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Farmers' resource endowment and risk management affect agricultural practices and innovation capacity in the Northwestern uplands of Cambodia

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Keywords

Farm typology, multivariate analysis, risk management, land frontier, agricultural innovation, Cambodia

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1. Introduction

Farming systems research considers the farm as a system and analyzes interactions between the internal components of the farm (e.g. sub-systems) and the external biophysical and socioeconomic factors (Shaner, 1982). We define a farming system as a population of individual farm households that transform, under the influence of external factors and internal resources (land, labor, and capital), crop and livestock systems to useful products for sale and/or for household consumption (Dixon et al., 2001; Fresco and Westphal, 1988). Acknowledging the reality of farming system diversity is the first step to improve their performances and sustainability (Ruben and Pender, 2004). Diversity can be better understood by grouping those farming systems sharing similar characteristics in terms of farm resources, crop patterns, livestock, off-farm activities, strategies and constraints (Köbrich et al., 2003). Understanding farm diversity with its characteristics, constraints, and opportunities is essential for supporting the sustainable development of farming systems (Giller et al., 2011). Farm typologies are widely accepted as a simple and efficient tool to understand the complexity of farming systems. The approach to building farm typologies has been gradually improved and enriched by research communities to adapt to different purposes and local contexts (Alvarez et al., 2014; Alvarez et al., 2018). Typology variables can be selected for instance in relation to water resource management for irrigated rice production, or cropping practices that control certain pests or improve water use efficiency and productivity.

The main objective of designating farm typologies is to cluster farm households with similar characteristics of farm endowments, resources, structure, livelihood, land use intensity, etc. Landais, (1998) used the term 'typology' to explain farm grouping as the science of type characterization. Alvarez et al. (2014) summarize 4 purposes of developing farm typologies: identifying appropriate interventions for each farm type, understanding how the interventions could be disseminated at a larger scale, selecting representative/prototype farms for detail analysis and extrapolating ex-ante impact assessment to a larger scale. Cortez-Arriola et al. (2015) harness knowledge on farm diversity to understand how farm characteristics influence farm capacity to seize opportunities for on-farm innovation. Typology methods can be grouped into two categories: structural, i.e. describing farm resources and asset levels, and functional, i.e. describing farm strategy and dynamic typologies (Tittonell, 2014). The method selection depends on typology objectives and resources, although Alvarez et al. (2014) recommend combining structural typology with multivariate statistics known as 'dimension reduction' or 'data-reduction' techniques (Pacini et al., 2014), complemented by expert knowledge. The benefits of combining these two methods for the delineation of recommendation domains for on-farm innovations are demonstrated for example in the study of Berre et al. (2016) in Southern Ethiopia and Kuivanen et al. (2016b) in Northern Ghana.

In Cambodia, a household typology has been developed at the national level based on the level of income calculated from the annual national socioeconomic survey (Sann, 2010; Tong, Lun, Sry, & Pon, 2013). The typology included 3 types: poor, medium and rich. It relies on expert knowledge and is generally used in the agricultural and rural development activities of government and non-government organizations. However, this classification system does not provide information on how the households reached that status, as the typology is static, nor does it provide the leverage points to lift the least endowed farms out of poverty. Nguyen et al. (2015) and Jiao et al. (2017) used multivariate statistics to construct a farm typology based on natural resource dependence and changes in livelihood strategies respectively. Recent academic research built a farm typology using the participatory approach based on farm history, resource base and production system to understand access to land and government services (Diepart and Sem, 2018). While these typologies dealt with the time dimension in understanding how the household diversity built up over time, the entry points for interventions could not be explicitly addressed because performance and sustainability aspects of each farm type were not studied.

Over the last 15 years, the Northwestern uplands of Cambodia experienced dramatic land use changes, involving massive land conversion from forest to agriculture (Kong et al., 2019). Under this massive and rapid LUCC that prevailed in a pioneer front context, farmers were often believed to all do the same things, i.e. 'grow maize'. However, the diversity of farms and their trajectories was little known (Bertrand, 2011). The multiple reasons why farmers 'grow maize', their decision-making process, their performances and capacity to innovate (i.e. adopt an innovative practice or engage in an innovative organization) are important underlying factors of the rapid maize expansion of the 2000s (Ornetsmüller et al., 2018). These individual drivers of change need to be understood in order to tailor interventions to the specificities of each farm type and especially their capacity to seize opportunities for on-farm innovation. In the context of our study, we defined innovation as any practice, technological or organizational, that farmers adopt and adapt to improve their resilience in a context of land productivity decline, increased production costs, decreased input use efficiency and increased vulnerability to market and climate uncertainties.

In this paper, we report on household surveys conducted in 10 villages to characterize the diversity of the farming systems and to understand its temporal and spatial organization. In addition, we assessed the technical and economic performances of each farm type. Finally, we investigated the influence of structure, resource endowment and resource use strategies on a farm's innovation capacity. This approach is aimed at identifying external interventions suitable to the characteristics and needs of different types of farming systems in a context of rapid land use changes.

2. Methods

2.1. Study area

Rotonak Mondol District in Battambang Province is one of the 4 districts where massive land use changes and rapid farming system transitions have been reported by Kong et al. (2019). This district was also selected by the Ministry of Agriculture, Forestry and Fisheries (MAFF) to implement a pilot extension program on Conservation Agriculture (CA) in the Northwestern uplands of Cambodia (Kong et al., 2016). It is geographically located between 12°43'26.55"N and 13°5'1.42"N latitude and between 102°45'7.42"E and 103° 2'57.80"E longitude with elevation of between 30m and 435m above sea level (Fig. 1). The district area is 792 km² with a density of 60 people per km². It is a dominantly undulating upland area with small lowland paddy areas. Based on Crocker (1962), there are 4 soil types in the district, including 39% *Brown hydromorphics*, 34% *Basic Lithosols*, 5% *Latosols*, and 22% *Regurs*, that are generally considered as medium to good soils.

The region follows the South-East Asia Monsoon of 5-month dry season from December to April and 7-month wet season from May to November. The data from the provincial weather station in Battambang from 1982 to 2016 shows an average annual rainfall of 1,310 mm, steadily increasing from 45mm in March to as much as 256mm in October. The average temperature is 28°C with an average maximum of 36°C in April and an average minimum of 20°C in December. The average relative humidity is 80% with a maximum of 86% in September-October and a minimum of 72% in March (Martin et al., 2013). Topography, soil types, and rainfall patterns allow farmers to practice two crop cycles per year, i.e. a dry season cycle from February-March to May-June and a wet season cycle from July-August to November-December, except for cassava, which is a more than 10-month cycle crop.

2.2. Data collection

The 38 villages in Rotonak Mondol District were stratified and 10 were randomly selected (Fig. 1). The village stratification was done through 2 multivariate statistical techniques sequentially, a Principal Component Analysis (PCA) and an Agglomerative Hierarchical Clustering (AHC) analysis. The village random selection was done proportionally. Then, 365 households were randomly selected from the 10 sampled villages for a questionnaire survey. We further stratified the household sample based on identified farm type and randomly selected 95 households for in-depth qualitative interviews. The details of household sampling procedures are provided in Table 1.

The household survey conducted in 2016 addressed household composition and education, labor resources, land holdings, productive assets, natural resources, production systems, production costs, gross incomes and off-farm activities. In addition, the questionnaire included open questions regarding the adoption of agricultural innovations. A list of 11 technical and organizational innovations was derived from the categorization of the responses to the questionnaire survey and were incorporated in the semi-structured guidelines of the subsequent qualitative survey (Appendix 1). Three of the innovations are organizational. The farmer cooperative and community forestry are official organizations registered by the MAFF, while the other farmer organizations are informal farmer groups, created mostly by development projects. During the interviews, the enumerators discussed the successive farming practices the farmers had used since their

arrival in the study area. The farmers were asked further about the reasons for adoption, number of years of experience, or the reasons for stopping or continuing with these practices. In-depth interviews were conducted to investigate the history of migration and settlement, conditions of land access, changes in farm resources including labor, land, and assets, evolutions of land use and farming practices, and farm constraints, decision making processes, and strategies.

To generate the village typology through PCA and AHC analysis, key variables (e.g. agricultural inputs and machineries, demography and socioeconomics) were extracted from the online 2016 communal database. In addition, land use data concerning the study villages were generated from the land use classification based on Landsat Imagery 2016 (Kong et al., 2019). A previous agrarian diagnosis and farm typology conducted in 2 of the 10 selected villages in 2010 was reviewed to assess the changes in farm diversity over time (Bertrand, 2011).

2.3. Data analysis

We analyzed data according to the 3 study objectives, namely: (i) characterizing farming systems diversity and trajectories, (ii) assessing the performances of farming systems, (iii) investigating the influence of a farm's structure on its capacity to innovate, as indicated in Table 2.

2.3.1. Characterizing farming systems diversity and trajectories

Fifteen variables describing the demography, economy, farm diversity and land use of the study villages were used to run the village PCA (Table 3). The first 5 factors explained 72% of the variability between the villages. The first 2 factors were selected to run the AHC as they combined several variables; the first factor combined crop area, paddy area, use of planter, number of cattle, tractor and insecticide sprays, while the second factor consisted of built-up areas, cars owned, females working in services, trade and shops and total households. The AHC analysis resulted in 4 village clusters or types with 72% variance decomposition between clusters (Appendix 2). Those types are Urban Village (5%), Upland-Intensive Village (8%), Lowland-Diversified Village (47%) and Upland-Diversified Village (40%). Urban Village type is characterized by high population, large built-up area and high availability of services. This type was excluded from further village selection as the research focuses on farming systems, which concern only a minority of households in urban villages. The Lowland-Diversified Village type has larger paddy area, up to 37%, and high proportion of households owning cattle, up to 50%. Farming is diversified with upland crops, paddy and cattle, and it is characterized by low intensification in terms of use of agro-chemical inputs and machinery (tractor, planter, etc.). On the other hand, the Upland-Intensive Village is characterized by the largest share (97%) of upland area and the highest percentage of households using agrochemical inputs and machinery. The average farm size is bigger than for other village types. The Upland-Diversified Village type has similar characteristics as the Upland-Intensified Village type in terms of agrochemical input use and machineries, although to a lesser extent. In addition, it has also larger paddy area and more cattle raising households (Appendix 3).

Variables were selected from the questionnaire survey to characterize the structures and functions of the farming systems, and their performances (Table 4). We included the variables related to the land size and distribution of land uses that were used for the functional typology in 2010 (Bertrand, 2011), resulting in the selection of 14 out of 27 variables to perform the PCA. In addition, boxplots were used to identify outliers, for example 7 households were taken out and kept for supplementary observation. The 7 households are capitalist farms with high income and assets, which are considered outliers and representing about 2% of the sample population.

The first 2 factors used for the AHC analysis capture 44% of the variability. The main variables that explain the first factor include total land, income from crops, production cost, off-farm income, power tiller, and total assets. The second factor combines paddy area, rice deficiency, cattle, and annual upland crops. The AHC resulted in 4 major farm clusters with 64% variance decomposition between clusters (Appendix 3).

The 365 surveyed households were then distributed according to the farm and village types to which they belong. Historical information of the farm obtained through retrospective in-depth interviews was further consolidated by farm type and organized according to the 3 periods identified by Kong et al. (2019). These 3 periods correspond to (i) 1976-2002 from civil war to peace, (ii) 2002-2010 peak migration for land access, and (iii) 2010-2016 shift to orchard plantation and diversification. For each period, we characterized farm structure transformations using 3 indicators: land, labor and capital.

2.3.2. Assessing the performances of farming systems and their innovation capacity

The in-depth interviews were consolidated by farm type. The technical and economic performances of the farming systems were assessed based on the use of farm resources to manage cropping and livestock systems in a specific spatial and temporal combination. Off-farm activities, livestock systems and collection of natural resources are included in the calculation of household income. Off-farm activities are categorized into 2 types, high-income and low-income off-farm (Table 4). The income of low-income off-farm activities is calculated by summing up monthly wage labor or salary for a period of 1 year. For the high-income households, farmers are asked to estimate the intermediate costs, salaries of permanent workers, depreciation costs if any and income per unit of service provisions such as a plowing services. For natural resources collection, only few households (less than 10% of interviewed households) generate income through these activities; collecting mainly bamboo shoots, mushroom, and fuelwood, the amount of which is highly variable depending on the seasonal availability and accessibility and generally contribute negligibly to the farm income.

The livestock systems mainly comprise cattle that are raised by around 40% of interviewed households, in particular in the villages with large paddy areas. This production system is similar to the traditional rice and cattle production in the lowland regions (Nesbitt, 1997), which is highly extensive without external inputs. The cattle ranching system enhances the productivity of paddy through provision of feedstock with rice straw and manure to fertilize the paddy fields, and is a form of capital accumulation and a financial safety net.

Therefore, the income calculation takes average annual income over the last three years assuming that intermediate costs and depreciation cost are negligible.

The analysis of cropping system performances include the description of techniques used, intermediary costs, land productivity, and labor productivity. Based on the information collected during the in-depth interviews, we categorized the crop successions or associations into 7 main cropping systems: cassava, maize, maize after secondary crops (mungbean, sesame, or peanut), paddy, vegetables, longan and mango. The vegetable-based cropping systems combine leafy green (lettuce, spinach, etc.), cruciferous (cabbage, cauliflower, etc.), and marrow (cucumber, eggplant, etc.).

The last step consisted in analyzing the influence of the farm structure and functioning on its capacity to seize on-farm innovation opportunities. The methodological framework in Fig. 2 describes how farm types, as documented through their trajectories, performance, resource endowment and use, were related to their capacity to adopt technical and organizational innovations, and how we used these elements to identify relevant interventions. Through in-depth interviews, we investigated the relations between the farm types and the reasons reported by farmers for innovation adoption or non-adoption: e.g. risk management, labor flexibility, and diversification of income sources. Innovations adopted were categorized and their frequency was assessed for each farm type, together with the period of use of each innovation once adopted.

3. Results

3.1. Farm typology

The 4 main farm types identified are: Upland crop-based smallholder farm (Type 1) 25%, Upland crop-based large farm (Type 2) 20%, Land-poor off-farm income dominated farm (Type 3) 34%, and Paddy based farm (Type 4) 19% (Table 5). The 7 outliers could be subdivided into 2 types: off-farm based investor (outlier 1) 0.5% and farm based investor (outlier 2) 1.5%. Outlier 1 type is characterized by a high income from off-farm activities, which includes commercialization of agricultural and non-agricultural products, land brokers, etc. Their farm size is among the largest in our sample (17ha) and is mostly used for orchards (76% of total farm area). In contrast, Outlier 2 type concentrates on farming activities on their large farms using their land for both orchards and annual upland crops. They own their machineries (e.g. tractor) and have a high financial throughput (25,900\$ annual debt). They practice the most intensive and mechanized cropping systems in the district. In addition, they use their agricultural machineries to service other farmers, which provides additional off-farm income.

3.1.1. Household diversity

Upland crop-based smallholder farm. Type 1 is characterized by relatively balanced farm land use between paddy (35%) and upland crops (40%), and balanced farm income with 53% and 45% generated from crop cultivation and off-farm activities respectively (Table 5). The off-farm income mainly relies on

low-income off-farm activities, which accounts for 29% of total income. With low to medium capital (total asset), land area and farm labor, this farm type generates relatively low household income in spite of having diversified income sources. They tend to diversify farm activities as well as the income sources as their level of rice deficiency is up to 58%. They manage to earn additional income from off-farm activities through seasonal migration. Annual crops and orchards incur high production costs (126\$/ha) and annual debt (881\$).

Upland crop-based large farm. Type 2 is characterized by a high level of total assets (7,500\$) and larger farm size (~11ha). The high level of agricultural investment (202\$/ha production cost) reveals farmers' intensification and mechanization strategies. For that, they mobilize large farm labor (2.8) to cultivate annual upland crops (70% of the total area) and orchards (11% of the farm area), which contribute 79% of the total farm income (~ 9,000\$). To operate such a large-scale production in the local context this farm type needs to take economic risks by contracting annually loans up to 4,800\$. This high level of debt and large cultivated area is made possible by a higher level of capital and productive assets (machineries, etc.) involved in farming activities. They also tend to diversify their activities as they cover only 56% of their rice needs (rice deficiency 44%). Off-farm activities, in particular the high-income off-farm activities, provide additional income.

Land-poor off-farm income dominated farm. Type 3 is characterized by small farm size, low total assets, and high percentage of migration. Their livelihoods are largely dependent on off-farm activities, up to 68% of total household income. Low-income activities (44% of total farm's income) make up the largest part of off-farm activities, and mostly rely on migration work. Because of their low risk management capacity, they use 60% of their small farm area for annual upland crops. However, the production is relatively intensive with 323\$/ha production costs. Having the highest rice deficiency (97%) and the smallest farm size (1.8ha) (Table 4), this farm type tends to prioritize a diversity of off-farm activities, leaving the farming activities as secondary income sources.

Paddy-based farm. Type 4 possess larger areas of paddy land than other farm types. They have the highest number of cattle and the lowest rate of rice deficiency. They own on average 3.8ha land, of which 60% is used for paddy production and about 25% for annual upland crops. Even though this farm type has higher total assets (2,400\$) and debt (960\$) than Type 1, they invest less in crop production with only 90\$/ha production costs. As they have larger cattle herds and larger paddy areas with almost no rice deficiency, they are often more conservative than other farm types and do not take risks in agricultural intensification. Their objective is to generate cash income from non-rice crops and off-farm activities with as little production costs and risks as possible. The off-farm activities largely take place in the vicinity of the farm (only 4% migration) contributing 36% to the total farm income as a complement to the crop's income (64% of total income).

The 4 farm types are distributed unevenly across the 10 selected villages. The village characteristics have an influence to some extent on the relative proportion of farm types as shown in Table 6. There are 56% of

Type 4 in the Lowland-Diversified Villages, while Type 1, Type 2, and Type 3 are dominant in the Upland-Diversified Villages accounting each 60-70%. Among the 4, Type 2 is observed the most (21%) in the Upland-Intensive Villages. Moreover, the geographic distribution of farm types is linked to the village history and patterns of socioeconomic development in line with its characteristics, such as the size of arable land areas. The newly created villages, e.g. Ou Khmum (2002), tend to have relatively larger and more fertile uplands. In contrast, the older villages, e.g. Serei Voant (1950s), are mostly paddy-based and with high population density since they are more accessible, with better infrastructures and safer from landmines for resettlement. As a result, the size of the land allocated to each household is generally smaller than in upland villages.

3.1.2. Farm trajectories

Fig.3 illustrates the process of farm differentiation, i.e. how each farm type was developed over time. The changes in farming systems since the 2000s are identified following the study of Kong et al. (2019). After peace establishment in 1998, there was a large-scale allocation of degraded forestlands to demobilized soldiers and the villagers were resettled. We distinguished 2 groups in the first wave of migration. On one hand were the former villagers or their relatives with paddy production background, considered as Type 4's origin. On the other hand were the demobilized soldiers or their relatives who decided to make a living with the upland crop production despite the risks associated with landmines and malaria in these forested environments. We consider them as Type 1 origin. The size of farmland these pioneer households could secure was defined by different factors: initial capital and labor availability that defined their capacity to clear the forest and therefore to secure ownership on that land (Kong et al., 2019), time of arrival (i.e. availability of land suitable for agriculture), relationship with authorities (i.e. kinship networks, position in the local administration).

The improvement of the road network and market access changed the farming objectives of newly settled households from subsistence to more market-oriented with soybean and peanut based cropping systems, and also increased in-migration. The level of income expected from upland farming on fertile newly converted forest soils encouraged some of Type 4's origin (Risk takers in Table 5) to take the risk of purchasing upland plots and expanding commercial crops after they had accumulated capital from the first years of upland farming and shifted to Type 1. The late comers with capital managed to buy some land in the upland villages and became Type 1 farmers while those who arrived only with their family labor force contributed to wage labor during the maize boom and formed the Type 3 farms.

The introduction of hybrid maize in the mid-2000s amplified the economic differentiation. Farmers who owned large upland areas, accumulated mostly through purchase with initial capital, could further generate capital through maize cultivation that provided a high profit at that time thanks to (i) high soil fertility and low input requirements and (ii) the possibility of cultivating two crop cycles per year with high yields and high market prices. They could gradually enlarge their farmland and buy agricultural and household assets to become Type 2 farmers. The new migrants, who had not enough initial capital but a relatively abundant

family labor force, could clear the forestland for the others in exchange for the right to cultivate the newly cleared land for the first 3 years. They used that initial income to purchase the land they had initially cleared for someone else to become Type 1 farmers.

After some years of intensive cultivation, crop productivity declined and the risks associated with irregular rainfall patterns and market price fluctuations increased (Kong et al., 2019). Risk management strategies of the different household types were investigated by Kong et al. (n.d.) using a role-play game. In the aftermath of the maize boom, risk management strategies through diversification of the farm activities with e.g. additional farm (crop and livestock) and off-farm activities, and the capacity/willingness to invest in the production of new commodities, largely determined the evolution of farm structures. For instance, Type 2 farms invested massively in tree crops (e.g. longan and mango) shortly after shifting from maize to cassava. A limited number of the Type 1 farmers could step up to Type 2 with additional investment or running the risk of taking on additional debt. However, some of them and some Type 4 farms eventually stepped down to current Type 3 due to distress land sales from repeated crop failures or sickness of family members. In addition, some Type 2 farmers are recent rich migrants who were originally from the cities or abroad investing in tree crop plantations.

3.2. Farming system performances

Our assessment of farm performances focuses on crop production, i.e. the main income source and core of our analysis. The other components of farming systems include livestock systems, off-farm activities and collection of non-timber forest products. The livestock system, mainly extensive cattle production, contributes only marginally to farm income (Table 7).

3.2.1. Cropping systems performances

We identified 7 cropping systems in Rotonak Mondol District. Each farm type practices different cropping systems on part of their land depending on their respective characteristics and trajectories. The technical and economic performances of each cropping system varies with the farm types as presented in Table 7. Among the systems based on annual upland crops, cassava and maize are predominant. However, the large (e.g. Type 2) and small (e.g. Type 3) farms prefer cassava over maize as the former requires less labor and expected productivity is higher. A period of drought at the start of the cycle combined with heavy rains at harvest time and a price drop in 2015 resulted in considerably reduced cassava productivity and revenue. The maize-based system with secondary crops, i.e. mungbean, sesame, and peanut, is constrained by high climatic risk (long drought between Feb-June) for the secondary crops, and vegetable expansion is constrained by the high labor requirement and price fluctuations. Farms with access to irrigation and abundant labor force (e.g. Type 4) grow vegetables, and those who have higher financial capacity (e.g. Type 2) grow more secondary crops. Types 1 and 4 used to practice the ‘maize plus secondary crops’ system; although they have recently abandoned this due to the high risk of failure related to climatic hazards.

Farms with large areas and high assets, such as Type 2, have invested in orchard plantation (longan and mango). Type 2 tends to have higher production costs in particular on hiring labor and using chemical inputs and as a result the labor and land productivities are lower than the other farm types even though they obtain higher yields. For instance, their cassava production obtains a 1-4 t/ha higher yield, although it provides about 15-75\$/ha less return on land than the other farm types. The lower productivity of cassava is also explained by the fact that Type 2 is likely to sell the harvest as fresh tuber while Types 4 and 3, who grow on smaller areas, prefer to process the harvest and sell dry chips for extra profit.

The yield and production costs of secondary crops are higher for Type 4 since they crop larger areas of peanut. This legume crop may influence the productivity of the following maize crop which yields 0.5 t/ha higher than without a preceding legume crop. Type 4 enjoys higher economic returns on labor as production costs are very low on paddies when compared to Type 1, and larger areas allow them to harvest by combined harvester. Type 2 tends to produce highly intensive vegetables (e.g. drip-irrigated cucumber) while the other types mostly produce low-investment and small-scale vegetables, e.g. wax gourd, pumpkin. In addition, Type 2 generally produces the off-season mango and longan by themselves since they have higher financial capacity for investment and risk management. Other farm types tend to rent out their plantations, in spite of lower profit than direct management, to reimburse rapidly their initial investments.

3.2.2. Farm income composition

Crops and off-farm activities provide the bulk of farm income (Fig. 4). The main income sources are from annual upland crops (cassava and maize) for Type 2 while off-farm activities, in particular the low-income ones, provide a large share of household income for Type 3. Types 1 and 4 have rather diversified income sources. The strategy of Type 4 is to maintain a safety net with the integration of rice production and cattle raising and to generate cash income from off-farm activities and annual upland crop cultivation. This farm type tends to minimize the production costs on the chemical inputs and services by relying on manual cropping practices thanks to an abundant family labor force. With smaller paddy areas, Type 1 intensified annual upland crops cultivation and invested in off-farm activities, especially the low-qualified ones. Type 2 is the most intensive farming system. Its strategy is to intensify land use through mechanization, inputs use and innovative techniques, then to expand orchard areas and diversify income with high-income off-farm activities. In contrast, the strategy of Type 3 is to focus on off-farm activities with high wages, particularly migration work in Thailand. Therefore, their cropping practices aim at saving labor and inputs through cultivation of cassava and orchards.

3.3. Farm structure and capacity to innovate

3.3.1. Innovation adoption

Farmers constantly test small changes in their cropping systems and their robustness to weather uncertainty, price fluctuations and soil fertility depletion. For example, they stopped the double maize cycle after a few years, as the first maize cycle was too dependent on the regularity of the first rainfalls. Then, they

replaced the first maize cycle by a legume crop (mungbean or peanut) which gave good results on low-elevation hydromorphic soils but was too risky on higher-elevation soils. On this higher part of the topo-sequence, they finally adopted a latter cycle of mungbean after maize to better valorize residual soil water at the end of the rainy season. The number of innovations tested by farmers increased after 2010 (Fig.4), when a project of the Ministry of Agriculture, Forestry and Fisheries promoted conservation agriculture in the study district (Kong et al., 2016). The project introduced farmers to the use of cover crop, no-till and no-burn, as well as improved pastures as options for sustainable land management. From 2012, new crop rotations were tested with maize and cassava, and the intercropping of vegetables, maize or cassava in orchards emerged as reactions to the observed decline in maize productivity (Kong et al., n.d.).

The percentage of innovative households (i.e. those who had adopted one of these innovative practices) reached a peak in 2015 and then decreased dramatically the following years, in particular innovations related to crop successions and rotations (Fig.5). Based on farmer interviews, the climatic risks for the 1st cycle crops and high price fluctuations for maize explain this drop. The conservation agriculture techniques (Kassam and Friedrich, 2012) aim to rebuild the soil functions and resilience to climatic risks through growing cover crops during unfavorable conditions as rotational or succession systems with the main crops. These cover crops are providing agronomic services to the main crops, but their adoption is also guided by commercialization purposes such as the 1st cycle crops. In short, farmers are more eager to adopt service crops if they can sell their products.

Type 2 farmers are the ‘innovators’ as there are more farmers belonging to this type who innovate. They tend to test a larger number of innovations (Fig.5), especially no-till and no-burn, cover crop integration, crop rotation and orchard intercropping. They explained this capacity to innovate during the in-depth interviews and the role-play games by their higher farm resources which buffered their risks when adopting a new crop or an alternative cropping practices (Kong et al., n.d.). Type 1 farms have similar characteristics in terms of adoption as Type 2 but lower capacity to take risks due to their limited resources. In contrast, Type 3 has the lowest rate of innovation due to their farm constraints related to land and financial capital, and also time constraints as most of their labor force is dedicated to off-farm activities. However, they have, like Type 4, a high involvement rate in farmer organizations, mainly focusing on saving and credit schemes. With a greater number of cattle, Type 4 adopted improved pastures earlier and with a higher percentage of farmers than other farm types (Fig. 4). They also have lower drop-offs in crop succession (i.e. double cycle cropping) since their fields are located in the lower part of the topo-sequence that is less vulnerable to drought and they have more farm labor force.

3.3.2. Levers for intervention

The room for maneuver for external interventions to improve farming system performances are different for each farm type since they have different constraints, strategies, expectations and trajectories. Based on the prioritization by respondents to the qualitative survey of the key factors for adoption of innovations, three of them emerged as core to their capacity to innovate, namely (i) risk management, (ii) labor productivity

and (iii) diversification of activities. Intervention mechanisms towards more sustainable practices must therefore be tailored to these three factors.

Types 1 and 4 farms already have a diversified activity portfolio to buffer the risks from rainfall variability and market price fluctuation. Agroecology practices could enhance the farm productivity, i.e. return on land, labor and capital through integrated management of all components of the farming system: paddy, cattle, and vegetable production in the lowland and intercropping and agroforestry in the upland. For instance, including a service crop, e.g. *stylosanthes guianensis*, in rice cropping systems can improve fertility as well as the rice yield and also produce good quality forage for the cattle fattening program. Besides providing the energy, the rich compost from biogas of cattle's manure and urine is used for the vegetables production (Hyman and Bailis, 2018). Promising options for the uplands could take the form of rotational systems based on maize, cassava, and soybean with relayed secondary crops such as mungbean and pigeon pea, commercial forage production, and/or intercropping of agroforestry systems with orchards and vegetables.

The appropriate scale mechanizations for sustainable intensification are highly appreciated by resource rich farmers such as those in Type 2, who are constrained by the availability of farm labor to engage in larger scale production. Rotational cropping systems combined with permanent cover crops in orchards are prioritized by Type 2 farmers. A possible diversification pathway would include improved pastures and rotational grazing with solar electric fences for cattle production and agroforestry systems. Mechanization efforts and more generally labor saving technologies provided by service providers are highly appreciated by resource poor farmers such as Type 3, who are constrained by the farm labor and capital. For example, this farmer type showed great interest in agroforestry systems, including orchards with permanent cover crops and forage production (Kong et al., n.d.).

The above-mentioned technical innovations are systematically associated with organizational innovations, which involve collective learning and sharing of knowledge on the common problems faced by sustainable intensification, especially those related to market access, access to production factors (especially through credit), and service provision by middlemen for agroecological practices. Surveyed farmers already know that to succeed in this systemic change, all stakeholders involved in the crop value chains have to develop coordination mechanisms, for example establishing market guarantee systems through contract farming with private companies (Begum et al., 2014; Sum and Khiev, 2015; Kyomugisha et al., 2018). Likewise, for access to agricultural services, the outliers, investors who own large plantation and machineries, could join with Type 2 farmers to provide agricultural services to other farm types. Many such initiatives already exist on the ground as revealed by our focus group discussions and in-depth surveys. They still need to be properly supported to engage the local stakeholders in an agroecology-based innovation system.

4. Discussion

4.1. *Farm typologies and trajectories: advantages and constraints*

Our approach to farm typology aims at explaining the evolving diversity of farming systems in a context of rapid land use changes. Our structural typology (Tittonell, 2014) builds on multivariable statistical analysis combining principal component analysis (PCA) and hierarchical cluster analysis (HCA) with discrimination variables related to the history of settlement, farm resources, structures, land uses, livelihood activities and economic performances. Within each element, 12 key structural (slow moving) and functional (fast moving) variables (Berre et al., 2016; Lopez Ridaura and Tittonell, 2011) (Table 4) were finally selected based on both expert knowledge (from focus group discussions) and a series of tests on different combinations of 27 variables. This approach yields a typology that explains how the differences between the household types built up over time. Our results are consistent with similar studies conducted in other contexts across Southeast Asia (Castella et al., 2013, 2005). These studies point to the crucial role played by interactions, coordination mechanisms between households and with other stakeholders, notably through off-farm activities and communication networks in driving agricultural innovations (Pretty, 2018; Rigg et al., 2016).

In addition, we conducted retrospective interviews with a randomly stratified subset sample of each identified farm type to understand trajectories of farm resources, activities, land uses and innovations. Understanding farmers' reasons of changes and decision making processes led to soft functional perspectives that help to explain the statistical relations between variables provided by the structural typology (Alvarez et al., 2014). By analyzing the spatial distribution of farm types and relations to biogeographical characteristics of their villages, we could explain the local patterns of farm resources, socioeconomic and biophysical conditions. Our approach is therefore complementary to previous typologies done based on the qualitative method in the Northwestern uplands of Cambodia (Diepart and Sem, 2018). More importantly, our approach includes the relations between farm types and capacity to innovate. It captures the decision making process and capacity to innovate of the different farm types as a basis to co-design appropriate innovations and intervention mechanisms.

The main limitations of our approach lie in the retrospective analysis of farm trajectories and the validity of the farm typology over a long period in a context of rapid changes. The previous typology done in 2010 by Bertrand (2011) included only 2 of the 10 sampled villages. It could therefore not be used as a baseline for a longitudinal analysis of the dynamics of farm differentiation, i.e. how and why farm types evolve in time (Jiao et al., 2017). Despite the explanation provided through qualitative in-depth surveys, the typology is constructed using the multivariate statistical techniques (Kuivanen et al., 2016a) and therefore provides a snapshot in a given time (Laurent et al., 1999) and thus its validity is limited. Nevertheless, our data may serve as a baseline for a longitudinal analysis, and would provide a reference point in time to analyze farm trajectories over a longer period.

4.2. *Dealing with impermanence in assessing farm diversity*

Farming systems are not static; they are rather moving targets (Giller et al., 2011). For instance, a longitudinal study of rural livelihoods in Cambodia from 2008 to 2012 found that more than 70% of households changed their livelihood strategies to more remunerative ones in response to evolving pressures, incentives and opportunities (Nguyen et al., 2015). Due to the rapid dynamic in particular in the context of forest frontiers and pioneering agriculture (Hall, 2011), the relative proportion of the different farm types in the typology will evolve, and thus needs to be regularly updated to keep an accurate picture of farm diversity in designing relevant interventions (Valbuena et al., 2015). Indeed, the maize boom of the 2000s affected the percentages of each farm type, particularly in the upland based villages. Types 1 and 2 were the most impacted by these changes. In the aftermath of the maize boom, the risks of market fluctuations and climate hazards are likely to increase the proportion of Type 3 farms and possibly lead to the emergence of a new type from Type 2. This new type would be characterized by large-scale agricultural production (likely orchards) with high levels of intensification based on advanced technologies.

In forest frontiers, rapid land use changes basically happen in the absence of a clear regulatory framework. Capturing changes in farm diversity becomes a challenge in such a context. Operational constraints to data collection require negotiating a compromise between the relevance of the typology for decision making and intervention and ease in capturing farming system diversity. A way to achieve such a balance is to adjust the combination of ‘slow moving’ variables including farm structure, farm resources and physical characteristics of farm land for the multivariable statistical analysis (Berre et al., 2016) and the ‘fast moving’ variables such as economic performances (income and its share) as done by Falconnier et al. (2015). The combination of structural and functional typologies have shown their relevance in documenting processes of agrarian change found across the upland frontiers of Southeast Asia and beyond under the strong influence of markets, technological and institutional globalization (Dixon, 2019).

4.3. Perspectives toward agroecology

Our farm typology approach prioritizes intervention mechanisms adapted to each farm type, and also adjust innovations to farmers’ perspectives on agroecology practices. The discriminating variables characterize farm types according to their resources, functions, performances, constraints and opportunities, as well as their capacity to innovate (Fig. 2). Technical innovations such as no-tillage, no-burning of crop residues, cover crops, rotational systems, etc. are categorized as conservation practices.

The farm types, which are the most impacted, or at risk of economic or climatic hazards, such as Types 1 and 2, tend to show more interest in land conservation practices (Kong et al., n.d.). In contrast, Types 3 and 4 farmers opt for innovative practices since their livelihoods depend primarily on less risky activities such as off-farm activities and paddy production. Although Type 4 farmers own more land than Type 1, they are not willing to invest in agroecology practices except if there is no extra cost and/or additional labor required. Type 3 are less committed than Type 4 in soil conservation since they own too little land and have no financial capacity to invest. They are, however, willing to adopt any innovations that could save labor whether it relates to land conservation or not.

Types 1 and 2 farmers are willing to adopt agroecology practices as their livelihoods are more dependent on farming activities, and thus are more affected by a decline in land productivity. Restoring land fertility and ecological functions through sustainable intensification (Campbell et al., 2014; Kassam and Friedrich, 2012) could buffer the negative impacts of climatic hazards and increase their adaptation to rapid changes in their production environment. Generally, farms with high resource endowments such as Type 2 and Outlier 2 have a relatively higher capacity to manage risks. Their adaptation mechanisms combine high assets and a financial capacity with diversified income sources, both agricultural and off-farm (Kuivanen et al., 2016a). Therefore, they are the most advanced in innovation processes by testing a large number of technical and organizational options. Kong et al. (n.d.) found that these farm types (Type 1, Type 2, and Outlier 2) are predominantly experimenting with agroecological techniques. These results can be generalized to similar vanguard farming systems found in land frontiers across the whole region. The on-farm researchers should consider them as ‘farmer-innovators’ and work closely with them in co-designing soil conservation practices (Husson et al., 2016).

5. Conclusions

Combining multivariate statistical analysis and analysis of the historical changes and decision-making process, this study identified four main farm types (smallholder farm, large farm, off-farm, and paddy farm). This farm typology approach allowed us to understand farm diversity through the characterization and analysis of the distribution in time and space of farm structures, functions and performances. We found that the capacity to innovate is strongly linked with the risks encountered and individual capacity to manage them, according to farm resource endowment, diversified land uses and opportunities for off-farm activities. The higher the capacity to manage risks, the more willing farmers are to experiment new techniques and innovate. It is therefore essential to buffer the risks associated with the transition from conventional to conservation agriculture through insurance systems or subsidized loans, for example, which could prevent income loss for the early adopters.

While maintaining the diversity of farming systems is an important component of sustainability, leverage points for intervention include the facilitation of exchanges between the farmers belonging to the different types. Leverage points for intervention should definitively include governance mechanisms aimed at strengthening social interactions within the farming community and with other territorial stakeholders and the value chains in which these farm types are embedded. After an intense period of agricultural expansion and intensification along a pioneer front, the shift from essentially individualistic behaviors to more concerted actions is associated with the emergence of new institutions, such as farmer groups and cooperatives. The complete reorganization of the agricultural systems should build upon the specific capacity and needs of the different types of farming systems to innovate as illustrated in the paper.

References

- Alvarez, S., Paas, W., Descheemaeker, K., Tittone, P., Groot, J.C.J., 2014. Constructing typologies, a way to deal with farm diversity: general guidelines for the Humidtropics. Wageningen University, Wageningen, the Netherlands.
- Alvarez, S., Timler, C.J., Michalscheck, M., Paas, W., Descheemaeker, K., Tittone, P., Andersson, J.A., Groot, J.C.J., 2018. Capturing farm diversity with hypothesis-based typologies: An innovative methodological framework for farming system typology development. *PLoS One* 13, e0194757.
- Barral, S., Touzard, I., Ferraton, N., Rasse-Mercat, E., Pillot, D., 2011. Assessing smallholder farming. Diagnostic analysis of family-based agricultural systems in a small region. Editions du SEARCA.
- Begum, I., Alam, M., Rahman, S., Van Huylenbroeck, G., 2014. An assessment of the contract farming system in improving market access for smallholder poultry farmers in Bangladesh, in: Silva, C.A. da, Rankin, M. (Eds.), *Contract Farming for Inclusive Market Access*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 39–56.
- Berre, D., Baudron, F., Kassie, M., Craufurd, P., Lopez-Ridaura, S., 2016. Different ways to cut a cake: comparing expert-based and statistical typologies to target sustainable intensification technologies, a case-study in Southern Ethiopia. *Exp. Agric.* 1–17. <https://doi.org/DOI: 10.1017/S0014479716000727>
- Bertrand, R., 2011. Agrarian diagnosis and characterization of farming systems in two villages in Battambang province (Cambodia) with the set up of a farming systems reference monitoring network. Montpellier SupAgro, Montpellier.
- Campbell, B.M., Thornton, P., Zougmore, R., van Asten, P., Lipper, L., 2014. Sustainable intensification: What is its role in climate smart agriculture? *Curr. Opin. Environ. Sustain.* 8, 39–43. <https://doi.org/10.1016/J.COSUST.2014.07.002>
- Castella, J.-C., Lestrelin, G., Hett, C., Bourgoin, J., Fitriana, Y.R., Heinemann, A., Pfund, J.-L., 2013. Effects of Landscape Segregation on Livelihood Vulnerability: Moving From Extensive Shifting Cultivation to Rotational Agriculture and Natural Forests in Northern Laos. *Hum. Ecol.* 41, 63–76. <https://doi.org/10.1007/s10745-012-9538-8>
- Castella, J., Boissau, S., Trung, T.N., Quang, D.D., 2005. Agrarian transition and lowland–upland interactions in mountain areas in northern Vietnam: application of a multi-agent simulation model. *Agric. Syst.* 86, 312–332. <https://doi.org/10.1016/j.agsy.2004.11.001>
- Cortez-Arriola, J., Rossing, W.A.H., Massioti, R.D.A., Scholberg, J.M.S., Groot, J.C.J., Tittone, P., 2015. Leverages for on-farm innovation from farm typologies? An illustration for family-based dairy farms in north-west Michoacán, Mexico. *Agric. Syst.* 135, 66–76. <https://doi.org/10.1016/j.agsy.2014.12.005>
- Crocker, C.D., 1962. The general soil map of the kingdom of Cambodia and the exploratory survey of soils of Cambodia. Royal Cambodian Government Soil Commission/USAID, Phnom Penh.
- Diepart, J.C., Sem, T., 2018. Fragmented Territories: Incomplete Enclosures and Agrarian Change on the Agricultural Frontier of Samlaut District, North-West Cambodia. *J. Agrar. Chang.* 18, 156–177. <https://doi.org/10.1111/joac.12155>
- Dixon, J., 2019. Concept and Classifications of Farming Systems, in: Ferranti, P., Berry, E.M., Anderson, J.R.B.T.-E. of F.S. and S. (Eds.), . Elsevier, Oxford, pp. 71–80. <https://doi.org/https://doi.org/10.1016/B978-0-08-100596-5.22155-0>
- Dixon, J.A., Gibbon, D.P., Gulliver, A., 2001. Farming systems and poverty : improving farmers' livelihoods in a changing world. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.
- Falconnier, G.N., Descheemaeker, K., Mourik, T.A. Van, Sanogo, O.M., Giller, K.E., 2015. Understanding farm trajectories and development pathways : Two decades of change in southern Mali. *AGSY* 139, 210–222. <https://doi.org/10.1016/j.agsy.2015.07.005>
- Fresco, L.O., Westphal, E., 1988. A Hierarchical Classification of Farm Systems. *Exp. Agric.* 24, 399–419. <https://doi.org/DOI: 10.1017/S0014479700100146>
- Giller, K.E., Tittone, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero,

577 M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der
578 Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M.,
579 Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: Integrated assessment of
580 trade-offs concerning soil fertility management within African farming systems to support innovation
581 and development. *Agric. Syst.* 104, 191–203. <https://doi.org/https://doi.org/10.1016/j.agsy.2010.07.002>

582 Hall, D., 2011. Where the streets are paved with prawns: Crop booms and migration in Southeast Asia. *Crit.*
583 *Asian Stud.* 43, 507–530. <https://doi.org/10.1080/14672715.2011.623518>

584 Husson, O., Quoc, H.T., Boulakia, S., Chabanne, A., Tivet, F., Bouzinac, S., Lienhard, P., Michellon, R.,
585 Chabierski, S., Boyer, J., Enjalric, F., Moussa, N., Jullien, F., Balarabe, O., Rattanatrak, B., Castella, J.,
586 Charpentier, H., 2016. Co-designing innovative cropping systems that match biophysical and socio-
587 economic diversity : The DATE approach to Conservation Agriculture in Madagascar , Lao PDR and
588 Cambodia 31, 452–470. <https://doi.org/10.1017/S174217051500037X>

589 Hyman, J., Bailis, R., 2018. Assessment of the Cambodian National Biodigester Program. *Energy Sustain.*
590 *Dev.* 46, 11–22. <https://doi.org/https://doi.org/10.1016/j.esd.2018.06.008>

591 Jiao, X., Pouliot, M., Walelign, S.Z., 2017. Livelihood Strategies and Dynamics in Rural Cambodia. *World*
592 *Dev.* 97, 266–278. <https://doi.org/10.1016/J.WORLDDEV.2017.04.019>

593 Kassam, A., Friedrich, T., 2012. An ecologically sustainable approach to agricultural production
594 intensification : Global perspectives and developments An ecologically sustainable approach to
595 agricultural p - roduction intensification : Global perspectives and developments 1. *F. Actions Sci.*
596 *Reports* 1, 1–7.

597 Köbrich, C., Rehman, T., Khan, M., 2003. Typification of farming systems for constructing representative
598 farm models: two illustrations of the application of multi-variate analyses in Chile and Pakistan. *Agric.*
599 *Syst.* 76, 141–157. [https://doi.org/https://doi.org/10.1016/S0308-521X\(02\)00013-6](https://doi.org/https://doi.org/10.1016/S0308-521X(02)00013-6)

600 Kong, R., Castella, J.-C., Suos, V., Leng, V., Pat, S., Diepart, J.-C., Sen, R., Tivet, F., n.d. Investigating
601 farmer's decision-making in relation with the adoption of conservation agriculture in the northwestern
602 uplands of Cambodia. *Int. J. Agric. Sustain.* under review.

603 Kong, R., Diepart, J.C., Castella, J.C., Lestrelin, G., Tivet, F., Belmain, E., Bégué, A., 2019. Understanding
604 the drivers of deforestation and agricultural transformations in the Northwestern uplands of Cambodia.
605 *Appl. Geogr.* 102, 84–98. <https://doi.org/10.1016/j.apgeog.2018.12.006>

606 Kong, R., Sar, V., Leng, V., Trang, S., Boulakia, S., Tivet, F., Seguy, L., 2016. Conservation Agriculture for
607 Climate-Resilient Rain-Fed Uplands in the Western Regions of Cambodia: Challenges, Opportunities,
608 and Lessons from a 10-Year R&D Program, in: Sajise, P.E., Cadiz, M.C.H., Bantayan, B.R. (Eds.),
609 Learning and Coping with Change: Case Stories of Climate Change Adaptation in Southeast Asia. The
610 Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA), Los
611 Baños, Philippines, pp. 55–81.

612 Kuivanen, K.S., Alvarez, S., Michalscheck, M., Adjei-Nsiah, S., Descheemaeker, K., Mellon-Bedi, S.,
613 Groot, J.C.J., 2016a. Characterising the diversity of smallholder farming systems and their constraints
614 and opportunities for innovation: A case study from the Northern Region, Ghana. *NJAS - Wageningen*
615 *J. Life Sci.* 78, 153–166. <https://doi.org/http://dx.doi.org/10.1016/j.njas.2016.04.003>

616 Kuivanen, K.S., Michalscheck, M., Descheemaeker, K., Adjei-Nsiah, S., Mellon-Bedi, S., Groot, J.C.J.,
617 Alvarez, S., 2016b. A comparison of statistical and participatory clustering of smallholder farming
618 systems – A case study in Northern Ghana. *J. Rural Stud.* 45, 184–198.
619 <https://doi.org/http://dx.doi.org/10.1016/j.jrurstud.2016.03.015>

620 Kyomugisha, H., Sebatta, C., Mugisha, J., 2018. Potato market access, marketing efficiency and on-farm
621 value addition in Uganda. *Sci. African* 1, e00013. <https://doi.org/10.1016/j.sciaf.2018.e00013>

622 Landais, E., 1998. Modelling farm diversity: new approaches to typology building in France. *Agric. Syst.* 58,
623 505–527. [https://doi.org/10.1016/S0308-521X\(98\)00065-1](https://doi.org/10.1016/S0308-521X(98)00065-1)

624 Laurent, C., van Rooyen, C.J., Madikizela, P., Bonnal, P., Carstens, J., 1999. Household typology for
625 relating social diversity and technical change. *Agrekon* 38, 190–208.

626 <https://doi.org/10.1080/03031853.1999.9524914>

627 Lopez Ridaura, S., Tiftonell, P., 2011. Coping with heterogeneity. Typologies for agricultural research and
 628 development, in: 5th World Congress on Conservation Agriculture & 3rd Farming Systems Design
 629 Conference. Brisbane, Australia.

630 Ly, P., Jensen, L.S., Bruun, T.B., Rutz, D., de Neergaard, A., 2012. The System of Rice Intensification:
 631 Adapted practices, reported outcomes and their relevance in Cambodia. *Agric. Syst.* 113, 16–27.
 632 <https://doi.org/https://doi.org/10.1016/j.agsy.2012.07.005>

633 Martin, B., Farquharson, B., Spriggs, J., Fitzgerald, R., Scott, F., El, S., Touch, V., Keo, K., 2013. Enhancing
 634 production and marketing of maize and soybean in north-western Cambodia and production of summer
 635 crops in north-eastern Australia. Australian Centre for International Agricultural Research (ACIAR),
 636 Canberra.

637 Mishra, A., Whitten, M., Ketelaar, J.W., Salokhe, V.M., 2006. The System of Rice Intensification (SRI): a
 638 challenge for science, and an opportunity for farmer empowerment towards sustainable agriculture. *Int.*
 639 *J. Agric. Sustain.* 4, 193–212. <https://doi.org/10.1080/14735903.2006.9684802>

640 Nesbitt, H.J., 1997. Rice production in Cambodia. International Rice Research Institute (IRRI), Manila, the
 641 Philippines.

642 Nguyen, T.T., Do, T.L., Bühler, D., Hartje, R., Grote, U., 2015. Rural livelihoods and environmental
 643 resource dependence in Cambodia. *Ecol. Econ.* 120, 282–295.
 644 <https://doi.org/10.1016/J.ECOLECON.2015.11.001>

645 Ornetsmüller, C., Castella, J.-C., Verburg, P.H., 2018. A multiscale gaming approach to understand farmer's
 646 decision making in the boom of maize cultivation in Laos. *Ecol. Soc.* 23, art35.
 647 <https://doi.org/10.5751/ES-10104-230235>

648 Pacini, G.C., Colucci, D., Baudron, F., Righi, E., Corbeels, M., Tiftonell, P., Stefanini, F.M., 2014.
 649 Combining multi-dimensional scaling and cluster analysis to describe the diversity of rural households.
 650 *Exp. Agric.* 50, 376–397. <https://doi.org/10.1017/S0014479713000495>

651 Pretty, J., 2018. Intensification for redesigned and sustainable agricultural systems. *Science* (80-.). 362.
 652 <https://doi.org/10.1126/science.aav0294>

653 Rigg, J., Salamanca, A., Thompson, E.C., 2016. The puzzle of East and Southeast Asia's persistent
 654 smallholder. *J. Rural Stud.* 43, 118–133. <https://doi.org/10.1016/j.jrurstud.2015.11.003>

655 Ruben, R., Pender, J., 2004. Rural diversity and heterogeneity in less-favoured areas: the quest for policy
 656 targeting. *Food Policy* 29, 303–320. <https://doi.org/10.1016/J.FOODPOL.2004.07.004>

657 Sann, V., 2010. Social protection in Cambodia: Toward effective and affordable social protection for the
 658 poor and vulnerable, in: Asher, M.G., Oum, S., Parulian, F. (Eds.), *Social Protection in East Asia-
 659 Current State and Challenges*. Economic Research Institute for ASEAN and East Asia, Jakarta, pp.
 660 316–345.

661 Shaner, W.W., 1982. Farming systems research and development: guidelines for developing countries /
 662 W.W. Shaner, P.F. Philipp, W.R. Schmehl; editorial assistance, Donald E. Zimmerman, Westview
 663 special studies in agriculture (aquaculture science and policy). Westview Press, Boulder, Colo.

664 Sum, S., Khiev, P., 2015. Contract Farming in Cambodia: Different Models, Policy and Practice. Cambodia
 665 Development Resource Institute (CDRI), Phnom Penh.

666 Tiftonell, P., 2014. Livelihood strategies, resilience and transformability in African agroecosystems. *Agric.*
 667 *Syst.* 126, 3–14. <https://doi.org/http://dx.doi.org/10.1016/j.agsy.2013.10.010>

668 Tong, K., Lun, P., Sry, B., Pon, D., 2013. Levels and Sources of Household Income in Rural Cambodia
 669 2012, CDRI Working Paper Series. Phnom Penh. <https://doi.org/10.1017/CBO9781316182635.003>

670 Valbuena, D., Groot, J.C.J., Mukalama, J., Gérard, B., Tiftonell, P., 2015. Improving rural livelihoods as a
 671 “moving target”: trajectories of change in smallholder farming systems of Western Kenya. *Reg.*
 672 *Environ. Chang.* 15, 1395–1407. <https://doi.org/10.1007/s10113-014-0702-0>

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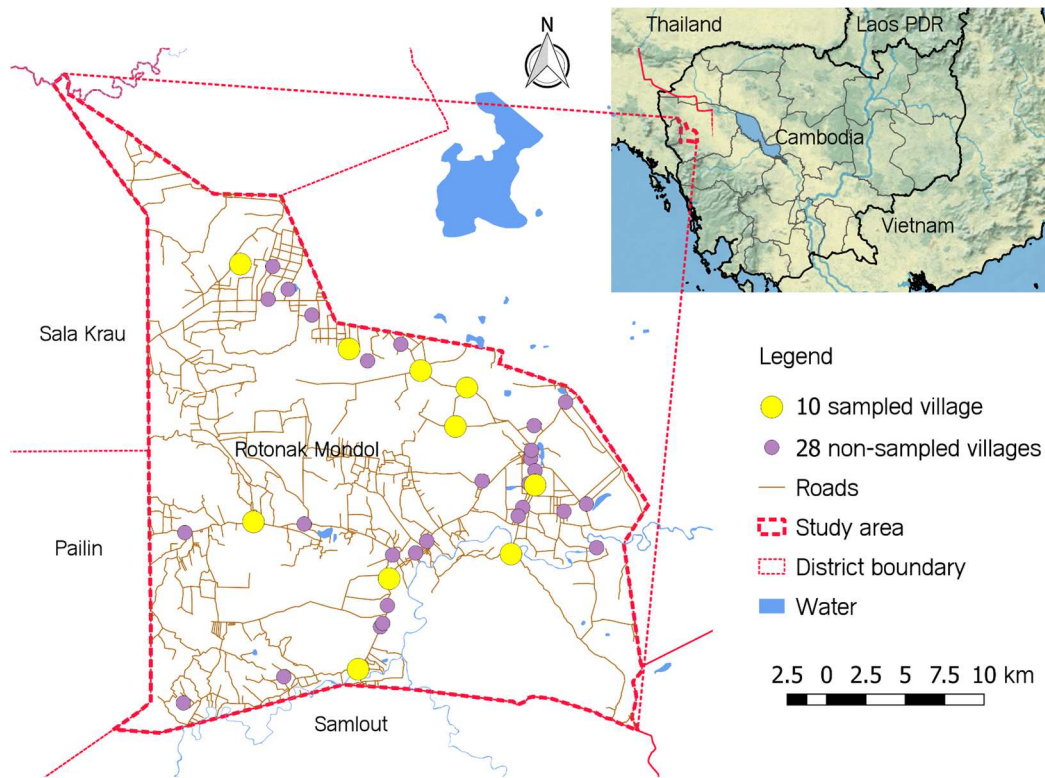
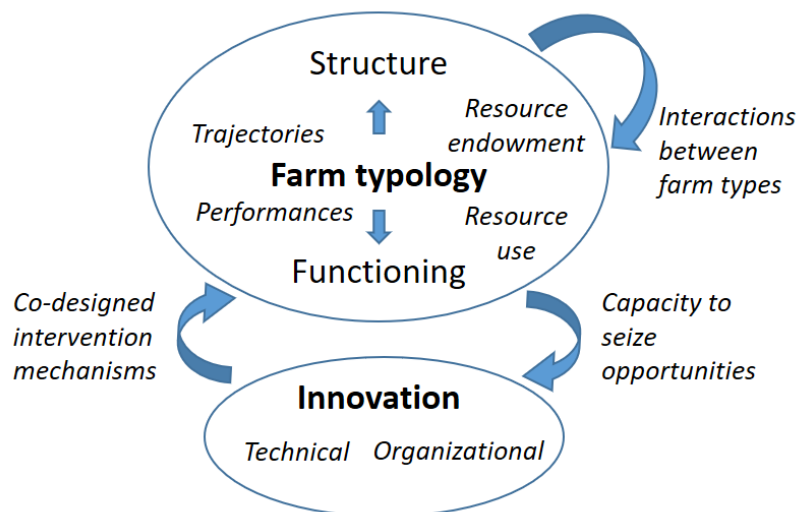


Fig.1. Geographical location of studied area



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Fig. 2. Methodological framework used for data analysis

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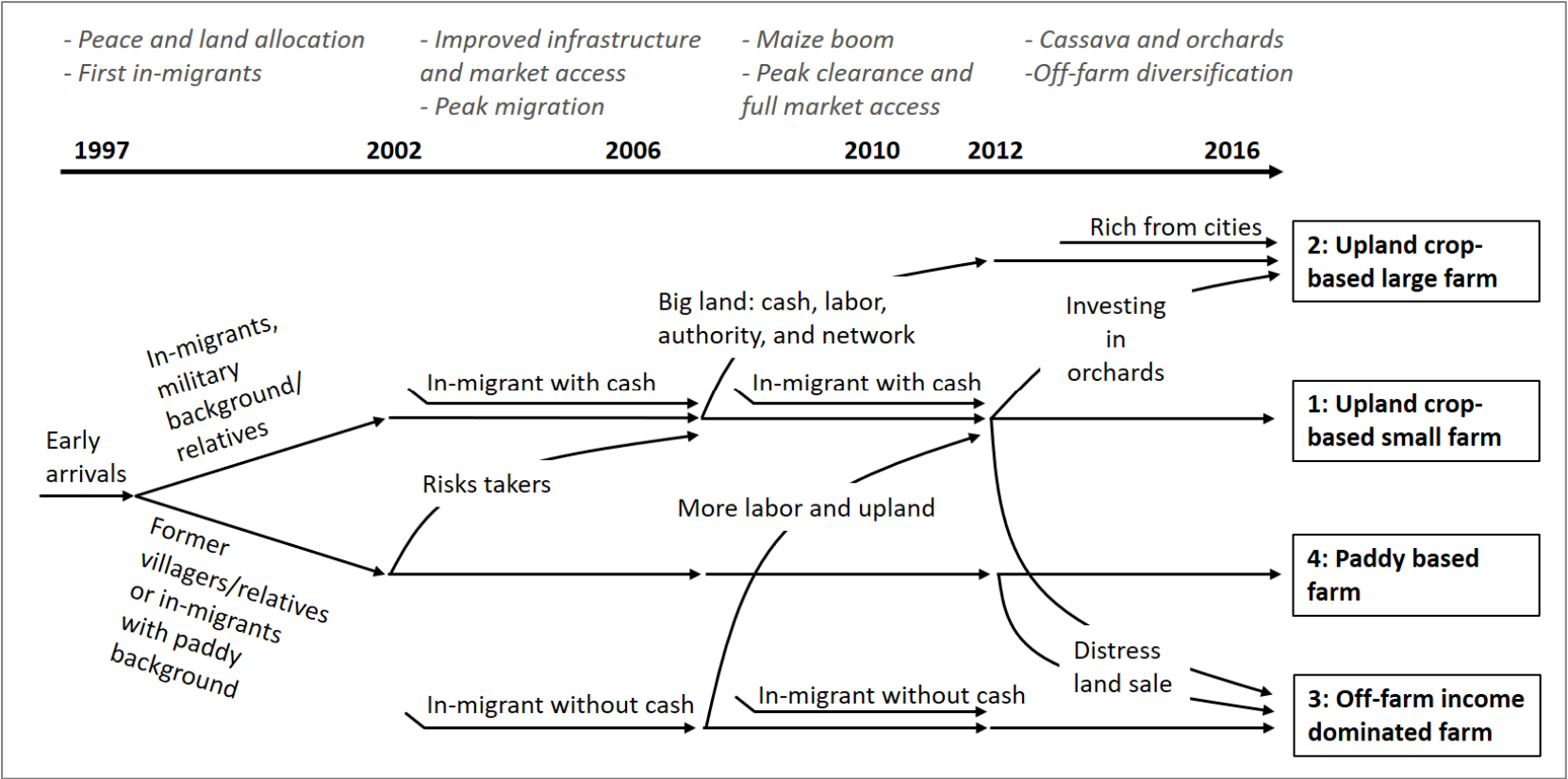


Fig.3. Farm differentiation process and current farm types

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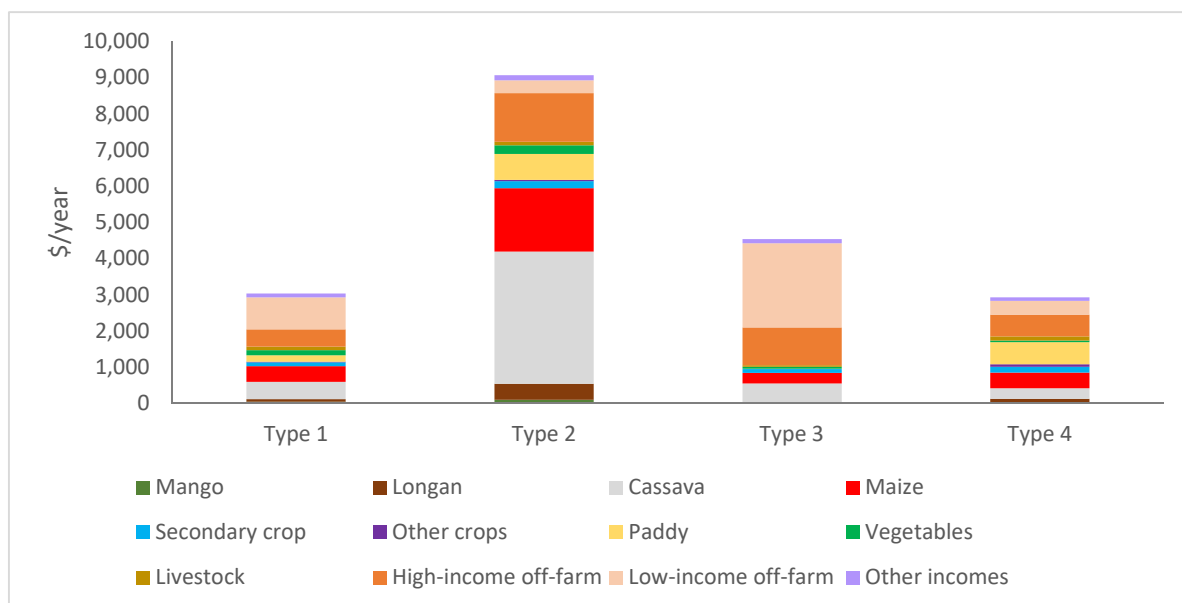


Fig.4. Sources of farm income and livelihoods' activities

N.B. Other incomes include collection of natural resources, remittance, and renting out land

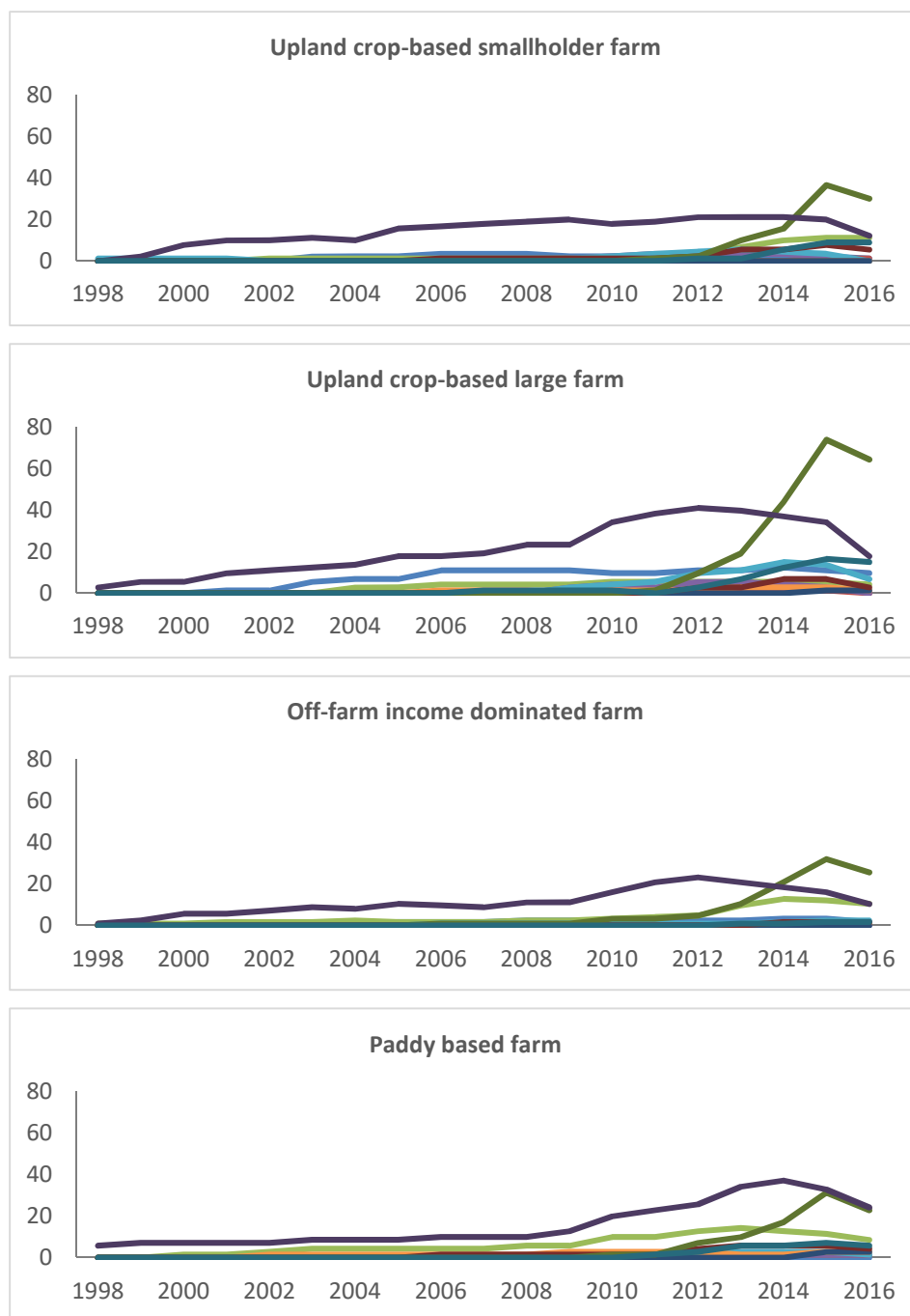


Fig.5. Evolution of the use of innovative agricultural practices and organizations from 1998 to 2016 per farm type

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Table 1. Number of sampled households and villages

Sampled village	Total households in 2016	Samples for questionnaire		Outliers	Sampled for in-depth interview	
		No.	%		No.	%
Baribour	161	36	22	0	10	28
Kouk Choar	97	31	32	0	8	26
Chi Pang	137	35	26	0	9	26
Phlov Meas	291	40	14	2	10	25
Ou Khmum	330	41	12	0	11	27
Pich Changva	174	37	21	1	10	27
Reaksmei Sangha	453	42	9	4	10	24
Serei Voant	146	35	24	0	9	26
Thvak	97	31	32	0	8	26
Svay Sar	175	37	21	0	10	27
Total	2,061	365	18	7	95	26

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Table 2. Analytical framework

Objectives	Scales	Methods	Analyzes	Outputs
1. Characterizing farming systems diversity and trajectories	- District - Village - Farm	- Extraction of communal database - Village land use 2016 (Kong et al., 2019) - Review farm typology 2010 (Bertrand, 2011) - 365 household questionnaire surveys in 2016 - 95 in-depth interviews in 2017	- Multivariate analysis of village and farm diversity - Comparison of the 2010 and 2016 typologies - Retrospective analysis and categorization of farming system evolution in time	- Village typology - Farm typology - Graphic representation of farming system trajectories and drivers of change
2. Assessing the performances of farming systems	- Farm - Field	- 95 in-depth interviews in 2017	- Technical and economic performances of cropping systems - Farm's income and activity portfolio	- Cropping system performances by type of farming system and its impacts on farm's income
3. Investigating the influence of farm's structure on its capacity to innovate	- Farm - Field	- Review 2010 farm typology (Bertrand, 2011) - 365 household questionnaire surveys in 2016 - 95 in-depth interviews in 2017	- Categorization of innovative systems by type of farming system - Identification of factors influencing innovation	Explanation of the influences of farming system structure on the adoption of innovative practices

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Table 3. Descriptive statistics of the variables used in PCA for village cluster (N = 38)

Name of variables	Code	Description	Unit	\bar{x}	σ
Demography					
Total household	TH	Total household number	hh	255.8	133.7
Economy					
%Female in services	FS	% female number of total female, from 18-64 years old working mainly in services	%	7.6	9.6
%Shop	SP	% shops/stores per household selling goods and services except those in the market	%	2.0	2.9
Household asset					
%Family car	FC	% of household owning family car	%	1.6	1.7
%Cattle	C	% of household raising cattle	%	31.3	26.8
%TV	TV	% of household having zinc-roof house and television	%	53.8	26.1
%Tractor	T	% of households owning a tractor	%	2.1	2.1
%Power tiller	PT	% of households owning a power tiller	%	7.5	5.2
%Planter	P	% of maize-planter per household	%	0.5	1.2
Agricultural input					
%Insecticides	IC	% of households using insecticides last year cropping season	%	64.0	29.0
Land use					
%Built-up area	BA	% built-up area of total village land	%	1.7	4.7
%Crop area	CA	% upland annual and perennial crop area of total village land	%	59.7	22.8
%Paddy area	PD	% paddy area of total village land	%	16.6	18.9
%Plantation area	PA	% of wet area of total village land	%	8.7	13.7
%Paddy<1ha	PD1	% of wet area of total village land	%	16.7	18.6

Note: \bar{x} = Mean; σ = Standard deviation; hh = Household

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Table 4. Descriptive statistics of the variables used in PCA for farm clustering (N = 365)

Name of variables	Code	Description	Unit	\bar{x}	σ	PCA
Farm labor						
Family member		Total family members	person	4.9	1.7	
Working labor		Total family members working more than 25% either on farm or non-farm	person	3.3	1.5	
Farm labor	FL	Total family members working on farm only	person	2.3	1.3	yes
% migration	M	% of family members living outside of the village more than 25% of their time	%	11.9	22.3	yes
Education of household head		Number of years education	year	4.2	3.4	
Age of household head		Age of household head	year	46.8	13.3	
Farm land						
Total land	TL	Total land area both cultivated and fallow including rent-in and rent-out	ha	4.3	4.9	yes
Cultivated land		Total cultivated land area computed based on area per crop and per cycle	ha	4.5	5.4	
Land/Labor ratio		Cultivated land area per farm labor unit		2.0	2.8	
%Paddy area	P	Share of paddy area to total farm land	%	25.5	32.6	yes
%Annual crop area	AC	Share of annual upland crop area to total farm land	%	50.1	39.5	yes
%Orchard		Share of orchard area to total farm land	%	6.6	18.6	
Farm's finance						
Total asset	TA	Total value of all assets calculated as the sum of real purchased price	\$	2,888	4,293	yes
Production costs	PC	Total cost of hired service and labor for all crops	\$/year	744	1,117	yes
Debt	D	Total pending debt both formal and informal credits	\$	1,674	3,010	yes
Power tiller	PT	Number of power tillers owned per household		0	0	yes
Cattle	C	Total number of cattle at all ages	head	1	1	yes
Farm's income						
Total household's income	HI	Sum of income and profit from all household's activities	\$/year	4,681	4,348	yes
Crop's income		Sum of total production multiplying with sold price for all grown crops	\$/year	2,510	3,435	
%Crop's income	CI	Share of crop's income to total household's income		52	36	yes
Low-income off-farm		Total wage or salary per year for unskilled works e.g. agricultural wage labor, construction work, house mate...etc.	\$/year	1,177	2,605	
%Income of poor off-farm	PO	Share of low-income off-farm to total off-farm income		26	34	yes
High-income off-farm		Total profit or salary per year for skilled or services related work and provision	\$/year	879	1,779	
Livestock's income		Total income from selling animals per year	\$/year	81	249	
Farm status						
House quality		The sum of score for roof, wall, latrine and well ranging from 2 to 8		4.4	1.1	
Rice deficiency	RD	Percentage of months without rice sufficiency in a year	%	61.0	43.3	yes
Year stay		Number of years the household live in the village.	year	16.5	9.0	

Note: \bar{x} = Mean; σ = Standard deviation

720 **Table 5.** Characteristics of farm types and P-value

Farm cluster	Type-1	Type-2	Type-3	Type-4	Outlier 1	Outlier 2		
Cluster name	Upland crop-based smallholder farm	Upland crop-based large farm	Land-poor off-farm income dominated farm	Paddy- based farm	Off-farm based investor	Farm based investor	Total	P- value
Number	90 (25%)	73 (20%)	125 (34%)	70 (19%)	2 (0.5%)	5 (1.5%)	365	
Farm labor								
Family member	4.9	5.1	5.0	4.7	3.0	4.6	4.9	.610
Working labor	3.3	3.6	3.2	3.3	3.0	3.4	3.3	.365
Farm labor	2.5	2.8	1.8	2.8	2.0	2.4	2.3	.000
% migration	8.8	6.3	21.8	4.0	50.0	27.0	11.9	.000
Education of household head	4	5	4	5	6	8	4	.066
Age of household head	45	48	46	49	47	45	47	.130
Farm land								
Total land	3.0	10.7	1.8	3.8	17.2	33.4	4.3	.000
Cultivated land	3.0	11.4	1.8	3.9	13.2	32.9	4.5	.000
Land/Labor ratio	1.4	5.0	1.1	1.6	6.6	16.0	2.0	.000
%Paddy area	35.5	14.5	4.4	62.0	0.0	3.7	25.5	.000
%Annual crop area	39.5	70.1	59.9	25.3	6.9	37.5	50.1	.000
%Orchard	7.7	10.9	4.6	4.2	75.9	33.9	6.6	.073
Farm's finance								
Total asset	1,786	7,541	1,222	2,429	19,238	31,627	2,888	.000
Production costs	381	2,290	323	352	5,164	11,014	744	.000
Debt	881	4,802	817	959	21,500	25,900	1,674	.000
Power tiller	0.3	0.8	0.1	0.5	1.0	0.6	0.4	.000
Cattle	1.5	1.3	0.7	2.5	0.0	0.4	1.4	.000
Farm's income								
Total household's income	2,937	8,981	4,450	2,850	32,705	44,750	4,681	.000
Crop's income	1,464	7,124	1,007	1,728	11,555	36,807	2,510	.000
%Crop's income	53	79	28	65	37	77	52	.000
Low-income off-farm	880	354	2,319	379	0	360	1,177	.000
%Low-income off-farm	29	3	44	15	-	2	26	.000
High-income off-farm	483	1,347	1,046	603	21,150	7,583	879	.006
Livestock's income	97	97	40	116	-	-	81	.135
Farm status								
House quality	4.3	5.2	4.1	4.4	8.0	6.0	4.4	.000
Rice deficiency	58.1	44.2	96.8	18.6	100.0	40.0	61.0	.000
Year stay	16.9	15.6	15.6	18.3	18.5	16.8	16.5	.190

721 Note: P-value is the results of One-Way ANOVA analysis in SPSS for the four farm types excluding the 7 outliers.

722 See variable description in Table 4.

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Table 6. Distribution of village types and farm types

Village	Sampled village	Type-1	Type-2	Type-3	Type-4	Outlier 1	Outlier 2	Grand Total
		Upland crop-based smallholder farm	Upland crop-based large farm	Off-farm income dominated farm	Paddy based farm	Off-farm based investor	Farm based investor	
Lowland diversified	Kouk Choar	10%	1%	4%	23%	0%	0%	31
	Serei Voant	6%	7%	8%	21%	0%	0%	35
	Thvak	16%	1%	6%	11%	0%	0%	31
Upland diversified	Baribour	12%	21%	6%	3%	0%	0%	36
	Chi Pang	12%	7%	14%	1%	0%	0%	35
	Phlov Meas	8%	5%	17%	9%	50%	20%	40
	Pich Changva	12%	18%	2%	14%	50%	0%	37
	Reaksmei Sangha	7%	8%	15%	10%	0%	80%	42
	Svay Sar	9%	11%	14%	4%	0%	0%	37
Upland intensified	Ou Khmum	9%	21%	13%	3%	0%	0%	41

725 N.B. The colors relate the farm types to the village types. For each farm type, the darker the color, the stronger is the
726 influence of village type.

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Table 7. Technical and economic performances of major cropping systems by farm types

Cropping system		Description	Type 1		Type 2		Type 3		Type 4	
			Number of plot		Number of plot		Number of plot		Number of plot	
		Average plot size (ha)	184	1.5	170	4.6	141	1.6	165	1.6
			Number of household	Mean	Number of household	Mean	Number of household	Mean	Number of household	Mean
Cassava		% Household		40.0		84.6		37.6		35.7
		% Area		17.4		55.4		30.7		10.3
		Production cost (\$/ha)	36	207	61	367	48	275	26	231
		Yield (kg/ha)	36	10,007	61	13,796	48	12,966	26	11,316
		Land productivity (\$/ha)	36	592	61	543	48	555	26	619
Maize		% Household		38.9		34.6		22.4		35.7
		% Area		18.6		11.4		16.4		12.4
		Production cost (\$/ha)	40	95	43	124	37	104	30	89
		Yield (kg/ha)	40	3,347	43	3,911	37	3,010	30	3,656
		Land productivity (\$/ha)	40	424	43	526	37	592	30	585
1st cycle crop / Maize		%,Household		13.3		19.2		8.0		12.9
		%,Area		4.3		4.8		3.3		3.1
		Production, cost, (\$/ha)	15	85	21	72	11	61	12	90
		Yield, (kg/ha)	15	268	21	326	11	223	12	822
		Land, productivity, (\$/ha)	15	164	21	179	11	198	12	498
Maize		Production, cost, (\$/ha)	15	109	21	104	11	117	12	133
		Yield, (kg/ha)	15	3,506	21	3,638	11	3,654	12	3 947
		Land, productivity, (\$/ha)	15	403	21	509	11	427	12	617
		% Household		68.9		53.8		7.2		100.0
		% Area		35.9		11.9		3.2		56.0
Paddy		Production cost (\$/ha)	62	128	44	106	9	110	68	87
		Yield (kg/ha)	62	1,338	44	1,804	9	864	68	1,526
		Land productivity (\$/ha)	62	168	44	305	9	66	68	254
		% Household		6.7		3.8		4.0		8.6
		% Area		2.4		0.5		2.0		0.7
Vegetables		Production cost (\$/ha)	6	123	5	1,175	5	1,118	6	2
		Yield (kg/ha)	6	15,318	5	35,869	5	15,463	6	15,723
		Land productivity (\$/ha)	6	4,510	5	7,059	5	3,859	6	5,303
		% Household		13.3		23.1		5.6		15.7
		% Area		4.9		8.5		2.2		2.1
Longan		Production cost (\$/ha)	12	3	18	94	7	23	11	66
		Yield (kg/ha)	12	4,702	18	3,279	7		11	7,222
		Land productivity (\$/ha)	12	1,299	18	912	7	-23	11	1,139
		% Household		8.9		15.4		6.4		7.1
		% Area		1.8		2.6		3.0		1.1
Mango		Production cost (\$/ha)	8	0	13	7	8	5	5	5
		Yield (kg/ha)	8	1,216	13	862	8	25,000	5	1,333
		Land productivity (\$/ha)	8	507	13	58	8	986	5	28

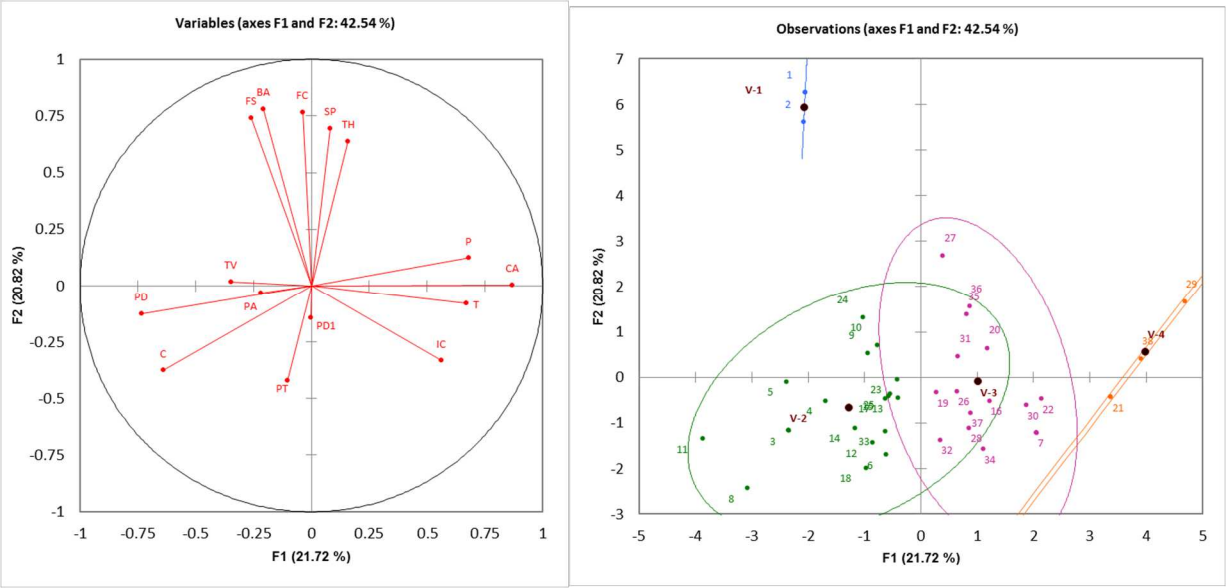
Appendixes. Supplementary data

Appendix 1. Definition of organizational and technical innovations

No.	List of innovations	Description of innovations
Organizational innovations		
1	Member of any group (farmer cooperative, contract farming...that impacts on decision making to the changes)	Deciding to be a member of any farmer groups is considered as part of organizational innovation. The farmer group could be official or unofficial form e.g. cooperative, contract farming, saving group...etc. creating for collective actions and benefits.
Technical innovations		
1	No-tilling and no burning	Residues of precedent crops are kept on the field and used as mulching for preceding crops without tilling and burning for instance keeping residues of precedent maize previous season as mulch for preceding maize next season.
2	Cover crops (e.g. pigeon pea)	Any leguminous and gramineae species grown in association, succession or rotation with the main crops for the purpose of soil improvements and breaking pests cycles.
3	Inter-cropping (e.g. orchards with annual crops or vegetables)	Growing vegetables in inter-row of orchards (mango or longan) plantation either during 2-3 first years of unproductive stage or permanent period for the benefits of improving the water and fertilizers efficiency. The intercropping annual crops such as maize and cassava is not considered as an innovation since it is a general practice for all farm types.
4	Crop succession (whatever succession with different species e.g. mungbean/maize, maize/mungbean...)	Growing two or more different species in successive cropping systems within a year cropping season for example mungbean is precedent or preceding crop for maize as the main crop.
5	Crop rotation (whatever rotation with different species and > 1year fallow e.g. maize/cassava)	Growing two or more different species in rotational cropping systems for a two-year or more rotation for instance biannual rotation of maize and cassava.
6	Elements of SRI (direct seeding, young seedling, spacing...)	Any practices of system of rice intensification (SRI) principles (Mishra et al., 2006; Ly et al., 2012) to express the agronomic and genetic potential of rice production for instance translating fewer younger seedlings.
7	Improved pasture (e.g. planting new grass or tree species)	Using high nutritious fodder species either single or mix gramineae and leguminous species to improve the pasture.
8	Others	

Appendix 2

2.1. Distribution of the variables in the village PCA (left) and the AHC (right).



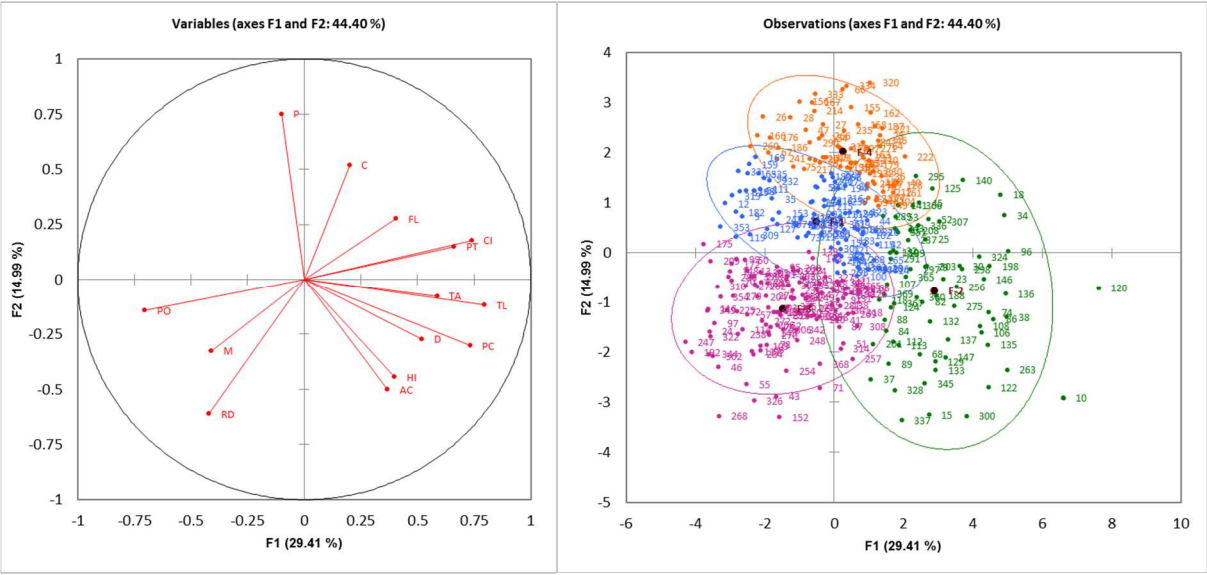
N.B. The full name of the variables used in PCA (left) is available in Table 3 for village cluster (N = 38).

2.2. Characteristics of village types

Village cluster	V-1	V-2	V-3	V-4	Total	P-value
Cluster name	Urban village	Lowland diversified village	Upland diversified village	Upland intensified village		
Number (%)	2 (5%)	18 (47%)	15 (40%)	3 (8%)	38	
Demography						
Total household	459	225	245	357	256	.053
Economy						
%Female in services	35.9	6.3	5.7	6.5	7.7	.000
%Shop	6.5	1.3	2.2	2.6	2.0	.107
Household asset						
%Family car	6.9	1.1	1.5	2.0	1.6	.000
%Cattle	12.9	49.1	17.7	5.6	31.3	.000
%TV	72.3	59.5	46.5	43.8	53.8	.338
%Tractor	1.1	1.4	2.2	7.2	2.2	.000
%Power tiller	3.0	8.7	7.2	5.2	7.5	.388
%Planter	0.0	0.0	0.4	4.1	0.5	.000
Agricultural input						
%Insecticides	17.1	55.8	73.8	95.8	64.0	.004
Land use						
%Built-up area	16.9	0.9	0.9	0.8	1.7	.000
%Crop area	37.6	42.8	76.5	92.4	59.7	.000
%Paddy area	30.5	27.4	5.1	0.3	16.6	.001
%Plantation area	2.5	13.2	5.3	2.7	8.7	.291
%Paddy<1ha	2.1	19.3	13.9	25.5	16.7	.474

Appendix 3

Distribution of the variables in the farm PCA (left) and the distribution of farm types in AHC (right).



N.B. The full name of the variables used in PCA (left) is available in Table 4 for farm clustering (N = 365).

Graphical abstract

