déterminants la mise en place et l'évolution de ces communautés d'adventices au sein des systèmes de culture ne seront pas forcément les mêmes en milieux tempérés ou tropicaux

(variations de températures et d'humidité différentes, saison de culture sur un pas de temps restreint, etc.) et les moyens mobilisés par les agriculteurs pour gérer ces adventices seront également différents. Les facteurs et les modes de gestion restent donc encore à étudier du fait du peu de données actuellement disponibles dans ce domaine en milieu tropical.

Alors que les agriculteurs des pays industrialisés auront probablement plus facilement accès aux subventions, au matériel et au crédit nécessaires pour se convertir à une gestion sans herbicides des adventices (mécanique, thermique ou par l'interculture et la rotation), les agriculteurs au seuil de pauvreté et non-subventionnés, auront plus de difficultés à saisir ces opportunités. Il nous semble donc d'autant plus pertinent que la recherche s'empare du challenge de la quantification des performances et impacts de différentes options de gestion alternatives des adventices, selon les itinéraires techniques et les milieux biophysiques dans lesquels les agriculteurs pauvres évoluent (Daum and Birner, 2020). Ces recherches à l'échelle du système de culture devront être contextualisées à l'échelle de l'exploitation afin de produire les données utiles à la mise en place des crédits ou politiques agricoles nécessaires à ces transitions.

L'évaluation pour la conception de systèmes de culture agroécologiques nécessite de comparer les systèmes actuels à des alternatives. Cependant, nous ne connaissons pas encore assez finement la variabilité des performances des alternatives agroécologiques en fonction de la maîtrise de l'itinéraire technique des agriculteurs, du type de sol, du climat, ou de la variabilité de la date de semis. Les performances, lorsqu'elles sont connues, sont issues pour la plupart d'un milieu expérimental contrôlé ce qui idéalise le système alternatif et peut l'avantager exagérément par rapport à un système de culture conventionnel pratiqué par les agriculteurs. Aujourd'hui, nous sommes donc limités sur la portée des conclusions sur les performances et impacts de ces alternatives en comparaison à l'existant. Ainsi, il est primordial que cette quantification aille au-delà du rendement pour mesurer des variables intermédiaires ou explicatives clefs permettant la modélisation des performances et impacts dans des climats, milieux et maîtrises techniques contrastés.

2.2 La modélisation des fermes et intégration des objectifs des agriculteurs

Un autre enjeu pour la recherche est le développement de modèles de fermes capables d'intégrer les multiples objectifs des agriculteurs dans l'analyse de la durabilité. Nous avons ouvert des perspectives nouvelles sur ce thème en mobilisant les méthodes de l'économie expérimentale, comme le « choice modelling » dans une recherche non présentée dans cette thèse (Jourdain *et al.*, 2020), ou le « Best-worst-scaling -BWS» (présentée dans le chapitre 4). Elles permettent d'identifier les objectifs des agriculteurs, de les pondérer et de quantifier l'ampleur des compromis entre objectifs. Dans le « choice modelling » par exemple, l'agriculteur enquêté doit choisir successivement l'alternative qu'il préfère (un système de culture par exemple) parmi plusieurs (Jourdain *et al.*, 2020). Il doit réaliser son choix à partir d'une description de chaque alternative par une liste d'attributs (le rendement, le travail, l'effet sur la fertilité par exemple). Ces méthodes quantitatives sont assez robustes, car elles permettent de quantifier les erreurs liées à l'incohérence des choix causées par le trop grand nombre de paramètres à considérer pour prendre une décision. Les agriculteurs sont confrontés plusieurs fois aux mêmes alternatives ce qui permet de calculer ces erreurs de cohérence décisionnelle et d'en tenir compte dans les conclusions.

Nous n'avons pas intégré ces objectifs dans la fonction objectif du modèle de ferme. Nous avons plutôt opté pour une approche à mi-chemin entre l'optimisation multi-objectif et l'optimisation d'un unique objectif sous contraintes. Notre modèle permet d'identifier les contraintes principales limitant les transitions (trésorerie, calendrier de travail, ressources, etc.). Nous utilisons les objectifs des agriculteurs dans l'analyse des compromis générés par différents scénarios de transition, une fois que le revenu des agriculteurs a été maximisé sous contraintes.

Il convient d'identifier si notre manière de modéliser les fermes a tout de même été pertinente. Certaines contraintes conditionnent fortement la réalisation des objectifs multiples des agriculteurs, nous avons donc représenté leurs objectifs dans les contraintes du modèle, plutôt que dans une fonction multi-objectif. L'objectif principal des agriculteurs était l'autosuffisance en riz et cet objectif est déjà représenté à son maximum possible (sur les zones de bas-fond irrigué) par notre version du modèle pour la « baseline » et les scénarios. Le second objectif des agriculteurs était la transmissibilité de la ferme aux générations futures,

représentée dans notre modèle par la quantité de terre, de matériels ou d'unités de bovins par enfant. Cet objectif est également déjà représenté à son maximum pour la « baseline » et les scénarios. Enfin, le troisième objectif des agriculteurs était la régularité de leurs revenus. Dans le modèle, cette régularité est assurée par le tissage, le travail extra-agricole et la vente des produits issus de l'élevage. Toutes ces variables sont également simulées par le modèle à leur maximum.

Intégrer ces objectifs dans une fonction multi-objectif n'aurait donc probablement pas changé les conclusions de cette étude. Dans une étude approfondie, il serait intéressant de modéliser cette fonction multi-objectif pour des profils d'objectifs contrastés et de comparer les résultats à ceux obtenus avec notre approche. Il serait également pertinent de mieux représenter le risque dans ce modèle, car les transitions, qu'elles soient agroécologiques ou d'amélioration techniques peuvent générer des risques (risques climatiques, de fluctuation des prix, risques de maîtrise technique). Mais pour être en mesure de représenter le risque à l'échelle des fermes, il convient dans un premier temps d'avoir une quantification précise de ce risque par des modèles biophysiques telle que décrite au début de la section.

3 Réflexions sur l'évaluation intégrée et multicritère de la durabilité : quelle généralité de l'approche ?

La finalité de l'évaluation était de diagnostiquer la durabilité des systèmes agricoles actuels, pour comprendre les facteurs bloquant ces systèmes dans des trajectoires non durables et identifier de meilleures trajectoires, afin d'*in fine* appuyer le développement de politiques agricoles avec des données quantifiées. Les étapes méthodologiques que nous avons développées et mobilisées sont relativement génériques: 1) Utilisation d'un diagnostic agronomique adapté combiné à des « jeux sérieux » pour identifier des critères de durabilité pertinents localement, 2) Utilisation du diagnostic agroenvironnemental pour évaluer, dans les parcelles des agriculteurs, les performances agronomiques et les impacts environnementaux de systèmes de cultures contrastés, 3) mise en perspective des résultats d'évaluation à la parcelle au niveau d'exploitations contrastées pour discuter de leurs marges d'amélioration de la durabilité suivant leurs contraintes et objectifs.

Pour les approches qui répondent à notre finalité d'évaluation, Sadok *et al.* (2008) oppose les approches dites de « décision multicritère » aux approches « d'optimisation sous contraintes ». Les approches de décision multicritère mobilisent des indicateurs organisés en niveaux hiérarchiques. La durabilité y est décomposée en enjeux, dimensions/attributs, critères puis indicateurs élémentaires permettant la quantification (Vasileiadis *et al.*, 2013; Iocola *et al.*, 2020; Craheix *et al.*, 2012). Les méthodes d'optimisation sous contraintes simulent la décision des agriculteurs sur le choix de leurs activités en vue de la maximisation d'un ou plusieurs objectifs liés à la durabilité.

Notre étude contribue aux recherches qui combinent ces deux approches : un modèle d'optimisation est utilisé pour calculer des indicateurs de durabilité hiérarchisés en critères (Dogliotti *et al.*, 2005; Timler *et al.*, 2020; Ditzler *et al.*, 2019). Nous avons réalisé une évaluation intégrée et multicritère avec un exemple de changement technique et d'environnement économique représenté par l'augmentation fictive du coût d'un système alternatif.

Les critiques les plus courantes faites aux méthodes d'optimisation pour l'évaluation *ex ante* d'alternatives sont i) les possibilités réduites d'utiliser des données qualitatives pour l'évaluation, ii) L'évaluation d'une unique solution dite « optimale » alors que des solutions suboptimales pourraient également être durables.

Quant aux méthodes de décision multicritère, la principale critique qui leur est faite est la trop grande sensibilité des classements des systèmes évalués aux choix réalisés lors de l'agrégation des indicateurs.

Combiner ces deux approches permet de limiter les défauts de chacune :

- Le modèle construit a permis de quantifier l'attractivité économique d'un système alternatif, c'est-à-dire d'identifier les conditions nécessaires à l'adoption d'un système alternatif, au lieu d'utiliser uniquement les indicateurs économiques standards tels que la marge brute, la productivité du travail ou le retour sur l'investissement. En effet, évaluer uniquement ces indicateurs ne permet pas de quantifier les effets que peut avoir un système alternatif sur les performances économiques des autres composantes de la ferme. Or dans nos contextes de fermes très contraintes et dont le

revenu dépend d'une multitude d'activités en interaction, il est primordial de tenir compte des effets d'une alternative sur le reste des activités de la ferme.

- Dans notre étude, la solution optimale en sortie du modèle de ferme n'est en aucun cas l'unique solution à considérer. Cette solution permet de construire un raisonnement sur les possibilités d'améliorer la durabilité de fermes contrastées en identifiant des marges d'amélioration. Il est aussi possible d'analyser des solutions suboptimales en réalisant des simulations avec des hypothèses différentes sur les objectifs des agriculteurs, sur les contraintes ou en introduisant ou omettant différents types de systèmes de culture dans la liste des options que l'agriculteur modélisé peut choisir.
- Les données qualitatives peuvent tout à fait être intégrées dans l'optimisation sous forme de scores, comparables à ceux utilisés dans les méthodes multi-attributs.
- La sensibilité des classements des systèmes évalués est assez limitée, nous l'avons vu, car notre étude classe les systèmes de culture en tenant compte des intervalles de confiance des indicateurs de durabilité et réalise une analyse de sensibilité sur le coût du système alternatif.

4 Les recommandations et les perspectives pour la recherche locale

Des solutions existent pour rendre le maïs de la plaine de Kham plus durable. Dans l'état actuel du système agraire local, ce n'est pas tant le maïs qui pose les problèmes de durabilité les plus préoccupants, mais la manière dont il est cultivé : monoculture, mauvaise maîtrise de la mise en culture, peu de gestion de la fertilité et utilisation d'herbicide en excès par rapport aux doses recommandées. Si ce maïs était mieux géré techniquement, le revenu et la productivité du travail des agriculteurs pourraient augmenter sensiblement et l'utilisation des herbicides serait réduite significativement.

En revanche, une meilleure maîtrise technique impliquerait une augmentation des coûts du système de culture et probablement de l'endettement pour les plus pauvres n'ayant pas la trésorerie suffisante pour réussir la mise en culture dans les bonnes conditions. En effet, pour que les agriculteurs soient en mesure de maîtriser la séquence des opérations de mise en culture, il est nécessaire qu'ils disposent d'un outillage nouveau, qu'il faudra acquérir et

amortir, ou qu'ils accèdent à un service de mise en culture par des tiers qui soit de qualité bien supérieure au service actuel. Dans ce dernier cas, on est conduit à supposer que les fournisseurs du service soient eux-mêmes mieux équipés et donc très probablement qu'ils facturent l'heure de service à un niveau plus élevé qu'actuellement. Pour faciliter l'accès des producteurs aux équipements et intrants nécessaires à l'amélioration des performances du système de culture, il faudra sans doute développer le système de crédits agricoles, non seulement de très courts termes (crédit de campagne agricole) mais aussi de plus longs termes (crédits d'équipement). C'est évidemment pour les agriculteurs les plus pauvres et les plus contraints que le développement d'un tel système de crédit sera le plus nécessaire, et en même temps le plus difficile à mettre en œuvre tant le revenu de leurs exploitations est faible faute de terre en quantité suffisante. Plus généralement, le développement du crédit sera probablement nécessaire pour amorcer la transition agroécologique dans ce contexte, par la mise en place d'un système moto-mécanisé performant.

L'appui et la formation de groupements d'agriculteurs autour des enjeux de mécanisation seraient également une solution pertinente pour une transition durable du maïs (Van Loon *et al.*, 2020). Un travail sur l'ingénierie de matériel agricole devra être mené localement notamment sur les outils de travail du sol et de mise en culture. Des outils d'hersage à dents plutôt qu'à disques pourraient être testés pour analyser leurs effets sur l'état de surface du sol et la gestion mécanique des adventices. Nous avons nous-mêmes amorcé ce travail avec l'école polytechnique de Vientiane pour construire un cultivateur à dents actuellement non-disponible sur le marché local, mais le matériau utilisé pour fabriquer les dents s'est avéré insuffisamment résistant pour détruire les mottes (Figure 20).



Figure 20 : Cultivateur à dents testé pour améliorer les états de surface

Le semoir de semis direct semble être également une option pertinente à tester ainsi que des options d'amélioration du système de distribution des semences qui ne se ferait plus par friction à la surface du sol d'une roue crantée, mais par rotation de la roue motrice principale (Hossain *et al.*, 2009). Ces conceptions et tests d'une petite mécanisation appropriée pourraient se réaliser pour la diversité des fermes et des milieux biophysiques de la région à partir des typologies de fermes et de systèmes de culture établies dans cette étude.

La monoculture, même améliorée techniquement, reste bien entendu un système imparfait sur beaucoup d'aspects. Dans l'idéal, il faudrait également tester localement des systèmes de culture basés sur les principes de l'agroécologie (De Schutter, 2011) : diversifiés avec des rotations, protégeant contre l'érosion, améliorant la fertilité et la biodiversité, etc., mais l'évaluation de telles alternatives est complexe dans ces contextes de transition rapide. Nous l'avons vu, évaluer les systèmes existants et les marges d'amélioration permises par une meilleure gestion technique était déjà un enjeu méthodologique conséquent. L'enjeu pour la recherche locale est d'élaborer des dispositifs de suivis de la variabilité des performances et impacts de ces systèmes agroécologiques. Cela a déjà été souligné par Hauswirth (2013) au Vietnam, un effort de quantification est à réaliser par exemple dans les dispositifs existants de conception et diffusion de systèmes de culture agroécologiques. Les données à collecter sur ces dispositifs doivent aller au-delà du rendement en station expérimentale ou des impacts environnementaux du système innovant. Il s'agit de quantifier des variables intermédiaires ou explicatives des performances et impacts sur des systèmes pratiqués par les agriculteurs : surface foliaire, compétition avec les mauvaises herbes, la réserve utile des sols, effets sur les états du milieu par rapport aux pratiques et climats, etc. Ces dispositifs pourraient s'inspirer de la métrologie mise en place dans cette étude pour établir une quantification de la variabilité des performances et impacts des systèmes agroécologiques.

5 Perspectives globales de l'étude

Partout dans le monde, lorsque la population augmente, les sociétés agraires de subsistance sont contraintes d'évoluer pour répondre à la demande croissante en alimentation (Mazoyer and Roudart, 2017). Dans le cas où les changements techniques sur les systèmes de culture sont difficiles (fortes pentes limitant la mécanisation, zones isolées et peu accessibles limitant

l'accès aux outils et technologies), la migration ou le travail extra agricole sont des alternatives pour limiter l'extrême pauvreté inhérente aux faibles productivités de ces systèmes de subsistance (Rigg, 2006b). En revanche, dans le cas de plaines céréalières relativement favorables à l'intensification et à la mécanisation, les changements techniques des systèmes de culture sont plus aisés et des transitions agraires profondes se mettent en place.

Notre cas d'étude a une portée globale. Il est un cas typique d'agriculture familiale de subsistance ayant augmenté sa durabilité économique en intégrant un marché par l'intensification et la mécanisation du système de culture. Partout dans le monde, les systèmes de subsistance dans des milieux relativement favorisés et proches d'un marché s'orientent vers la vente et se mécanisent (Van Loon *et al.*, 2020; Grillot *et al.*, 2018; Adu-Baffour *et al.*, 2019; Diao *et al.*, 2014).

Ces nouveaux systèmes moto-mécanisés augmentent la productivité du travail et permettent d'améliorer le niveau de vie des ménages ruraux, que les enfants échappent aux travaux agricoles et accèdent à l'éducation, de réduire la pénibilité du travail agricole ou de répondre à la pénurie de travailleurs. À l'échelle de la parcelle, l'augmentation de la fréquence d'une culture par rapport aux systèmes de subsistance relativement extensifs, entraîne souvent des perturbations des propriétés fonctionnelles de l'écosystème (Hooper *et al.*, 2005; Altieri, 1999) compensées par toujours plus d'interventions humaines utilisant davantage d'intrants externes (engrais, herbicides) et de mécanisation (Altieri, 1999; Altieri *et al.*, 1983; Meynard *et al.*, 2013). Toutes ces technologies sont nouvelles pour les agriculteurs pauvres et peuvent ne pas être bien maîtrisées. Les performances des systèmes de culture peuvent être loin des résultats escomptés générant un revenu insuffisant pour sortir réellement de la pauvreté. De fortes incidences environnementales ou sociales peuvent également apparaître.

En réponse aux impacts de ces intensifications conventionnelles des systèmes de culture, des initiatives visent à promouvoir une intensification durable et à éviter le recours excessif aux intrants extérieurs en appliquant les principes de l'agroécologie. Cependant, ces alternatives sont rarement adoptées par les agriculteurs aux ressources limitées à cause de leur impact négatif sur le revenu agricole à court terme, car même après l'intégration aux marchés, ces agriculteurs restent proches du seuil de pauvreté et continuent de subir des problèmes de

subsistance. Les contraintes de trésorerie, d'organisation territoriale ou de filière peuvent également être un frein à l'adoption de ces alternatives agroécologiques.

Pour qu'une transition agroécologique véritable ait lieu, cela requiert des investissements importants dans les politiques publiques afin de faciliter l'émergence de nouveaux dispositifs institutionnels, économiques, financiers et résoudre les tensions entre contraintes à court terme des producteurs et enjeux environnementaux (Côte *et al.*, 2019). En attendant les transformations politiques nécessaires pour ces transitions agroécologiques profondes, cette étude montre qu'il est cependant pertinent d'en amorcer certaines, peut-être moins ambitieuses mais sans doute plus directement accessibles. Ces transitions intermédiaires sur les meilleures maîtrises techniques, pourraient contribuer à avancer vers une véritable transition agroécologique dans les nombreux contextes à travers le monde où des transformations conventionnelles se mettent en place et conduisent à une maîtrise très imparfaite des systèmes de culture à base de maïs générant des impacts environnementaux exacerbés par la pauvreté des agriculteurs.

Conclusion générale

Notre étude a contribué aux travaux sur l'évaluation intégrée et multicritère capable de discuter de compromis localement les plus acceptables entre objectifs socio-économiques de court terme et objectifs de durabilité à long terme pour des systèmes de culture s'intensifiant dans des fermes au seuil de pauvreté. Dans les contextes particuliers où les données sont rares et où les revenus des agriculteurs dépendent encore très largement de la productivité des systèmes de culture, nous avons donné des pistes originales pour la combinaison d'outils et d'approches à mobiliser pour l'évaluation de la durabilité de la parcelle à l'exploitation.

Aujourd'hui, après la révolution verte, une autre révolution est en marche intensifiant les systèmes de culture : l'intégration au marché et le développement d'une petite mécanisation de plus en plus accessible aux fermes de petites tailles. Le cas d'étude a une portée globale, car il s'agit du cas très répandu d'une plaine céréalière où les agriculteurs sont passés récemment de systèmes de subsistance non durables économiquement à des systèmes intégrés au marché en intensifiant leurs systèmes de culture. La plupart du temps, ces systèmes génèrent des risques pour l'environnement, mais l'étude permet de conclure que ces impacts ne sont pas inéluctables et que certains pourraient même être résolus par une meilleure gestion technique. La durabilité des fermes pourrait augmenter significativement et servir de tremplin à une réelle transition agroécologique ambitieuse si les politiques agricoles nécessaires à la transition se mettent en place dans les pays en voie de développement.

Un enjeu crucial pour l'avenir sera de combiner évaluation multicritère à évaluation prospective de scénarios permettant une sortie réelle de la pauvreté de millions d'agriculteurs. Ces évaluations prospectives sont essentielles à la décision politique, mais pour cela, la recherche doit se donner les moyens d'acquérir des données sur la multitude de systèmes actuels et alternatifs tels que pratiqués par les agriculteurs.

Annexes

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Appendix 5: Soil diversity on field monitoring network.

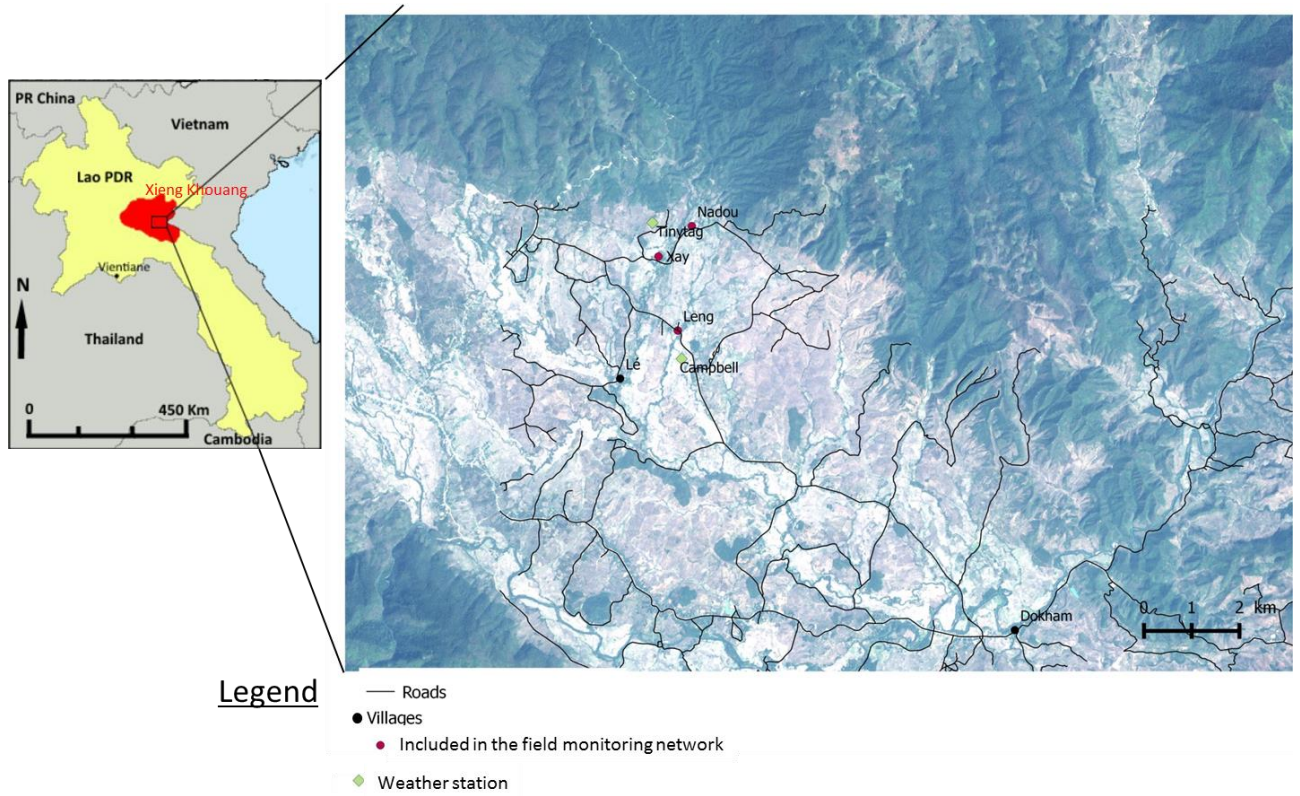
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Appendix 1: Map of the study region, Kham District in Xieng Khouang province in Lao PDR.



Appendix 2: Q-sort average values for each statement for the three types of opinions revealed by the Q-methodology.

	Opinions		
	O1	O2	O3
1. Soils fertility has decreased because of ploughing every year	1	0	0
2. If the soil is black, it is a fertile soil and if the soil is red or yellow it is an unfertile soil	4	-2	-3
3. A fertile soil is soft and has a good structure after ploughing	0	5	3
4. No matter the colour and the structure of the soil, a fertile soil is the one with high yield without fertilizer addition	-1	-5	-1
5. Legumes crops can improve soil fertility	5	0	1
6. Maize grows well even if the soil is not fertile, unlike other upland crops	-5	-2	-4
7. Growing maize every year makes soil fertility decline over the years	0	1	0
8. Soils in flat land cleared from very old forest remain fertile even after 15 years of maize cultivation	3	4	4
9. The use of herbicide makes the soil less fertile	0	-2	-4
10. Mineral fertilizer are making the soils stronger	-5	0	-4
11. High yield is not the only criteria to know if the soil is fertile or not	-2	1	3
12. Unfertile maize fields have a lot of weeds	-3	-5	-3
13. If the soil is unfertile I cannot have good yields even if I put fertilizer	-1	-3	2
14. It is important to prevent soil fertility loss even if we have a lower income today by doing so	2	-4	0
15. It is important to prevent soil fertility loss even if we have to work more by doing so	1	-1	4
16. Even if soil fertility has changed it is not a big problem because farmers are wealthier thanks to maize	-3	0	1
17. I want to preserve the fertility of my soil for the future farm of my children	4	1	2
18. Farmers have a duty to conserve soil for the next generation, whatever the impact on today's profits	2	-4	2
19. Maintain soil fertility is not only about immediate yield, it is a long term investment	1	-1	2
20. I prefer to have a high income today because I need money immediately, even if I don't preserve soil fertility	-4	-3	-2
21. Farming practices today will impact the future generations but there is no other alternative	-2	0	4
22. Fertilizer and cow manure are the same for fertility improvement	-3	-2	-5
23. Maintaining soil fertility is not labour intensive	-4	-3	-5
24. It is not worth it to invest time and money in soil fertility	-4	-2	-2
25. The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition	5	4	5
26. The soil is unfertile when young maize is yellowish	4	2	3
27. Even if today soil fertility is low, soil has the capacity to be fertile again if we let him rest long enough	1	1	-2
28. Soil is degraded for good, it is not possible to come back to the way it used to be before maize	-3	-3	-1

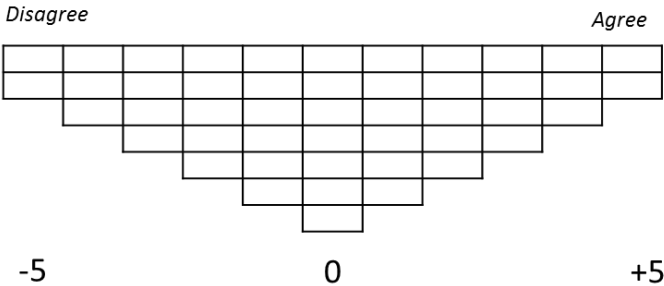
29. Soil erosion leads to a decline in fertility because the most fertile layer disappears	2	3	5
30. Fallow was used before maize to make the soil rest and soil fertility increase	3	4	3
31. There are green and very beautiful maize in the village, it is the sign that the soils are still fertile in some areas	3	2	0
32. Soils that dry quickly is a sign of low fertility	-2	-1	0
33. When there is enough rain most of the soils of the village still are able to give good yields	1	3	2
34. The soils are addicted to fertilizer and need more of it than in the past	1	2	0
35. If the soil is deep, I know for sure that the soil is fertile	3	1	1
36. There are special species of weeds that are only in unfertile soils and other species of weeds only in fertile soils	0	2	-1
37. Low crop yield in a good climatic year is an indicator of low fertility	2	2	1
38. Fertility degradation is not the principal factor in yield decrease, other more important factors explain low yields	-2	0	1
39. Water stress at the beginning of the cropping season is the main cause of low yield compare to low soil fertility	-1	0	-3
40. Weed invasion is the main cause of low yield compare to low soil fertility	0	1	0
41. Low maize density is the main cause of low yield compared with low soil fertility	-1	-1	-1
42. Soils are more exhausted than before but could give more yield today thanks to mineral fertilizer, good variety and herbicide	-2	-1	-1
43. Some soils were unfertile before maize, other became unfertile due to maize cultivation	-1	-4	-2
44. 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
45. 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
46. A fertile soil is a soil where it is easy to obtain a good density at emergence despite heavy rainfalls	0	-1	1
47. After ploughing, a fertile soil has clods that easily burst with rainfall	-1	5	-1

Appendix 3: The Q-methodology with A) farmers reading the statements of Q-method and B) the normal design following which farmers had to place the statements.

A



B

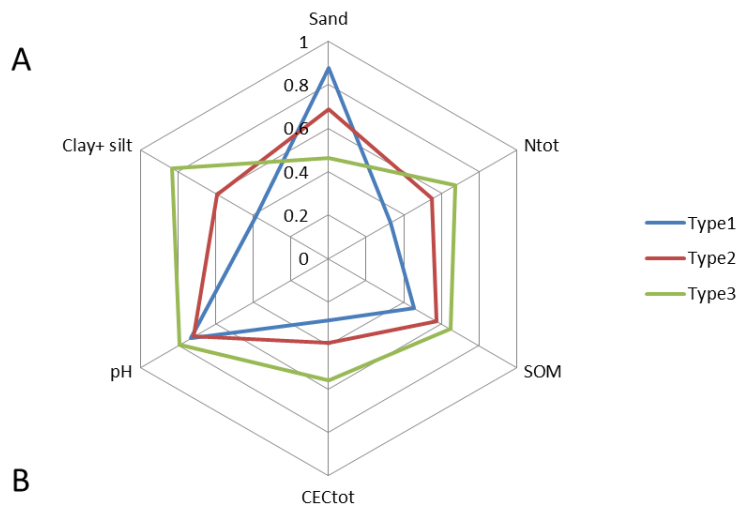


Appendix 4: List of all the constraints and sustainability issues possibly occurring in maize areas of Kham basin and suspected causes according to the initial knowledge from literature (extended to northern Laos).

Some sources were published after 2016, the year of set up of the field monitoring network but were useful to illustrate the local discourse on constraints and expected causes afterward.

Constraints	Suspected causes	Source
• Economic performances		
Low maize yields	Soil fertility decrease	Farmers interviews +literature (Southavilay <i>et al.</i> , 2012b)
Low prices/unstable markets	?	Farmers interviews
High costs	Fertilizer, herbicide, hybrid seeds	Farmers interviews
• Agronomic performances (yield)		
Low nitrogen availability	Low soil fertility due soil nutrient depletion caused by maize mono-cropping No fertility management	Farmers interviews +literature (Viau <i>et al.</i> , 2009)
Weed	Weed resistance to herbicide	Farmers interviews
• Environmental impacts		
Erosion, soil degradation	Slopes, bare soils, heavy rains	Literature (Dupin <i>et al.</i> , 2009; Valentin <i>et al.</i> , 2008; Kallio <i>et al.</i> , 2019)
Herbicide leaching	High amounts of herbicide	Literature (Bartlett, 2016)
Deforestation	Maize expansion	Literature (Kallio <i>et al.</i> , 2019)
Biodiversity	Landscape segregation/homogenisation due to mono-cropping	(Castella <i>et al.</i> , 2013; Viau <i>et al.</i> , 2009)
• Social impacts		
Farmers Indebtedness, risks	High cash needed for maize cultivation	Literature (Hepp <i>et al.</i> , 2019; Viau <i>et al.</i> , 2009)

Appendix 5: Soil diversity on field monitoring network. For each attribute of soil type data are expressed in ratio [mean of attribute for the type]/[maximum value of the attribute on the total sample]



B

Soil type	Sand (%)	Ntot (g kg ⁻¹)	SOM (%)	Total CEC (me/100 g)	pH	Clay + silt (%)
Type 1 <i>15.51% of plots</i>	71.1	0.47	1.7	4.91	5.57	28.91
Type 2 <i>15.51% of plots</i>	55.74	0.791	2.166	6.72	5.45	44.27
Type 3 <i>68.98% of plots</i>	37.59	0.96	2.44	9.7	6.01	62.4

Appendix 6: GAMS equations used for optimisation

SET	c(*)	cropping activities	
	cropWinter(c)		dry season crops on lowland
	cropRiz(c)		different rice
	mais(c)		different maize
	z(*)	agroecological zones	
	zoneail(z)		
	basfond(z)		
	t(*)	periods	
	prem(t)		first period
	periodend(t)		
	periodmiddle(t)		
	therbe(t)		
	a(*)	livestock activities	
	porc(a)		porc units
	vache(a)		cattle units
	p(*)	farm products	
	herbe(p)		
	prodHum(p)		
	prodPorc(p)		
	g(*)	type of workers	
	adu(g)		adult labor only
	cz(c,z)	crop*zone	

PARAMETERS

area(z)	area in each zone in ha
req_work(c,z,t)	required working time for crop c in zone z at period t (in human working days per ha)
DISPOW(g,t)	working time available by type of workers and by period
Yield(c,z,p,t)	Yield of product p from crop c in zone z at period t
pricevente(p,t)	Price of selling product p at period t
priceachat(p,t)	price of buying product p at period t
ventesAni(a,t)	Sales per livestock porc unit and per period
IntrantsAni(a,t)	Purchases per livestock unit porc and per period
Req_WAni(a,t)	Required Labour per unit livestock of pork
valEnerH(p)	Energy content of product p por human consumption
HEnerNeed(t)	Human needs in energy per period
Stock_Ini(p)	Initial stock of product p
cout(c,z,t)	costs of crop cultivation
f_Expens(t)	minimum family expenses per period
valEnerRum(herbe)	
Anim_EnerNeed(a,t)	Energy requirements for porc per period (Kcal per period)
tresoi	Initial treasury

workOffMax(adu,t) maximum number of days where outside job can be found (in days)
 WorkInMax(adu,t) maximum number of days where labour force can be found on the market(in days)
 sal(adu,t) salariés
 weaving income from weaving
 transac1 cout de transaction achat vente produit
 transac2 cout de transaction MO
 taux(t) interest rate per period
 IFT(c,z,t)
 coutfix(t)
 sizeFamilly

VARIABLES

variable ut
 Y;
 positive variable
 X(c,z) area of zone z grown with crop c
 Xani(a) number of porc or cattle units
 CASHBEGIN(t)
 CASHEND(t) Cash balance at the end of a period
 Ventes(p,t) Sales of product p at period t
 consoH(p,t) Human consumption of product p at period t
 Stock_begin(p,t) Stock of product p at begin of period t
 Stock_end(p,t) Stock of product p at end of period t
 W_OUT(adu,t) working time outside the farm (in days)
 W_IN(adu,t) employed workers in the farm (in days)
 achats(p,t)
 consoRum(vache,p,t)
 emprunt(t) emprunt sur la période
 cashregul(t)
 binary variable
 bov
 maize

EQUATIONS

Fonction objectif :

REVENU..

sum((p,t), Ventes(p,t) * prixvente(p,t))
 + sum((a,t), ventesAni(a,t) * Xani(a))
 - sum((a,t), intrantsAni(a,t) * Xani(a))
 +sum((porc,t), ventesAni(porc,t) * Xani(porc))
 - sum((porc,t), intrantsAni(porc,t) * Xani(porc))
 - sum((c,z,t), X(c,z) * cout(c,z,t))

```

+ sum((adu,t), W_OUT(adu,t) * sal(adu,t)* (1-transac2))
- sum((adu,t) , W_IN(adu,t) * sal(adu,t)*(1+transac2))
- sum((p,t), ACHATs(p,t) * prixachat(p,t))
- sum(t,emprunt(t)*taux(t))
+ weaving
-sum(t,coutfix(t))
=e=Y ;
#####land constraints#####

COMPATIBILITE(c,z)$ (not cz(c,z)) .. X(c,z) =e= 0;
CLAND(z)$ (not (zoneail(z)))..sum(c,X(c,z))=L=area(z);
CLAND2(zoneail)..sum(cropwinter,X(cropwinter,zoneail))=L=area(zoneail);
CLAND3(basfond)..sum(cropRiz, X(cropRiz, basfond))=L=area(basfond);
Cmaize1..sum(z,X('mais1',z))=l=100000*maize;
Cmaize3..sum(z,X('mais3',z))=l=(1-maize)*100000;

#####sales/buying constraints#####

CVENTERiz(prodHum,prem)..ventes(prodHum,prem)=e=0;
achatprod(t)..sum(p$(not(prodHum(p))),achats(p,t))=e=0;

#####livestock constraints#####

CELEV.. Xani('bovin4')=l=12*bov;
CELEV2.. Xani('bovin3') =l=6*(1-bov);
CELEV5..sum(vache,Xani(vache))=l=100000*sum(basfond,area(basfond));
CELEV3.. sum(porc, Xani(porc)) =l=2;
CELEV4.. sum(porc, Xani(porc)) =l=100000*(basfond,area(basfond));

#####labor constraints#####
CWORK(t) .. sum((c,z)$cz(c,z), REQ_WORK(c,z,t)* X(c,z))
+ sum(a, Xani(a)* Req_WAni(a,t))
+ sum(adu, W_OUT(adu,t) - W_IN(adu,t))
=l=sum(g, dispoW(g,t));
*limited off-farm work opportunities
WORKOPP(adu,t).. W_OUT(adu,t) =l= workOffMax(adu,t);

*limited availability of labour force in the market
LABAVAI(adu,t)..W_IN(adu,t) =l= WorkInMax(adu,t);

#####feed/food constraints#####
*autosuffisance en fourrage sur la saison des cultures (pas de libre divagation dans cette
période donc obligés d'avoir une surface dédiée au fourrage)

```

```

ruminERGYBBAL(vache,therbe)..sum(herbe,
consoRum(vache,herbe,therbe)*valEnerRum(herbe))=g= Xani(vache) *
Anim_EnerNeed(vache,therbe);

```

*besoin alimentation pour les humains

```

HUMENERGYBAL(t).. sum(prodHum, CONSOH(prodHum,t) * valEnerH(prodHum))=g=
HEnerNeed(t);
RizPluv(t)$(Stock_Ini('RizPluvial')=0).. sum(prodHum,CONSOH('rizPluvial',t))=e=0;

```

```

#####flux produit#####
S_INI(p,prem) .. stock_begin(p,prem) =e= stock_ini(p);

```

```

CPROD(p,t) .. stock_begin(p,t)
+ sum ((c,z)$cz(c,z), X(c,z)*yield(c,z,p,t))
- Ventes(p,t)
-consoH(p,t)
-sum(porc,consoPorc(porc,p,t))
+ ACHATS(p,t)
-sum(vache,consoRum(vache,p,t))
=e= stock_end(p,t);

```

```

TRANSPROD(p,t)$(not(prem(t))).. stock_begin(p,t) =e= stock_end(p,t-1);

```

```

S_END(prodHum,PeriodEnd) .. Stock_end(prodHum,PeriodEnd) =e= stock_ini(prodHum);

```

```

#####cash constraints#####

```

```

CINI(prem) .. CASHBEGIN(prem) =e= tresoi;

```

```

CTRESORprem(prem).. CASHBEGIN(prem)
- F_EXPENS(prem)
-sum(adu, W_IN(adu,prem) * SAL(adu,prem)*(1+transac2))
-sum(a, IntrantsAni(a,prem)* Xani(a))
-sum(p, ACHATS(p,prem) * prixachat(p,prem))
-sum((c,z)$cz(c,z), X(c,z) * cout(c,z,prem))
+weaving/5
-coutfix(prem)
+emprunt(prem)
=e= CASHEND(prem);

```

```

CTRESOR(t)$(not(prem(t))) .. CASHBEGIN(t)
- F_EXPENS(t)
+sum((p), ventes(p,t) * prixvente(p,t))
+sum(adu, W_OUT(adu,t) * SAL(adu,t)*(1-transac2))

```



```

-sum(adu, W_IN(adu,t) * SAL(adu,t)*(1+transac2))
+sum((a), ventesAni(a,t) * Xani(a))
-sum(a, IntrantsAni(a,t)* Xani(a))
-sum(p, ACHATS(p,t) * prixachat(p,t))
-sum((c,z)$cz(c,z), X(c,z) * cout(c,z,t))
+weaving/5
-coutfix(t)
+emprunt(t)
=e= CASHEND(t);

```

```

TRANSTRESOR(t)$not(prem(t)).. CASHBEGIN(t) =e= CASHEND(t-1) ;

```

```

FundMaintenance(periodEnd).. -sum (t,emprunt(t))
+CASHEND(periodEnd)=g= tresoi;
CEMPRUNT(t)$not(prem(t)).. emprunt(t)=e=0;

```

```

LIMEMPRUNT.. sum(t,emprunt(t))=l=9500000;

```

Appendix 7: Parameters taken for rice needs for human consumption according to age and sex and energy content of rice (Leung, 1972)

	cal per kg unmilled
Sticky rice	3600
Upland rice	3410

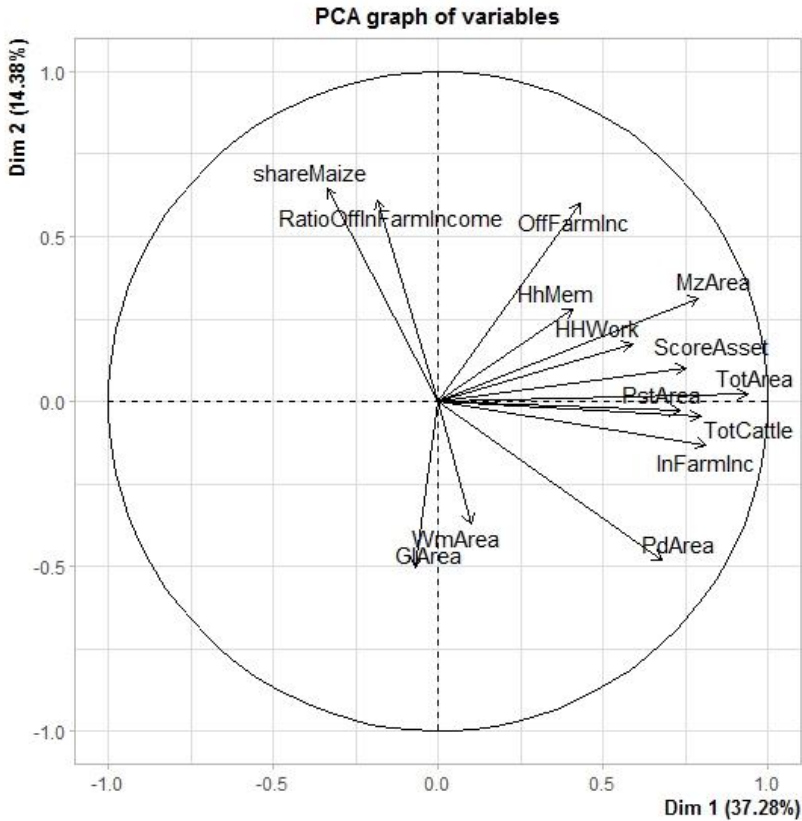
	cal needs per days from unmilled sticky rice
Male	2829
Female	2254
Kids	1680
Baby	704
senior	1050

Appendix 8: Principal Component analysis and hierarchical clustering results on farm land allocation variables, family size and workforce, asset and income.

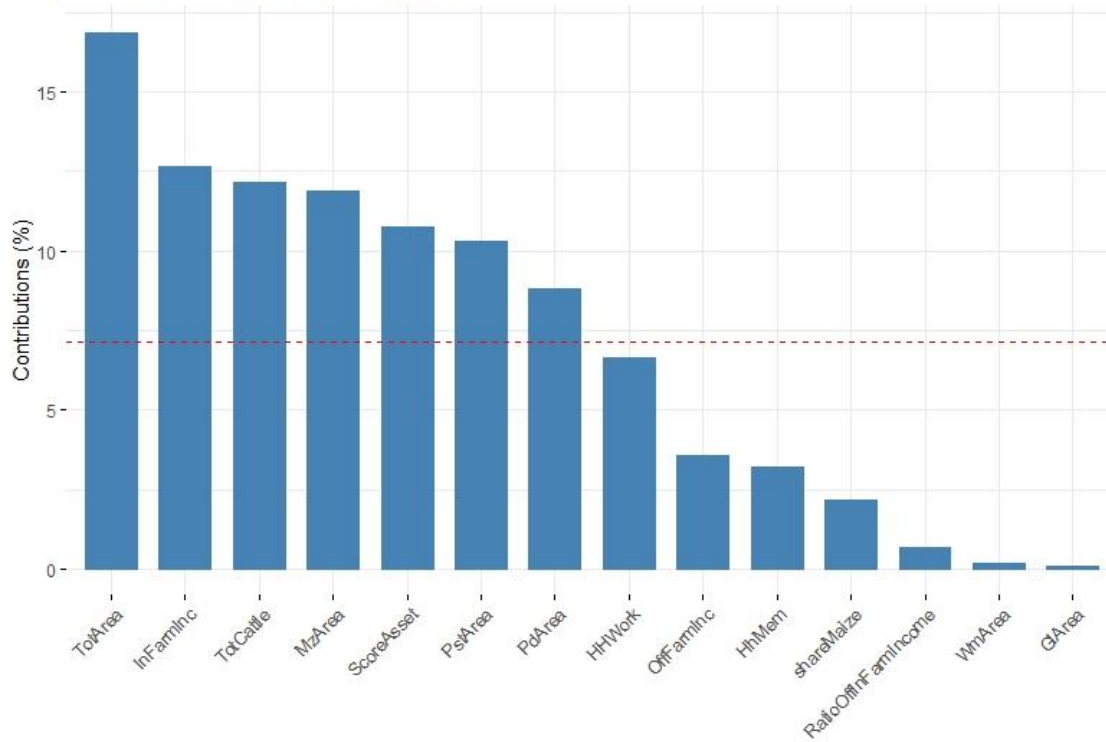
From the initial sample of 120 farms, eight farms were removed due to no maize cultivation (abandonment the year of survey).

	eigenvalue	variance.percent	cumulative.variance.percent	
Dim.1	4.988986	31.181165		31.18116
Dim.2	1.881228	11.757672		42.93884
Dim.3	1.554822	9.717638		52.65648
Dim.4	1.262621	7.891384		60.54786
Dim.5	1.121991	7.012445		67.56030

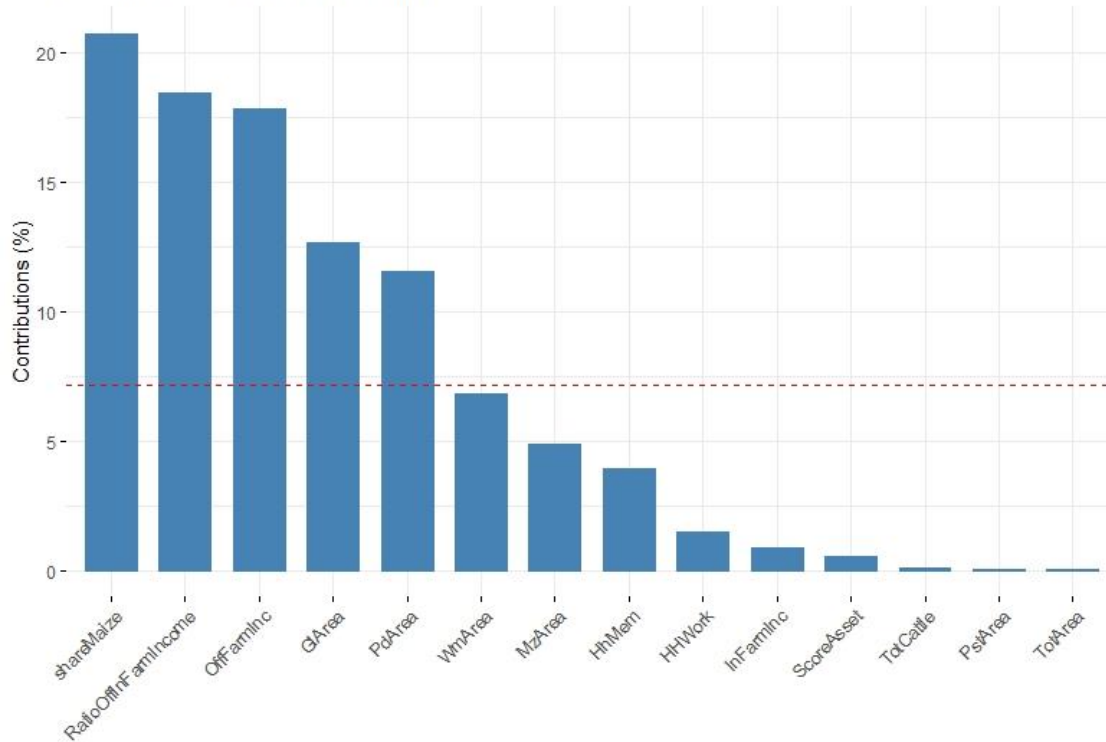
PCA graph



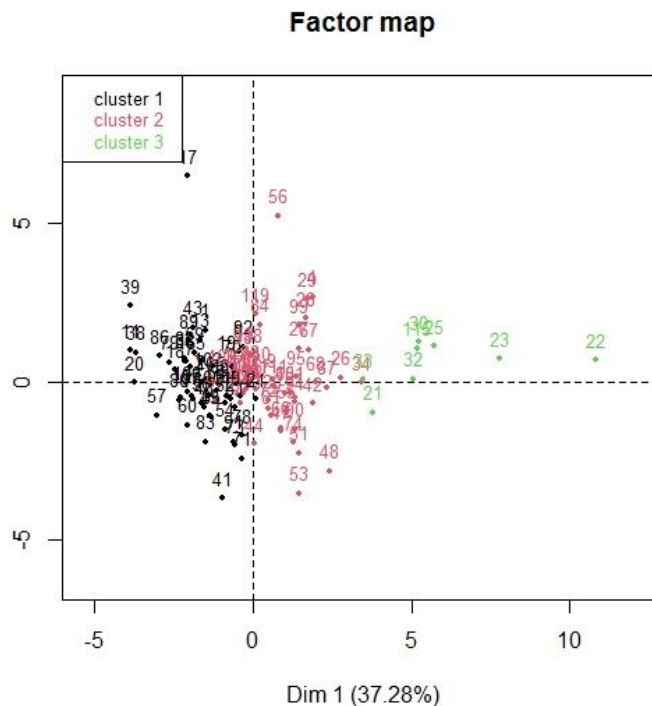
Contribution of variables to Dim-1



Contribution of variables to Dim-2



Hierarchical clustering



Cluster 1 (47% of farms). Small farms constrained on rice production (2.6 ha in total on average). Small area of paddy land (0.8 ha) and maize (1.6 ha). Small family (4.2 household members) with low workforce (0.56 workers per household member to feed). 1 cattle unit on average and few assets (score: 3.4).

Cluster 2 (47% of farms). Medium maize/rice farm. Medium area of paddy rice (1.4 ha) and medium area of maize (2.6 ha). Large family (6.4 household members) with low workforce (0.6 workers per household member to feed). 2.7 cattle units on average and more assets (score: 5).

Cluster 3 (7% of farms). Large maize farm with cattle. Large paddy rice area (2.2 ha) and maize (4.6 ha). Large family (6 household members) with more workforce available than for cluster 2 and 1 (0.73 workers per house member to feed). 6.7 cattle units and more assets than cluster 2 and 1 (score: 7.5).

Annexe 9: analyse de sensibilité du paramètre de la réserve utile dans le modèle PYE.

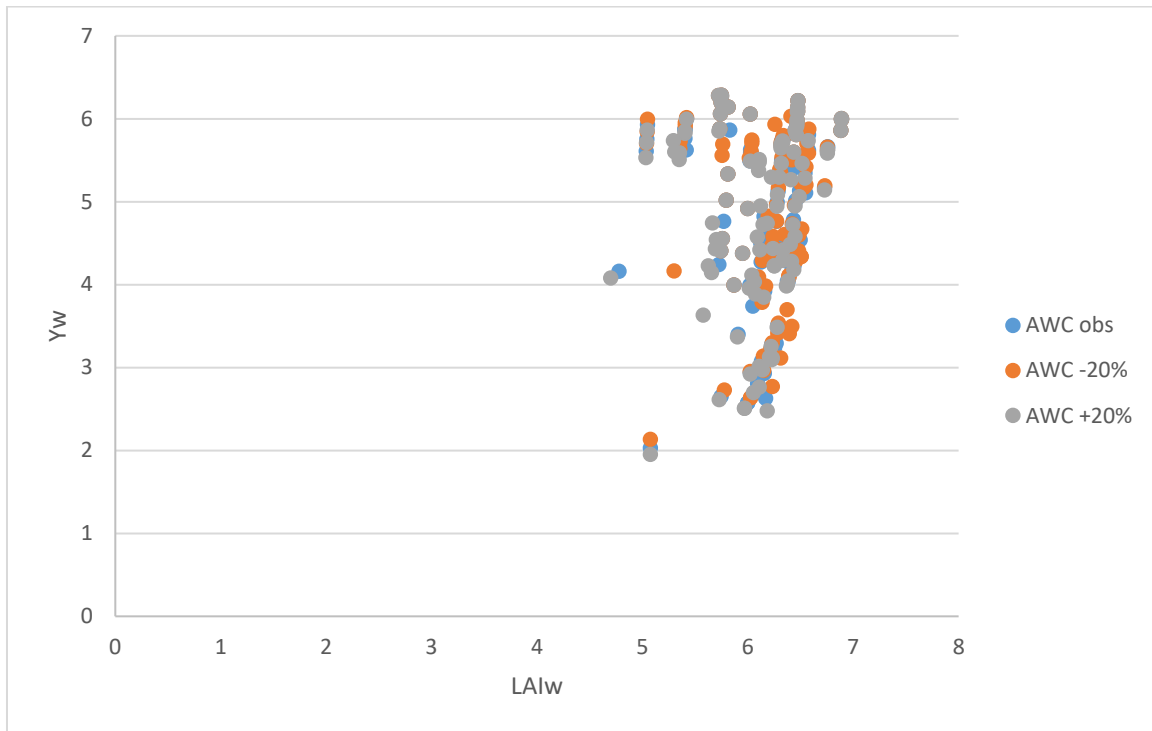


Figure 1 : Rendement limité par l'eau (Y_w) en fonction de l'indice de surface foliaire limité par l'eau (LAI_w) pour la réserve utile observée (AWC obs), la réserve utile à -20% de l'observé (AWC-20%) et la réserve utile à +20% de l'observé (AWC +20%)

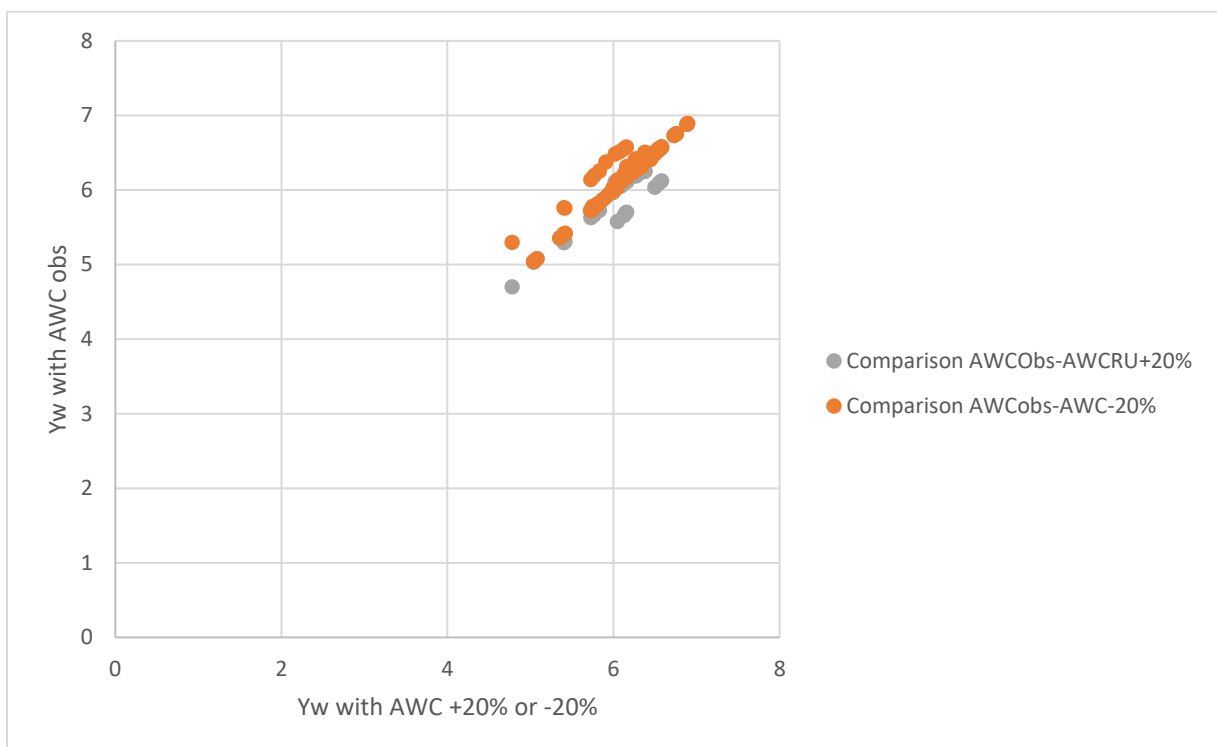


Figure 2 : Rendement potentiel limité par l'eau à la réserve utile observée en fonction du rendement potentiel avec des réserves utiles à + ou - 20% de l'observé

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