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Drivers of land use complexity along an agricultural transition gradient in Southeast Asia

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ABSTRACT

Agricultural systems in Southeast Asia are rapidly transitioning from subsistence-oriented to market-oriented agriculture. Driven by the highly complex and variable decision processes of individual farm households, these transitions have produced a diverse landscape mosaic across the region. Elucidation and characterization of underlying decision-making processes, and the factors that influence land use choices, are thus essential for sustainable land use planning. To enable a study that seeks to understand these linkages, data on plot-level 10-year land use history, management and farm performance indicators were collected from 163 households in the Northern Lao uplands and in the Central Highlands of Vietnam, areas chosen to represent two extremes of the transition gradient. The objectives of the study were (i) to describe plot-level sequence patterns of seasonal variation of land use over several years, (ii) to apply a sequence dissimilarity metric, the complexity index (CI), to measure land use transition in an agricultural system, and (iii) to identify the key drivers of land use change and their linkages with farm performance indicators and plot level characteristics through multi-dimensional analysis. CI allowed compressing historical land use data and quantifying land use complexity in a simple and efficient manner. Land use dynamics varied strongly between the two sites, with 66% of the land use types in the Laos site being completely replaced by others during the recall periods, compared to only 15% in the Vietnam site. Associated key drivers of land use change also differed significantly: while end use of agricultural products was the main driver behind land use changes in the Vietnam site, a more complex relationship between topography and management vs. land use change was evident in the Laos site. Likewise, land use complexity does not exhibit the same relationship with farm performance in the two sites: in the Central Highlands, households with higher food availability are half as likely to transition, while in the Lao uplands, land use complexity was significantly correlated with the Progress out of Poverty index. Multidisciplinary studies remain necessary to assess the impact of innovative sustainable intensification options on system performance and environmental sustainability, before policies are enacted to support their dissemination in Southeast Asian smallholder agricultural systems. Context-specific CI thresholds associated with system quality indicators could support this by informing decision-makers on the pace of agricultural transformation and its environmental impacts.

1. Introduction

Agricultural activities account for 62% of the observed land use changes in Asia during the last decades (Song et al., 2018). In Southeast Asia, agricultural systems are undergoing a rapid transition from subsistence towards market-oriented agriculture (Diez, 2015; Ashraf et al., 2017; Goto and Douangngeune, 2017). Smallholder farmers replacing subsistence crops with cash crops typically follow market demands and economic opportunities (Alexander et al., 2017; Dawe, 2015; Green and Vokes, 1997; Rigg, 2012). However, transition

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processes are complex and nuanced: a transition to cash cropping systems is not a unidirectional pathway, but rather a dynamic process in which a return to subsistence farming may occur. These transitions are driven by complex and varying decision processes of individual farm households, producing a diverse mosaic across the landscape. It is not uncommon, for example, to find villages comprised of a mixture of market-oriented farms, subsistence-oriented farms and farms that still practice shifting cultivation (Milne, 2013), sometimes with seasonal cropping transitions that seem random.

Although the transition towards intensive and market-oriented agriculture generally improves overall income for smallholders (Hettig et al., 2016), it often occurs at the expense of ecological and environmental sustainability, as well as livelihood security (Klasen et al., 2016; Dressler et al., 2017; Ditzler et al., 2019). Beyond its effects on key performance indicators such as smallholder income and food availability, land use transition is linked to plot management practices such as agrochemical use or soil tillage that influence soil health and fertility, as well as plot allocation to particular seasonal, annual, or permanent land uses.

Just as the factors affecting adoption of sustainable management practices must be well understood to ensure positive impact at scale, the drivers of land use change at the farm household level must be considered by policy makers and development actors for sustainable land use planning. It is essential to understand and characterize the decision-making processes of smallholders, and the myriad of factors that influence their choices (Lambin et al., 2003; Southworth et al., 2012; Ashraf et al., 2017). In reality, this has often not been the case, and relevant government policy has often been misguided and even contradictory, with some policies e.g. encouraging upland farmers to replace swidden agriculture for monoculture (Dressler 2017), and others redirecting the trajectory of these transitions in a manner that attempts to balance financial stability and environmental sustainability (Fröhlich et al., 2013). Indeed, land use planning and other regulatory approaches to environmental services issues have had little success in Southeast Asia to date, and a more robust understanding of the linkage between policy and underlying biophysical and decision-making processes could help to expand the range of policy options for supporting sustainable land uses (Tomich et al., 2004).

The aim of this study was to discern linkages between land use change and plot-level and household-level characteristics and processes: information that could ultimately inform land use policy. However, drivers of land use change are known to be highly context- and location-specific (Lambin et al., 2000). Therefore, the two sites for this study were chosen to represent two extremes of the transition gradient in Southeast Asia: (1) a site in the uplands of northern Laos which is highly subsistence-oriented, has low levels of formal education, has poor accessibility, and garners little attention from policy makers (Hepp et al., 2019; Thanichanon et al., 2019); and the Central Highlands of Vietnam, an example of forward-looking, market-oriented agriculture that has a high degree of political involvement (Müller and Zeller, 2002).

Most studies that assess land use change are based on remote sensing or geographic information system (GIS) data products. Since open source remote sensing data products are of low spatial but relatively high temporal resolution, a comprehensive understanding of complex land use patterns is typically lacking, particularly in the context of smallholder farming systems (Kammerbauer and Ardon, 1999). Additionally, contextual knowledge, such as factors contributing to a particular land use, cannot be effectively gathered solely with the use of remote sensing data products. Mixed approaches, in which GIS analysis is combined with contextual knowledge obtained through surveys, have the potential to overcome challenges associated with GIS-only or survey-based approaches. With the development and increased use of new statistical approaches such as sequence analysis, it is now possible to better leverage spatial and temporal dimensions of data that is collected using mixed approaches. For instance, the temporal dimension of land use data can be used to construct time-series indicators, which can then be combined with contextual survey-based knowledge, to better understand drivers of land use (Ritschard and Studer, 2018). Multidimensional characterization of complex farming systems and associated land use is necessary to design intervention strategies that enhance sustainability across several community dimensions, such as financial, environmental, and health.

The objectives of this study were therefore (i) to describe plot-level sequence patterns of seasonal variation of land use over several years, (ii) to apply a sequence dissimilarity metric, the complexity index, to measure land use transition in an agricultural system, and (iii) to identify the key drivers of land use change and their linkages with farm performance indicators and plot level characteristics through a multidimensional analysis.

2. Materials and methods

2.1. Site description

The study was conducted on the hillsides of the Xieng Khouang plateau in northern Laos (site XK), within a 40 km radius from Phonsavanh (19°26′59.30″N, 103°13′16.43″E), and in the Central Highlands of Vietnam, in DakLak and DakNong provinces (site CH). Sites XK and CH typify transitions in smallholder agricultural production systems of Southeast Asia. While farming systems in XK are currently transitioning from subsistence, low-intensive to market-driven, high intensive production, site CH underwent such a transition in the late 1980′s and early 1990′s. Site XK is approximately 1095 m above sea level, with two seasons a year: a cool and dry season between November and March, and a warm and rainy season from April to October. Site CH consists of several plateaus ranging from 500 to 1500 m above sea level, with an annual rainfall ranging from 1500 to 2400 mm. The CH rainy season typically lasts from May to October, with April and May being the hottest months of the year.

2.2. Data acquisition and surveys

To characterize farming systems in the study area, a baseline survey was conducted in December 2015 among 366 and 310 households selected randomly in site XK and site CH, respectively (Ritzema et al., 2019), using the Rural Household Multi-Indicator Survey (RHoMIS) tool (Hammond et al., 2017). RHoMIS questionnaire modules were administered using the Open Data Kit (ODK) and included questions on household level social and demographic characteristics, food security indicators, poverty, crops and livestock including yields, sale prices and inputs, and measures of off-farm incomes. Focus group discussions with local experts in each site, and exploration of the RHoMIS data using unsupervised clustering analysis, identified cumulative diversity (combinatorial counts of crop and livestock species diversity) and market orientation (a dimensionless ratio defined as relative importance of crop and livestock sales in generating potential total food energy) as the two main drivers of variation in the RHoMIS dataset (Epper et al., 2020).

Subsequently, a stratified sampling approach capturing contrasting levels of these two variables was used to sample a subset of the RHoMIS households. Seventy-two households and 91 households were sampled for a detailed temporal land use survey in sites XK and CH, respectively. The standardized CAPI-based (computer assisted personal interviewing) survey was conducted in March and May 2017 by teams of trained local enumerators. The survey instrument consisted of the following modules: a) a household datasheet capturing descriptive socio-economic indicators from the household head (household level data, punctual), (b) a field properties registration sheet, which contained geotags of all the plots belonging to the interviewed household, historical land use based on farmer recall for every plot and season for the time period spanning from 2007 to 2016 (plot level data, temporal, 10 years), and (c) a broad

Table 1
Variables used to characterize households, plots and system performance in the regression analyses.

Class	Variable name	Unit	Type	Definition
Household level	Ethnic group	n.a.	categorical	Ethnic group of the household head. CH site: Kinh, Mnong, Tay or Thai; XK site: Loum or Hmong
	Origin	yes or no	categorical	Origin from current location or migrated from elsewhere (y/n)
	Off-farm employment	yes or no	categorical	Presence of income from non-farming activities
	Labor distribution	n.a.	categorical	Predominant source of labor for agricultural activities: family, contracted, community members, or combination
	Household size	AME[3]	continuous	Number of people in the household
	Education	n.a.	categorical	Education level of the household head: illiterate, primary, secondary or post-secondary
	Land cultivated	ha	continuous	Total area cultivated
	Fertilization	kg $N.year^{-1}$	continuous	Total chemical nitrogen inputs on the farm
	Crop diversity	n.a.	continuous	Number of different crop species cultivated
	Livestock diversity	n.a.	continuous	Number of different livestock species cultivated
	Number of plots	n.a.	continuous	Number of plots cultivated by the household
Plot level	Soil tillage	yes or no	categorical	Practice of tillage
	Agrochemical inputs	n.a.	categorical	Use of chemical fertilizers, pesticides or both
	Property	n.a.	categorical	Ownership type: collective, family owned or on rent
	Irrigation	n.a.	categorical	Irrigation source: canal, pump or rainfed
	Slope	n.a.	categorical	Slope estimation: flat, modest or strong
	Source of planting material	n.a.	categorical	Source of planting material: bought, subsidized, exchanged, own or a combination
	Final use	n.a.	categorical	Fate of crop products: for sale, home consumption or both
Performance	Progress out of Poverty	n.a.	continuous	Likelihood of household's total expenditure below the national poverty line [2]
	Total income	$USD.year^{-1}$	continuous	Sum of income from agricultural activities
	Food availability	$kcal.AME^{-1}.year^{-1}$	continuous	Potential amount of food that can be generated from on and off-farm income [3]
	Food Self-sufficiency	$kcal.AME^{-1}.day^{-1}$	continuous	Capacity to fulfill the household energy requirements from food produced on-farm
	Food insecurity	n.a.	continuous	Household Food Insecurity of Access Scale (HFIAS) score [4]
	Total Energy Available	MJ	continuous	Sum of energy from crop and livestock products produced on-farm, as well as from food bought in the market

[1] Adult male equivalent (adult = 1; child = 0.5)
[2] PPI score = Desiere, S., Vellema, W., D'Haese, M., 2015. A validity assessment of the Progress out of Poverty Index(PPI)(TM). Eval. Program Plan. 49, 10-18.
[3] Ritzema et al., 2019
[4] HFIAS measures the frequency and severity of hunger (Coastes et al., 2007). Scores range from 0-27, where a score of 0 signifies that the respondent is 'food secure' and a score of 27 is the severest level of food insecurity. Obtained from Ritzema et al. (2019).

spectrum of socio-economic, biophysical and cultural factors that influence land use such as access to resources (e.g. markets, water etc.), slope, soil fertility management, irrigation, final use, transport, and source of planting material for the last season (plot level data, punctual).

Land use was classified into 34 and 41 plot-level land uses for site CH and XK, respectively. Minor plot level land use types that were not present in the predetermined list of land use types (i.e. either the 34 and 41 for site CH and XK respectively) were coded as "others". The main fruit trees (cashew, mango, durian and avocado) were recorded separately, while the others were grouped under one land use type ("fruit trees"). The land use type "fallow" was used for plots without crops for both long and short durations between cropping periods, whereas "forages" included all material planted for grazing or livestock feeding using the cut-and-carry system.

2.3. Data analysis

2.3.1. Data processing and transition rate

Punctual data was classified into plot-level characteristics, household-level characteristics and system performance (Table 1) indicators, based on the assessment methodology of smallholder agricultural systems described in Hammond et al. (2017). All analyses were performed in R statistical computing environment (v 3.4.1).

For temporal data, and separately for the dry and wet season, the total number of plots and total area for each land use type were calculated from the field properties registration sheet, using R packages 'reshape2' (Wickham, 2012) and 'dplyr' (Wickham et al., 2015). The resulting bar charts were produced using R package 'ggplot2' (Wickham, 2011). The land use type and the corresponding time dimension of recall data was used to develop a "state-sequence" for each plot, wherein the state corresponds to the land use type, and sequence corresponds to the sequence of land use types, across the recall period for each plot. This state sequence was further used to calculate a transition rate matrix, using the R package 'TraMiner' (Gabadinho et al., 2011), which calculates the rate of probability of transition between all combinations of plot level land use types captured across time, thereby providing a proxy for stability of a specific land use type.

The transition rate between two states s_i and s_j is calculated using the following formula:

$p(sj|si) = \frac{\sum_{t=1}^{L-1} n_{t,t+1}(sj,si)}{\sum_{t=1}^{L-1} n_t(si)}$wherein $p(s_j|s_i)$ is the probability of switching at a given position from state s_i to s_j, L is the maximum observed sequence length, $n_t(s_i)$ is the number of sequences that do not end in t with state s_i at position t, and $n_{t,t+1}(s_i,s_j)$ is the number of sequences with state s_i at position t, and state s_j at position $(t+1)$. Each row in the resulting transition rate matrix provides the transition distribution from the originating state s_i in t, to the states in $(t+1)$, such that each row equals to one, while the diagonal provides an assessment of the stability of each state. The transition rate matrix was visualized using a heatmap produced using R package 'ggplot2' (Wickham, 2011).

2.3.2. Complexity index

To compress historical patterns of land use (i.e. state-sequence), comprised of each crop/crop combination (as a state), and the recall period (as a sequence) into a single metric, a Complexity Index (CI) was calculated for each plot (Gabadinho et al., 2015). This composite measure combines the number of transitions occurring on each plot across multiple land uses (i.e. states), across time (i.e. sequence) with the longitudinal entropy.

CI is calculated using the following equation:

$C(x) = \sqrt{\frac{l_d(x)}{l(x)} \frac{h(x)}{h_{max}}}$wherein C(x) is the complexity index (CI) of a given plot ×, h_{max} is the theoretical maximum value of the entropy given the state i.e. h_{max} = log (a). The entropy is a measure of the diversity of states at site level at a given position in the sequence.

A CI score of 0 is reached by a sequence with a single distinct state; i.e. with no transition and an entropy of 0, meaning a constant land use type between 2007 and 2016 for the present study. CI reaches a maximum of 1 only if the sequence x is such that i) x contains each of the states of the total states, ii) the same time $\ell(x)/a$ is spent in each state, wherein a is the size of each state and iii) the number of transitions is $\ell(x) - 1$. This is the case when there has been a different plot level land use type every season during the recall period.

2.3.3. Linkages between CI, performance, plot and household level characteristics, and assessment of within-site variation

The linkages between CI, performance, and plot- and household-level characteristics were explored through logistic regression for site CH and a generalized additive model for site XK. The analyses were performed separately for each of the sites, as they were distinct in terms of land use, biophysical conditions and topography, and different drivers of land use change were expected at each site. For the regression with household characteristics and performance variables, CI was averaged across all plots for each household, and this averaged value (agg-CI) was used as a response variable instead of CI.

For site CH, the distribution of CI and agg-CI showed extreme left-skew, and was converted into a binomial response variable, with all CI and agg-CI values equal to 0 in one group (n = 115 plots, n = 24 households) and all scores above 0 (n = 82 plots, n = 43 households) placed in another group. Summary statistics, particularly counts of unique occurrences of variable combinations across both groups (i.e. transition and no-transition outcomes), were performed using R package 'dplyr'. Logistic regression analysis was performed to identify variables that significantly influence CI and agg-CI. A stepwise (forward and backward) model building strategy was employed, using a 'full model' containing all explanatory variables and the response variable, and a 'null model' containing only the intercept and the response variable. The Akaike Information Criterion (AIC) was used for model selection. The selected model was further assessed for fit by performing a comparative Analysis of Variance test (ANOVA) on the residuals of the selected, the full and the null model. Pseudo-R squared values are most commonly used to assess fit of logistic regression models (Hu et al., 2006; Marmolejo-Ramos et al., 2020). In this case multiple pseudo-R squared indices (Cox and Snell and Nagelkerke index) were calculated for both the "full" and the "selected" model, using the LogregR2 function in package descr in R statistical environment (Aquino, 2018). Only those models that displayed significantly higher pseudo-R squared values across both the indices, in comparison to the "full" model were selected and described. To confirm the model selection results, a single term deletion analysis was performed to quantify the impact of the presence or absence of each variable used in the model selection on the AIC score of the model, using Chi-square tests. Additionally, diagnostic checks of the residuals, such as QQ plots of the residuals and the fit of residuals against the fitted values, of the selected model were performed. The coefficients of the selected model were exponentiated to obtain the odds ratio.

For site XK, summary statistics (i.e. mean and standard deviation) of CI and agg-CI disaggregated by plot-level, household-level, or performance-based characteristics were calculated using R package 'dplyr'. For characteristics that were continuous in nature, the Pearson correlation coefficient was calculated between agg-CI and each characteristic. All variables, including agg-CI, were log-transformed to compute the Pearson correlation coefficient. In order to model the relationship between plot-level, household-level and performance-based characteristics with CI and agg-CI for site XK, generalized additive regression modelling was performed using the GAMLSS package in R. The GAMLSS framework addresses the skewed distribution of the response variable (i.e. CI and agg-CI), enables modelling of response variables that do not belong to an existing set of exponential families, and allows for modelling of multiple parameters (i.e. location, shape and scale) of the response variable distribution (Stasinopoulos and Rigby, 2008). Selection of an appropriate distribution function of the response variable was obtained by fitting multiple continuous distributions defined on the real line, using the 'fitDist' function in GAMLSS, and the distribution that obtained the lowest Global Akaike Information Criterion score (GAIC), was used for subsequent analysis. This analysis showed that for both CI and agg-CI, sin-arcsinh distribution had the lowest GAIC score, and hence provided the best fit, in comparison to all continuous distribution families tested. The 'histDist' function was used to develop histograms that overlay sin-arcsinh distribution over the distribution of either CI or agg-CI (Supplementary materials, SM 1). Model selection followed the same steps as for the CH site. Models with interactions between explanatory variables did not converge and resulted in a poor fit compared to models with no interactions, hence interactions were not included. Additionally, Cragg-Uhler and Cox-Snell pseudo-R squared values were derived for the selected model and were compared with the same values derived from the full model. Models that either had higher pseudo-R-squared values or had similar values but with fewer explanatory variables in comparison to the full model, were selected and described. The pseudo R-squared values for the GAMLSS models were calculated using the Rsq function in GAMLSS package in R (Rigby and Stasinopoulos, 2005). Multicollinearity among explanatory variables in the final model was checked, and variables with a variance inflation factor (VIF) lower than 2 were selected in the final model. Selected models were subjected to additional diagnostics based on the residual distribution, and only those models whose mean and coefficient of skewness were closest to 0, a variance closest to 1, and a coefficient of kurtosis closest to 3 were selected and described in detail. Model diagnostics based on residual distribution for the selected models (for plot-level, household-level and performance-based variables) are presented in the supplementary materials (SM 2). Model outputs were visualized using the package 'ggplot2′ in R (Wickham, 2011), and presented using the package 'stargazer' (Hlavac, 2014). Site CH included six villages, and five villages constitute Site XK. To assess if CI and agg-CI differed between villages in each site, a Pearson's chi-square test was performed in the case of site CH, and the Kruskal-Wallis rank sum test (the non-parametric equivalent to ANOVA) was performed in the case of site XK, with CI and agg-CI as the response variable and the village as the explanatory variable.

2.3.4. Spatial data analysis

To complement Pearson's chi-square test and Kruskal-Wallis rank sum test, an assessment of spatial relationships between plots with differing CI values was performed. A spatial point pattern analysis identified differences in distances between plots that belonged to specific CI categories. For site CH, similarly to the regression analysis, plots with CI equal to 0 were grouped into one category, while those above 0 were grouped into another. For site XK, plots were categorized into groups by subjecting CI values to the Jenks natural breaks classification method (Rabosky et al., 2014). The optimal number of breaks was identified based on a goodness-of-fit measure using the 'GmAMisc' package in R (Alberti 2020). The highest goodness-of-fit score was obtained by using three breaks. Based on these results, plots in site XK with CI between 0 and 0.3 were categorized into Group 1, while Group 2 consisted of plots with CI between 0.3 and 0.6, and Group 3 consisted of plots with CI above 0.6. Centroids were extracted from each plot polygon using ArcMap 10.7 and the ESRI default satellite base layer. The CI values were added to the centroids based on the common plot identification numbers, using the 'join' function. The point shapefile was exported and the attribute table was saved in spreadsheets format for further analysis. Subsequently, pairwise distance (in km) between the centroids was calculated separately for each category of plots (i.e. two categories for site CH, and three for site XK) using the 'gDistance' function in R package 'rgeos' (Bivand and Rundel, 2020), and was then used to calculate the mean distance between each plot and all other plots belonging to the same category. The mean distance measure was used to produce density-based histograms for each category of plots, for sites CH and XK using the R package 'ggplot2'.

3. Results

3.1. System performance and characteristics

In both sites, most households reported no off-farm employment and relatively similar cultivated areas and crop diversity (Table 2), but the two sites differed in several other key characteristics. Compared to site XK, households in site CH had more plots per household (averaging 74% higher), more migrants, and higher education levels of household heads. They reported higher nitrogen fertilizer use, higher levels of soil tillage, and higher prevalence of pump-based irrigation systems despite 52% of the plots being located on flatlands. A greater proportion of CH farmers bought seeds, and production was market-oriented. CH households indicated a higher average Progress out of Poverty Index (PPI) and total mean food availability score than XK households, which had higher modal values for livestock diversity, higher household sizes and higher food self-sufficiency scores.

Table 2
Farming system characteristics in the Central Highlands of Vietnam (Site CH) and in Xieng Khouang province in Laos (Site XK).

Class	Variable name	Unit	CH Mean ± SD or %[1]	XK Mean ± SD or %[1]
Household level [2]	Ethnic group - Minority	n.a.	10	74
	Origin - Migrated	yes or no	91	16
	Off-farm employment - Yes	yes or no	29	42
	Labor - No contracted labour	n.a.	38	68
	Household size	AME[3]	3.30 ± 1.23	5.04 ± 2.5
	Education - Post secondary	n.a.	21	2
	Land cultivated	ha	2.40 ± 1.78	2.25 ± 1.52
	Fertilization	kg N. $year^{-1}$	93.0 ± 74.5	0.09 ± 0.80
	Crop diversity	n.a.	4.4 ± 1.5	4.3 ± 1.8
	Livestock diversity	n.a.	2.1 ± 1.1	3.1 ± 1.4
	Number of plots	n.a.	2.5 ± 1.5	1.78 ± 0.5
Plot level [4]	Soil tillage - Yes	yes or no	87	50
	Agrochemical inputs - No chemicals	n.a.	0	86
	Property - Owned	n.a.	99	89
	Irrigation - Pump	n.a.	74	0
	Slope - Flat	n.a.	52	22
	Source of planting material - Bought	n.a.	89	18
	Final use - Sale	n.a.	83	12
Performance [2]	Progress out of Poverty	n.a.	70.4 ± 18.8	55.16 ± 12.13
	Total income	USD. $year^{-1}$	15,843 ± 84,038	8,980 ± 67,094
	Food availability	kcal. AME[1]. $year^{-1}$	159,975 ± 739,967	44,421 ± 271,645
	Food Self-sufficiency	kcal. AME[1]. day^{-1}	4,179 ± 5,286	5,736 ± 6,075
	Food insecurity (HFIAS)	n.a.	5.14 ± 4.46	2.25 ± 3.51
	Total Energy Available	MJ	892,847 ± 4,641,712	366,276 ± 2,449,482

[1] Mean ± SD for quantitative variables; % of occurrence for the most striking of the categories for categorical variables.
[2] n = 68 for site CH, n = 76 for site XK.
[3] Adult Male Equivalent (adult = 1; child = 0.5).
[4] n = 211 for site CH, n = 153 for site XK.

3.2. Land use changes and transition rate

3.2.1. Site CH

Thirty-four different plot level land use types were identified in site CH over the recall period. Fig. 1 (A-E) shows the temporal changes in land size for the top five land use types, in terms of total area occupied in the dry season of 2016. Since 2007, the land area dedicated to mixed cropping systems increased, with cashew-coffee land use constituting 2% of the total surveyed area in 2007, and 9% in 2016 (Fig. 1A). However, when planted as monocultures, cashew and coffee declined by 7% and 10%, respectively, after 2007 (Fig. 1B and 1C). Although not a major crop in terms of total area for the dry season of 2016, pepper, as a monoculture system, increased from 1% to 6% of the total surveyed area between 2007 and 2016. The increase of pepper in mixed cropping systems has been comparatively higher, from 3% to 16% of total surveyed area between 2007 and 2016. Monoculture plots of annual crops showed a slight increase: from 21% to 26% of the total surveyed area in the case of sugarcane (Fig. 1E), and from 2% to 7% in the case of cassava (Fig. 1D). Maize production area decreased in both monoculture (8%) and mixed cropping systems (12%). Similarly, fallow-based plot level land use decreased by 3%, as a proportion of total area surveyed, between 2007 and 2016.

Average plot size varied significantly between plot level land use types but were relatively consistent across the recall period. Rice as an annual monocrop was associated with smaller plots (approximately 0.2 ha), while sugarcane, as an annual monocrop, was associated with larger plots (approximately 1.8 ha). Tree-based perennial plot level land use types such as cashew, coffee and their respective combinations in mixed cropping systems were associated with plots with an average size of 0.6 ha.

All plots surveyed without agricultural use in 2007 were replaced by cashew-based land use (Fig. 2A). Likewise, all plots with forages progressively shifted towards fruit trees. Transition rates of 100% were also observed from cassava-maize to rice-cassava. The inclusion of pepper in diverse tree-based land uses (plots including cashew, coffee and avocado) was observed in 50% of the cases, while coffee-based systems (intercropping with cashew, pepper or both) were stable. Cashew was replaced by rubber in a few instances, while 5% of plots returned to fallow land from cassava-maize.

3.2.2. Site XK

In site XK, 41 different land use types were captured over the recall period. Fallow land remained relatively constant, contributing approximately 60% of the total surveyed cropping area in the dry seasons (Fig. 1F). During the wet seasons, the area under fallow was minimal, as many plots were used for rice or maize. Rice area constituted an average of 34% of the total surveyed area between 2007 and 2016, and maize areas increased from 15% in the wet season of 2007 to 21% in the wet season of 2016. Interestingly, the area under fallow in the wet seasons decreased by 15% between 2007 and 2016. A small proportion of these fallow areas were improved with planted forages, particularly from 2011 with an increase of 3% (Fig. 1G). At the same time, forage plots indicated a considerable increase in area during the wet seasons, from 3% proportional contribution to total surveyed cropping area in the 2007 wet season, to 9% in the 2016 wet season (Fig. 1H). Tea emerged in 2008, and showed a strong increase in total proportional contribution to the surveyed cropping area, contributing to 10% of the total surveyed cropping area in 2016 (Fig. 1I). The contribution of cassava as a monocrop increased similarly by 3% between 2007 and 2016 (Fig. 1J), similar to site CH.

Compared to site CH, less variation in average plot size was observed between the major plot-level land use types in the dry season of 2016,

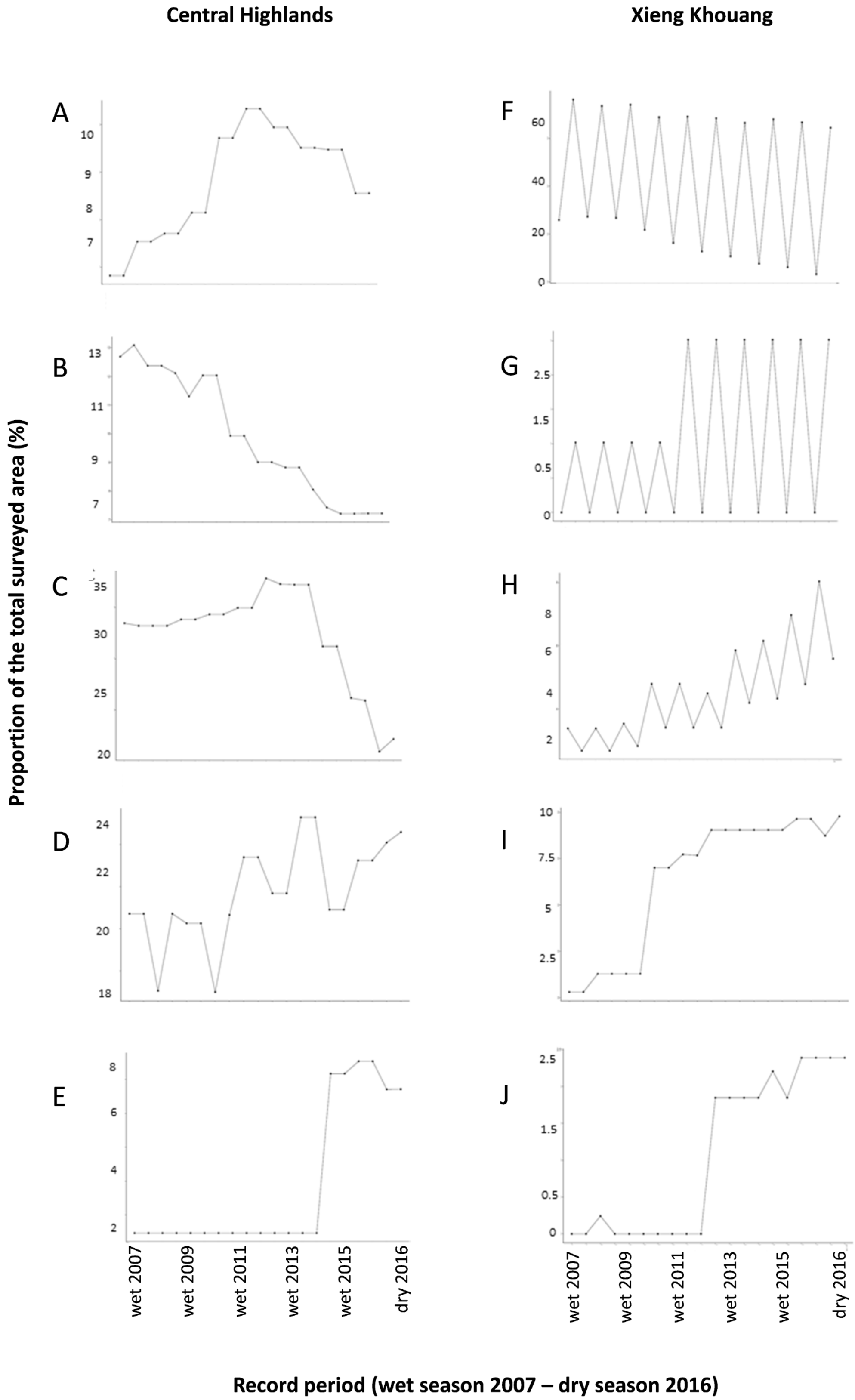

Fig. 1. Temporal changes for the top five land use types in the last season recorded by the survey (dry season of 2016), i.e. (A) Cashew-Coffee, (B) Cashew, (C) Coffee, (D) Sugarcane, (E) Cassava in Central Highlands (Site CH), and (F) Fallow, (G) Forages-Fallow, (H) Forages, (I) Tea, (J) Cassava in Xieng Khouang (Site XK), in proportion of crop area (in %) in relation to total surveyed area, across successive dry and wet seasons for the recall period (from 2007 to 2016).

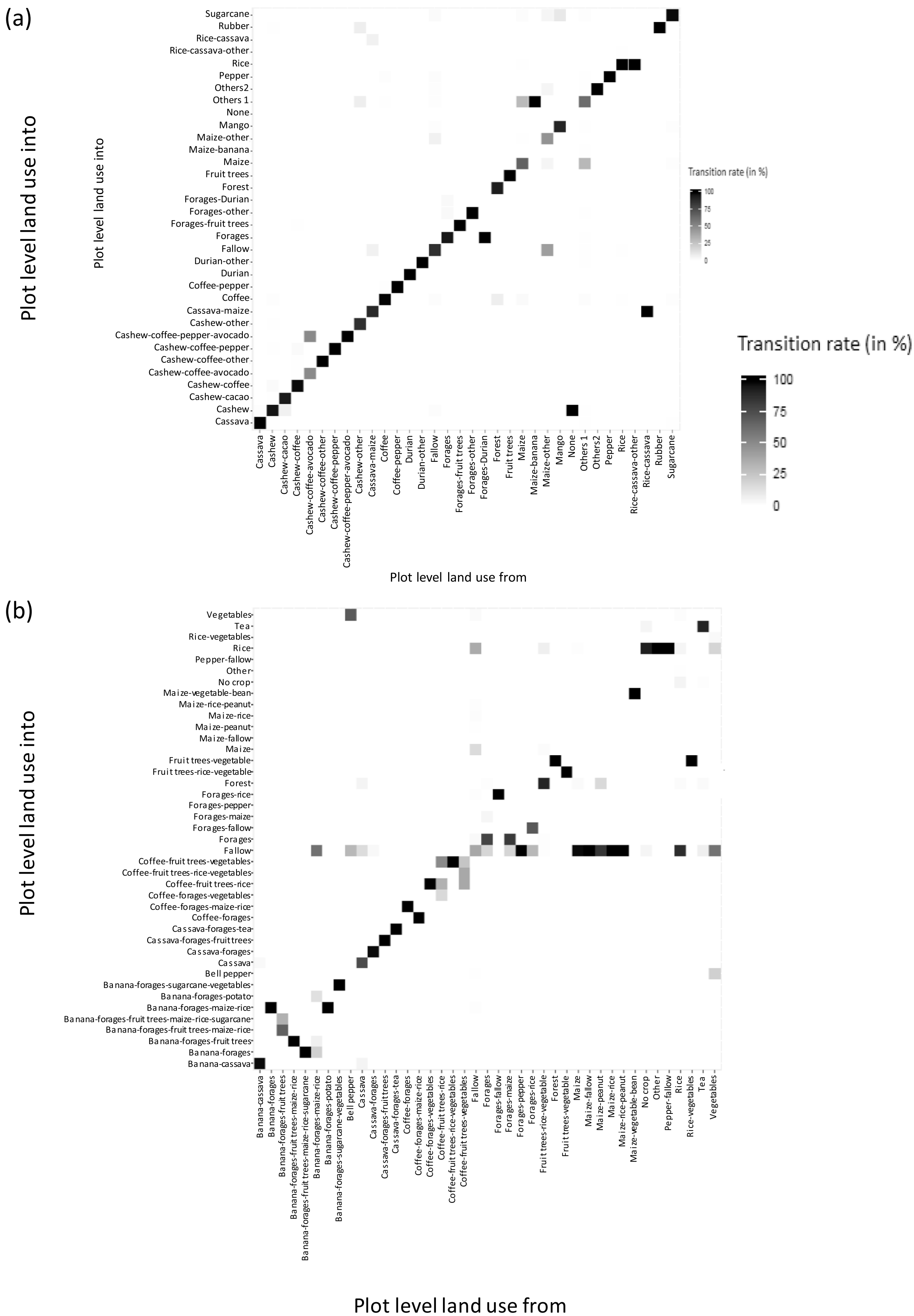

Fig. 2. Transition rate (in %) between plot level land use types from 2007 to 2016 in (a) the Central Highlands of Vietnam (site CH), and (b) Xieng Khouang province in Laos (site XK). Minor plot level land use types that were not present in the predetermined list of land use types (i.e. either the 34 and 41 for site CH and XK, respectively) were coded as Other_1, while plot level land use types that were intercropped with Other_1, and were not in the predetermined list of land use types were coded as Other_2.

and across the recall period, indicating consistently diverse land use types in site XK. Seasonality, however, was evident, specifically with land use types such as forage-fallow.

Land use transition was much more dynamic in site XK compared to site CH (Fig. 2B). High transition rates to fallow were observed, with 90% from maize plots, 80% from maize-peanut plots, and 70% from rice plots, highlighting seasonal rotations. Most of the remaining maize-peanut plots returned to forage. The remainder of the rice plots were converted to vegetable production or back to forage, while forage is then replaced in 10% of the cases by rice. Maize and rice, also intercropped with banana and forages, disappeared from the rotation in 5% to 20% of the cases and were replaced by potato or fruit trees. Upland rice also disappeared progressively from home gardens, as 80% of the fruit-rice-vegetables land was converted into fruit-vegetable plots. Likewise, 80% of the pepper plots were replaced by vegetable production. Few cassava plots transitioned into forest, fallow, or cassava-banana intercropping.

3.3. Complexity index

In site CH, both CI and agg-CI display a left-skewed distribution pattern, with several plots (n = 115) and households (n = 24) showing a CI of 0 (Fig. 3A). In site XK, 46% of the plots and 44% of the households score between 0.4 and 0.5 (Fig. 3B). The highest CI are 0.51 (Fig. 3A) and 0.65 (Fig. 3B) for site CH and site XK, respectively. The highest agg-CI scores are 0.47 and 0.65 in site CH (Fig. 3A) and site XK (Fig. 3B), respectively. Pearson chi-square test results for site CH, and Kruskal-Wallis rank sum test for site XK show that although each site consists of several villages, inter-village differences in CI and agg-CI are insignificant.

At site CH, most of the plots were tilled, whether showing transition (88%) or not (90%; supplementary materials, SM 3). Topography was also similar between transitioning and non-transition plots, with 45% and 55% of land area, respectively, consisting of flat lands, and 15% and 12% of land area, respectively, consisting of steep slopes. However, the final use of agricultural production differed, with 20% of the non-transitioning plots and only 5% of the transitioning plots designated for home consumption.

Ninety one percent of the transitioning households were from the Kinh ethnic majority group, which does not originate from the Central Highlands, whereas 17% of non-transitioning households identified as ethnic minorities (SM 4A). Most household heads had a secondary and post-secondary level of education, both for transitioning (77%) and non-transitioning (83%) households. Household size and total number of plots per household were higher on average for transitioning households (SM 4B). However, household welfare appeared higher for non-transitioning households, as indicated by better food availability, income, and Progress out of Poverty scores (SM 5).

At site XK, transitioning plots were tilled more, were flatter, and were managed using higher levels of fertilizers and irrigation than non-transitioning plots (SM 6). These plots were also more often rented than collectively owned or owned by the household. Households from the Lao ethnic majority, as well as households with post-secondary education (SM 7A), tended to transition more than households from the Hmong minority. A relatively strong positive relationship was observed between land use complexity and crop and livestock diversity, while a negative relationship was observed with the total number of fields, household

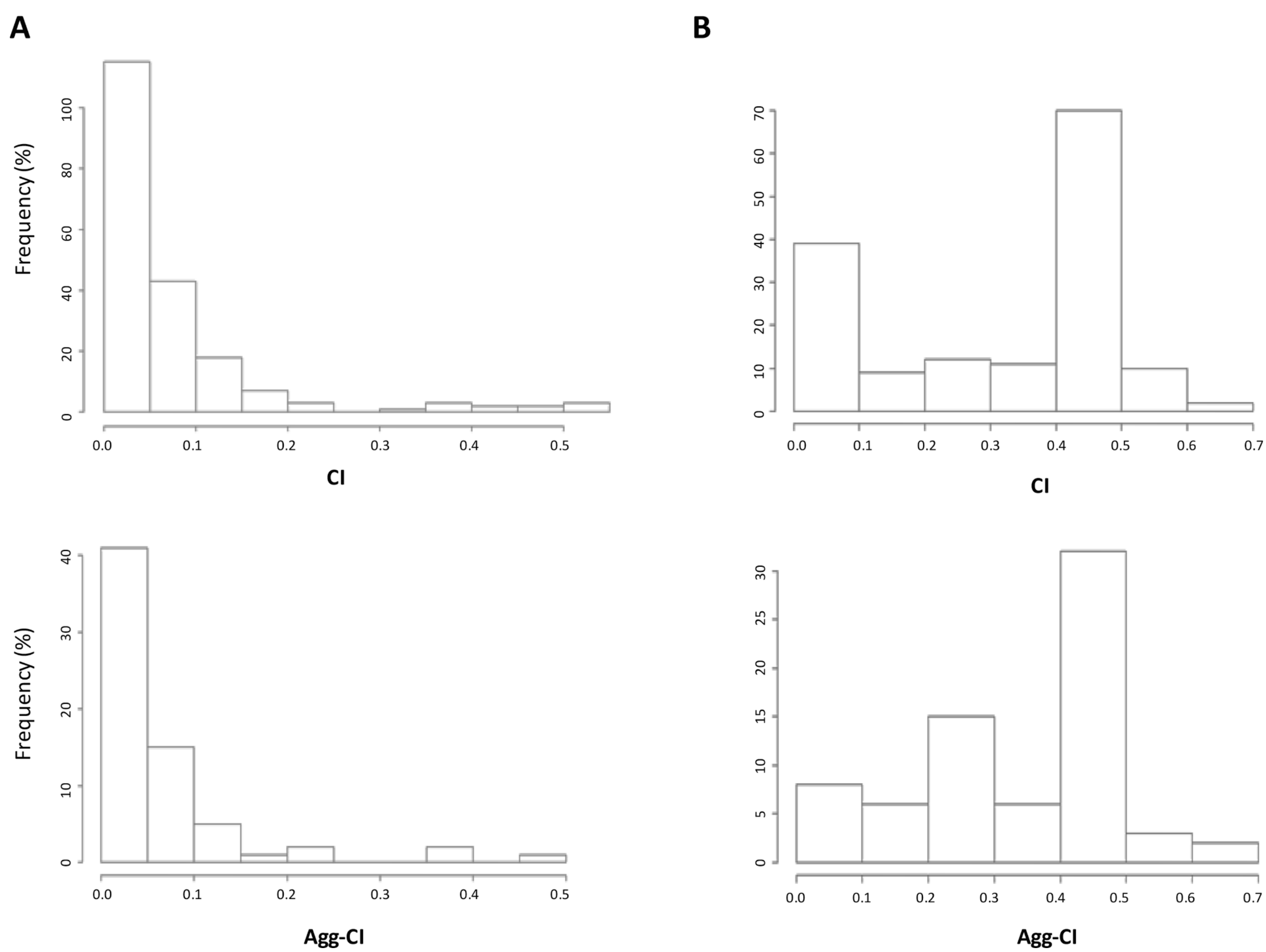

Fig. 3. Distribution of the complexity index per plot (CI) and the aggregated complexity index per household (agg-CI) for (A) Central Highlands, Vietnam, and (B) Xieng Khouang, Laos.

Table 3
Model selected for the logistic regression between complexity index (CI) and plot level variables, and between aggregated complexity index (agg-CI) and household level and performance in the Central Highlands of Vietnam (Site CH).

Response variable[1]	Explanatory variables	Estimate	Standard Error	t-value	Odds ratio	2.5% CI	97.5% CI	p-value	Pseudo R^2	
									Cox and Snell	Nagelkerke/Cragg-Uhler
CI ($n = 197$)	**Plot level variables**								0.071	0.095, p-value < 0.05
	Final use for sale	1.58	0.5631	2.813	4.87	1.78	17.15	<0.05		
agg-CI ($n = 67$)	**Household level variables**								0.206	0.285, p-value < 0.05
	Number of fields	0.69	1.18	−2.47	0.05	0.03	0.45	<0.05		
	Household size	0.64	0.33	1.91	1.89	1.04	3.96	<0.1		
	Performance variables								0.064	0.088, p-value < 0.05
	Food availability	−6.5	3.34	−1.94	0.001	1.16E-06	0.72	0.05		

[1] Within-site variation was not significant (Pearson's chi-squared test p-value < 0.0001 for both CI and agg-CI).

size, and total area cultivated (SM 7B). In terms of performance, a positive relationship was observed between land use complexity and the Progress out of Poverty index, food availability and total energy available (SM 8).

3.4. Relationship between CI and plot-level characteristics

The best-fit model for site CH, based on both stepwise variable selection and single term deletion analysis, revealed that only production for the market was associated with CI (Table 3; SM 9). More plots dedicated for home consumption did not transition. This was different for plots dedicated to market production, with 92 plots showing no transition and 78 exhibiting transition. The odds ratio calculation revealed that a plot dedicated for market production was four times more likely to display transition than a plot dedicated to home consumption.

In site XK, the best-fit model revealed that CI was significantly associated with degree of tillage, irrigation use, agro-chemical use, planting material and slope (Table 4). Plots on flat land or gentle slopes that were managed with tillage and irrigation systems had higher CI scores compared to rainfed plots on steep slopes that are not tilled. Fertilized plots had significantly higher CI scores compared to untreated plots or plots receiving pesticides only. Finally, relatively lower CI scores were observed for plots growing planting material that was obtained through subsidies, in comparison to plots with owned or gifted planting material.

3.5. Relationship between agg-CI and household-level characteristics

At site CH, both the stepwise variable selection approach and single term deletion analysis showed that agg-CI was significantly associated with the total number of plots owned by the household (Table 3, SM 10). Odds ratio analysis revealed that households with more plots and with a larger household size were twice as likely to show transition. While the stepwise variable selection approach showed a trend in the relationship between household size and agg-CI, single term deletion analysis revealed significant association between the two, wherein households with higher male adult equivalence have higher mean agg-CI values (Table 3, SM 10). The converse was true at site XK where the relationship between agg-CI and the number of plots owned was negative (Table 4).

3.6. Relationship between agg-CI and system performance

Models fitted with both stepwise variable selection and single term deletion analysis revealed that only food availability had a significant impact on agg-CI in site CH (Table 3, SM 11). Households with higher food availability are half as likely to show transition, compared to receiving an agg-CI score equal to 0 (Table 3). Households with higher food availability are also less market-oriented. The selected model for site XK showed contrasting characteristics: agg-CI was not associated with food availability and a significant positive relationship between agg-CI and the Progress out of Poverty index was apparent (Table 4).

3.7. Spatial distribution of CI

Satellite views of the two sites show contrasting features, with a rather flat topography and crowded land use in site CH, and a hilly landscape with still large forest patches in site XK (Fig. 4). In both districts of site CH, around 40% of the plots showed transition (43% in Dak Lak and 37% in Dak Nong). Their spatial distribution does not seem to follow any pattern. In site XK, the majority of plots have a low (40%) or medium (59% plots) complexity with only 1% of the plots falling in the high complexity category. Low complexity plots tend to be more on forested hill slopes and slightly more remote areas, while medium complexity plots prevail in the valley lowland area, especially for the

Table 4
Model selected for the generalized additive regression between complexity index (CI) and plot level variables, and between aggregated complexity index (agg-CI) and household level and performance in the Xieng Khouang province of Laos (Site XK).

Response variable[1]	Explanatory variables	Estimate	Standard Error	t-value	p-value	Pseudo R^2	
						Cox and Snell	Nagelkerke/Cragg-Uhler
CI *(n = 153)*	**Plot level variables**					−42.58	0.001
	Soil tillage_Yes	3.40E-01	6.10E-06	55209.62	<0.05		
	Input agrochemicals_No	3.20E-05	5.20E-06	6.13	<0.05		
	Input agrochemicals_Pesticides	−9.20E-03	1.20E-05	−755.41	<0.05		
	Irrigation_rainfed	8.40E-05	4.00E-06	20.68	<0.05		
	Slope_Modest	−1.00E-04	3.30E-06	−31.84	<0.05		
	Slope_Strong	−8.70E-03	8.10E-06	−1085.33	<0.05		
	Planting material_combination	1.50E-04	7.40E-06	20.54	<0.05		
	Planting material_exchange	−8.40E-02	1.30E-05	−6328.11	<0.05		
	Planting_material_Gift	4.00E-01	1.30E-05	29774.98	<0.05		
	Planting material_own	1.10E-04	6.90E-06	15.32	<0.05		
	Planting material_subsidized	−4.30E-01	1.20E-05	−35408.85	<0.05		
	Transport_Motorbike	5.94E-02	1.79E-05	3325.473	<0.05		
	Transport_Tractor	8.45E-02	1.26E-05	6720.49	<0.05		
	Transport_Walking	8.44E-02	1.21E-05	6989.305	<0.05		
agg-CI *(n = 72)*							
	Household level variables					38.36	0.31
	Number of fields	−0.08	0.04	−2.08	<0.05		
	Crop Diversity	0.01	0.01	1.35	0.17		
	Performance variables					−37.47	0.3
	Progress out of Poverty Index	0.46	0.03	12.34	<0.05		
	Farm income	0.02	0.01	2.62	0.2		
	Food availability	−0.01	0.02	1.27	0.55		
	Food self-sufficiency	−0.01	0.01	−0.59	0.87		
	Total energy available	0.01	0.03	−0.16	0.6		

[1] Within-site variation was not significant (Kruskal-Wallis rank sum test p-value < 0.001 for both CI and agg-CI).

third group.

Spatial point analysis revealed opposing patterns between the two sites (Fig. 5). In site CH, non-transitioning plots were homogenously distributed with a mean pairwise distance of 0.4 km, while transitioning plots had a relatively larger spatial spread around two groups of similar size, peaking at 0.36 km and 0.45 km. The pattern was more complex in site XK, with heterogenous plot distribution for the three categories. Low- and medium-complexity plots (i.e. plots with $0 \leq CI \leq 0.3$ or $0.3 \leq CI \leq 0.6$) had a more heterogeneous spatial distribution than high-complexity plots (i.e. $0.6 \leq CI$). They were distributed in two groups, one important and compact group with mean average pairwise distances of<0.2 km, and one smaller group, more sparsely distributed, with mean pairwise distance of more than 0.8 km. The high complexity plots had mean pairwise distances of 0.4 and 0.7 km. Therefore, while low-CI plots are homogenously distributed in site CH, they show heterogenous distribution in site XK.

4. Discussion

4.1. Evaluation of CI as a metric for land use complexity

The application of sequence data analysis to agriculture proved to be an efficient and useful method to compress and quantify land use complexity. This compression results into a single metric, based on the number of transitions occurring on a single plot over time and the longitudinal entropy. Although, in consequence, the transformation impedes the study of spatial–temporal land use patterns, it allows making linkages with indicators that are typically not captured over time. CI calculation is simple, with a low level of parameter uncertainty, and can be applied at a variety of levels. Indeed, the level of definition of transition depends on the user: for example, if the inclusion of hedgerows in a field qualifies for a new land use type, the resulting CI will be very different than if these types of land use are considered equal. This makes CI very flexible in its use and able to capture a wide variety of transition types, but also might restrict its potential for *meta*-analysis if the level of definition varies significantly between studies. When CI is mapped, it highlights trends at the landscape level. Similarly to the definition of land use, the size of the unit of observation will influence the type and scale of the drivers of change observed. Compared to land use changes observed based on satellite data (Huang et al., 2019; Yang et al., 2020), the level of definition is much more precise, and more appropriate to capture crop sequences and seasonal changes. Developing context-specific CI thresholds associated with system quality indicators would be useful as ecological engineering control to inform decision makers on the pace of agricultural transformation and its environmental impacts.

The disadvantage is that CI integrates seasonal information without consideration for the novelty of the crops: rice-fallow rotations are treated equivalently to switching from one crop to a completely new one (from coffee to sugarcane, for example). This has no consequence on the complexity of the system, but care must be taken in not translating this complexity as a measure of diversity, which is best considered by looking at Fig. 2.

CI reflects crop transition at the plot level and agg-CI is useful to evaluate transition at the household level. In this study, performance indicators and household characteristics are defined at one point in time (2017) whereas agg-CI is the aggregate result of 10 years. This assumes that there has been no major alteration in the households and that the present situation comprehensively summarises all happenings on the farm during the last ten years. This was deemed to be a reasonable assumption for the purposes of this study. Future studies could bring more time variant perspective into household and plot level characteristics if some form of agricultural census data is available, but it would be difficult to do so on a recall base, as farmers might have difficulties remembering some of this information precisely for remote years. Still, some form of aggregation would need to take place for a regression with CI. The use of plot level and agg-CI in this context although is unique, and the models obtained are parsimonious and provide a significantly better fit than the full model. Regression analysis suggests that, in order to obtain robust results, there is a need to calculate CI scores from a larger set of households and their plots, to obtain significantly higher

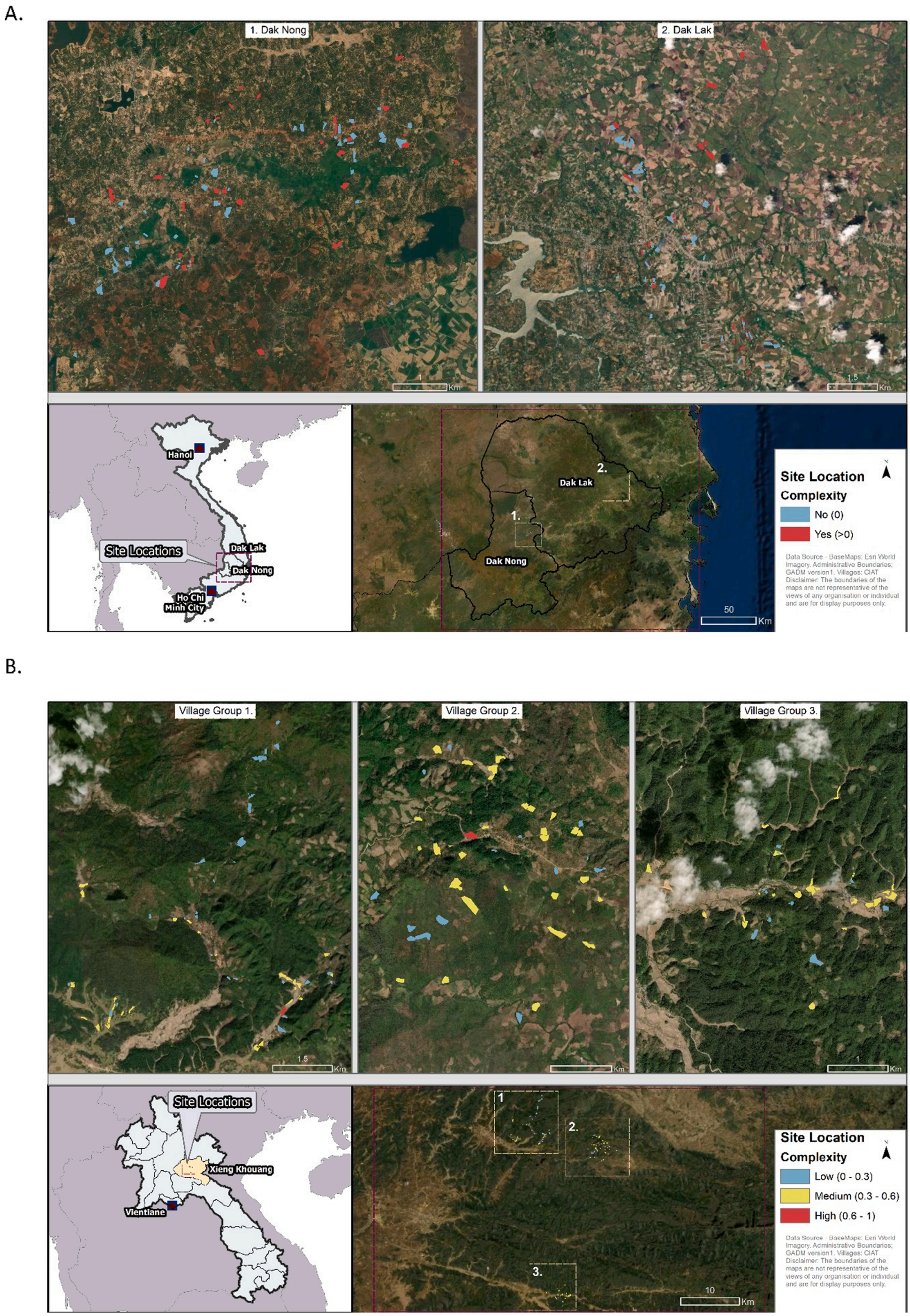

Fig. 4. Spatial distribution of the complexity index (CI) in (A) the Central Highlands, Vietnam, and (B) Xieng Khouang, Laos.

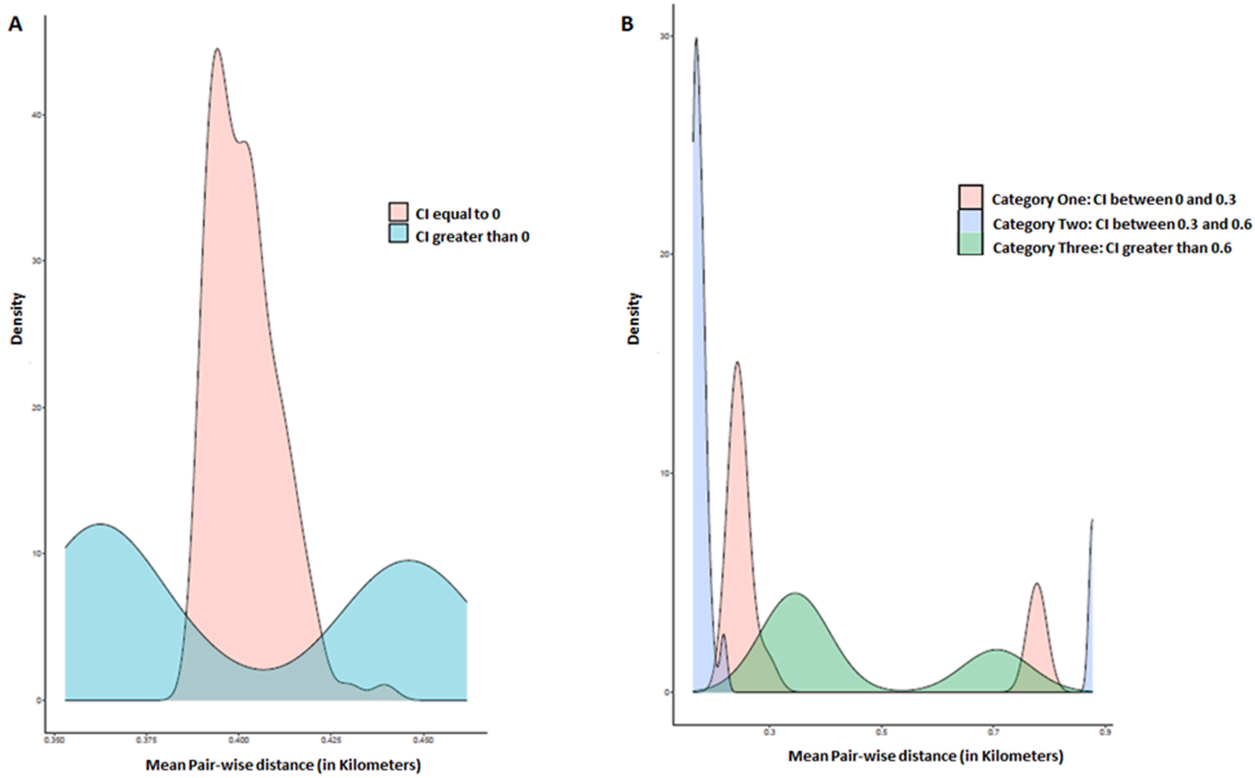

Fig. 5. Density histograms of the mean pairwise distance between plots for different complexity index (CI) categories in (A) the Central Highlands, Vietnam, and (B) Xieng Khouang, Laos. The categories were produced for each site by subjecting CI to Jenks natural break classification method.

resolution between households, plots and their locations based on the derived CI scores.

4.2. Land use complexity and drivers of change

Land use complexity in sites XK and CH contrast starkly. While site XK shows a much more dynamic, heterogeneous and complex land use pattern, site CH has an established and developed landscape. Indeed, as displayed in Fig. 2, only 15% of land uses show significant changes in site CH, while high transition rates from one land use type into another are more frequent in site XK, with 66% of the land use types being completely replaced by others during the recall period. Site CH presents a core area under stable tree and shrub cultivation with only small changes in composition, such as the inclusion of cashew plants in coffee plantations. Intensive production systems are not yet a reality for XK farmers, who rely exclusively on rainwater for irrigation. Thus, the typical cropping system in XK follows clear biannual patterns of paddy and maize-based land use in the rainy season to produce for household consumption (Table 2), with some additional dry season crops such as vegetables and forages, but at a much smaller scale. Since no farm households in our XK sample have water pumps, dry season production area is limited to 40% of the total area. Thus, most of the observed intensification is constrained to the wet season, accompanied by a decrease in rainy season fallow area of 15% over the past 10 years.

Results reveal that the most prevalent dry season crop is improved forage production (Fig. 1H), highlighting the importance of integrated crop-livestock systems for site XK. Other crops which showed increased uptake by farmers are cassava, maize and peanuts, which are all known to be relatively suitable in dry conditions. The agronomic challenges of these changing systems are readily apparent in this analysis, as all significant plot-level explanatory variables concern agronomy (Table 4). Factors associated with reduced land use complexity in XK are the degree of sloping topography, pesticide use, and planting material from sources beyond farmers' control (subsidies or exchanges).

In contrast, at site CH, the only plot-level explanatory variable for land use change is market orientation (Table 3, "final use for sale"). A plot dedicated for home consumption is four times less likely to show transition than a plot dedicated to market crops, suggesting that CH farm households adapt quickly to local market conditions. For example, pepper production has increased mainly within existing land use types via progressive inclusion in coffee and cashew plantations, reflecting Vietnam's place as one of the world's leading exporters of pepper. However, the land use changes were not reflected in dietary changes: the crops designated to household consumption stayed the same (Ritzema et al., 2019). In CH, the binding constraints to changing systems are the number of plots in the household and availability of family labor (Table 3). Thus, if labor and plots are abundant, households can allocate these resources to on-farm experimentation of new mixed crop-tree systems.

Households with higher food availability are also those that are less market-oriented: cash crops result in less food energy than staple crops such as tea, pepper and vegetables. These households tend to avoid experimentation and do not follow market trends, as seen in Table 3, where households with higher food availability typically do not implement complex land use sequences. Those who have low food availability, i.e. households that do not manage to obtain much food energy from both on-farm activities and purchased items, also have more incentive to adapt and innovate, especially in a market-driven environment. Households characterized by high complexity were in most cases from the Kinh ethnic majority, which has better access to markets and education.

In XK, poverty is much higher, with close to half of the households situated below the national poverty line, compared to only 30% in CH (Table 2). Poor farmers must allocate resources carefully, illustrated by substantial differences in plot management and experimentation. Indeed, households showing better Progress out of Poverty index values had more complex land use patterns (Table 4). The transition rate was also strongly affected by seasonal changes via the staple crop: rice.

Farmers seek first to secure their consumption with more intensive management strategies such as irrigation and labor-intensive paddy production, while other secondary crops bolster self-sufficiency. Rice production is also a primary focus for government subsidies and support in most Southeast Asian countries, e.g. substantial investments in Laos in the development of direct rice seed planting (Xangsayasane, 2018; Laiprakobsup, 2019). In parallel, we see that land area devoted to low-input, low-risk cash crops such as wild tea or forages have been increasing in the area, consistent with other studies that note the risk-averse perspective of Lao farm households (Sagemuller and Musshof, 2020).

Topography is a key driver of complexity in site XK. Tillage, irrigation, and flat lands are characteristics of the lowlands and were associated with high transition rates (Table 4), a finding further supported by CI spatial distribution (Fig. 4). Transitioning households are mainly from the lowlands-based Lao ethnic majority while the Hmong minority occupies the highlands. In the relatively flat plateau of site CH, topography is less relevant whereas national policies have greatly influenced land use over the past decades, as lowland people were encouraged to colonize the area and invest in coffee production (Doutriaux et al., 2008). Market prices also incentivize land use change, when farmers are well-informed of price changes through strong market connectivity. However, it is ultimately the farmer's own capacity for change that will determine if a change occurs, and this therefore drives the arising pattern of complexity in land use. Innovation capacity and likelihood to take risks are further factors that should be explored in future studies.

4.3. Agricultural system transformation in Southeast Asia

The historical and political contexts in Laos and Vietnam are very different (Ritzema et al., 2019), and so are the drivers of land use change. In the CH site particularly, falling coffee prices in the last decade have induced smallholders to partially reconvert coffee or pepper farms into more diversified livestock-crop-tree-fish systems (D'Haeze et al., 2005). Intensification in Laos in the last decade is due to other factors, including land use regulations introduced by the government to reduce forest clearings in the uplands to protect natural resources from overly-intensive short-cycle shifting cultivation practices. These regulations, in tandem with recent demographic growth (Bouahom et al., 2004), placed increased pressure on available land for cultivation (Lestrelin and Giordano, 2007; Lestrelin, 2010). Site XK is also relatively isolated in comparison to other areas of Laos, with less access to markets and education than the lowlands. Indeed, while the Lao lowlands are further along the 'transition gradient' towards market-oriented and intensive farming, the uplands are still in an early stage of transition and face numerous structural constraints, such as low access to high-quality seeds, insecure land tenure and limited access to advisory services, irrigation, finance and markets (Thongmanivong and Fujita, 2006; Heinimann et al., 2013; Southavilay et al., 2013; Hirota et al., 2014; Castella et al., 2018).

Land use intensity and structural complexity of landscapes are separate landscape level factors, at small spatial scales (Persson et al., 2010). This study identified plots that were used to cultivate a combination of cash crops and subsistence crops, and others that were dedicated entirely to commercial production. Thus, both subsistence, home-oriented and commercial, market-oriented farming systems can coexist within the same farm. Most farms oscillate along a transition pathway (from subsistence to market-oriented) rather than following a linear path towards one end of the spectrum, as the regional narrative suggests. Hence, land use change is not homogenous and irreversible, and it does not follow a consistent progression, in accordance with the findings of Ritzema et al. (2019). These agrarian transitions are not ubiquitous in both northern Laos and in the Central Highlands region of Vietnam. There were indeed several farmers and plots in the study sample that have not yet made the transition from subsistence to cash crop production. In addition, some farmers previously cultivated a combination of both food and cash crops, while others dedicated all plots entirely to commercial production. Therefore, the current landscape of agrarian systems across both these sites, and in general across Southeast Asia, is diverse, and both traditional and intensive farming systems co-exist simultaneously.

At the plot level, transition patterns contrast to those at the household level: this study shows that no transition is expected for home consumption plots in Site CH (Table 3), and only minimal transition for plots on sloping land in site XK (Table 4). Sloping plots generally have poorer soil fertility, and investment in rice terraces is only economically attractive if water is available for irrigation (Castella, 2012). Alternatively, less water-demanding crops like maize and cassava can be used in the uplands, assuming that some soil conservation measures, such as contour farming, are simultaneously implemented (Castella, 2012). But such measures require substantial investment in agricultural extension. Therefore, whenever innovative land use options for sustainable intensification are discussed with farmers, chances for adoption are much higher when the plots under consideration are not allocated to staple crops (unless it complements rather than replaces them) and are not located on steep slopes. Innovative land use options would be successful on slopes only if complemented by appropriate soil and water conservation measures that are acceptable from a capital and labor investment point of view.

Although the transition from extensive to more intensive forms of agriculture seems to have overwhelmingly negative impact for farmers' livelihoods and the environment (Dressler et al., 2017), there may be little choice in view of increasing climate, population and market pressures. Declining farm sizes and increasing wage rates are further constraints for production efficiency and will need to be addressed with strong policies to ensure that agricultural production in Southeast Asia keeps a comparative economic advantage to other regions (Fan and Chan-Kang, 2005; Otsuka et al., 2016). In the long term, it is unclear whether intensification will plateau. In the future, the Lao uplands and the Central Highlands may have similar complexities and land use dynamics, or alternatively might evolve separately.

5. Highlights and conclusions

This study has described plot-level sequence patterns of seasonal variation of land use in two sites of Laos and Vietnam, characterized by contrasting stages of intensification and market orientation, using CI, a sequence dissimilarity metric. CI allowed compressing historical land use data and quantifying land use complexity in a simple and efficient manner.

In Vietnam's Central Highlands, relatively well-educated migrants have increasingly applied intensive agricultural practices in market-oriented intercropped tree-based systems during the 2006–2017 period, accompanied by a decrease in monoculture production and fallow land. These 'highly transitioned' systems result in relatively high income and food availability. In the Xieng Khouang plateau of Laos, self-sufficient farmers are in the initial stages of reducing forest and fallow land to increase their rain-fed low-input staple crop production, with progressive inclusion of vegetable crops and forages as well as several cash crops. Land use dynamics vary strongly between the two sites, with 66% of the land use types in site XK being completely replaced by others during the recall periods, compared to only 15% in site CH. Associated key drivers of change also differed significantly: while end use of the agricultural products is the main driver behind land use changes at site CH, the relationship is more complex at site XK, with changes associated with topography and management. Households with higher food availability in site CH are less likely to show transition, while in site XK, complexity was significantly correlated with the Progress out of Poverty index.

For smallholder farming systems already showing high levels of intensification, innovative land use options have a higher likelihood of adoption when these include market-oriented crops that are not labor-intensive and that do not replace staple crops. For low-input subsistence farming systems, these options should target low risk plots first, ensuring seed availability and avoiding sloping lands and areas where intensive management can be difficult.

Multidisciplinary studies remain necessary to assess the impact of innovative sustainable intensification options on system performance and environmental sustainability, before policies are enacted to support their dissemination in Southeast Asian smallholder agricultural systems. Context-specific CI thresholds associated with system quality indicators could support this by informing decision-makers on the pace of agricultural transformation and its environmental impacts.

CRediT authorship contribution statement

Dharani Dhar Burra: Conceptualization, Indicator Development, Formal analysis, Visualization, Writing (original draft and review). **Louis Parker:** Survey methodology, Data collection, Visualization of spatial data. **Nguyen Thi Than:** Data collection, Data curation. **Phonepaseuth Phengsavanh:** Site coordination in Laos. **Chau Thi Minh Long:** Site coordination in Vietnam. **Randall S. Ritzema:** Secondary data contribution, Writing (review and editing). **Frederik Sagemueller:** Conceptualization. **Sabine Douxchamps:** Conceptualization, Supervision, Project management, Visualization, Writing (original draft, review and editing).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107402.

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