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Household-level drivers of dietary diversity in transitioning agricultural systems: Evidence from the Greater Mekong Subregion

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ABSTRACT

Over the past four decades, agricultural systems in the Greater Mekong Subregion (GMS) have largely evolved from a subsistence orientation toward commercial production, but the multi-faceted changes behind this evolution vary in substance and degree. Despite connoting economic progress, effects of these changes on household welfare indicators such as dietary diversity have been unclear. By taking a comprehensive view of the farm household, this study discerns the drivers of household dietary diversity in this transitional context by linking the Household Dietary Diversity Score (HDDS), as an indicator of dietary diversity, to key household characteristics, livelihood strategies and indicators of farm performance in three study sites in Cambodia, Laos and Vietnam. The Rural Household Multi-Indicator Survey (RHoMIS) tool, a combined survey and analysis platform, was employed to collect data from over 1300 farm households. HDDS is found to increase among the sites in a way that is roughly associated with their state of agricultural transition, though differing combinations of market orientation, specialisation, and intensification traits that describe such a transition suggest that the pathway to commercialisation, and dietary diversity, is not a linear one. Drivers of dietary diversity vary markedly between the sites. In the Laos site, HDDS is most closely correlated to a set of variables closely linked with agricultural transition, while in the Cambodia site it is associated more with other farm and household characteristics. In the Vietnam site, dietary diversity is correlated to the overall value of crop production. Findings point to the need to contextualise site-specific knowledge of linkages between dietary diversity and ongoing agricultural transition in the GMS, as well as policy and interventions seeking to improve dietary diversity in the face of such transition.

1. Introduction

Throughout the tropics, smallholder livelihoods rely upon mixed agricultural systems that integrate a variety of on-farm crop and livestock enterprises. Increasing population pressures in these areas have been fueling agricultural intensification and transitions to alternative forms of agriculture through processes outlined by Boserup (1965). Though the ability of intensification to meet growing household income and food needs in the tropics remains unclear (Herrero et al., 2014), Boserup's description of agricultural transformation has been useful in describing changes observed throughout the developing world, such as those among smallholder systems supplying agricultural products to rapidly-developing urban centers in sub-Saharan Africa (Herrero et al., 2017).

Perhaps the starkest examples of tropical agricultural transformation can be found within the Greater Mekong Subregion (GMS), a geopolitical area encompassing the Mekong River Basin in Southeast Asia and including the six states of Cambodia, China (specifically Yunnan Province and Guangxi Zhuang Autonomous Region), Laos, Myanmar, Thailand, and Vietnam. Agricultural systems in the GMS

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have experienced profound and multifaceted transitions over the last four decades, evolving from traditional subsistence agriculture toward commercialised production (Alexander et al., 2017; Ashraf et al., 2017; Johnston et al., 2009; Kenney-Lazar, 2012; Li et al., 2014; Vicol et al., 2018). Changes in the GMS follow pathways differentiated by local and national contexts, but overall are driven by infrastructure development and modernisation, improved market access, and government policy (Diez, 2016; Goto and Douangngeune, 2017; Kyeyune and Turner, 2016). Regional examples include Vietnam's shift from centralised to market-oriented agricultural systems in the 1990's (Cochard et al., 2017; Diez, 2016; Knudsen and Mertz, 2016; Kyeyune and Turner, 2016; Meyfroidt et al., 2013; Nguyen et al., 2015; Truong et al., 2017) and the transition of shifting cultivation into other forms of commercialised agriculture in Laos (Heinimann et al., 2013; Hirota et al., 2014; Ornetsmuller et al., 2016; Southavilay et al., 2013) and Cambodia (Baird and Barney, 2017; McAndrew, 2000; Milne, 2013).

CIAT (2014) specifically focuses on three key characteristics of these transitions in the GMS:

- *Market orientation*. As market linkages strengthen, farmers increasingly produce crop and livestock goods for the market rather than for household consumption.
- Production *specialisation*. In response primarily to market forces, farmers increasingly allocate their production resources to e.g. cash crops, monocropping, specialty crops, and intensive animal production methods, sometimes at the expense of on-farm biodiversity (Rerkasem et al., 2009).
- *Intensification* of production. Farmers introduce nitrogenous fertiliser usage and irrigation for crop production (Johnston et al., 2009), as well as intensive livestock production methods (Stür et al., 2013).

Though evidence of these transitions and their associated influences is ubiquitous across the GMS, the geographic distribution, characteristics, and rates of change of these transitions are not uniform, but rather vary considerably across the region (Johnston et al., 2009). Even at the local level, progressive farmers may seize opportunities to commercialise production while others retain more traditional attitudes and practices (Martin and Lorenzen, 2016), giving rise to a spectrum of households at various stages of agricultural transition. Inter-household variations are then magnified by differences in market access, agricultural systems, and household resource endowments when viewed from a regional perspective. Furthermore, transformations have extended beyond the farm, shifting the balance between on-farm livelihoods and off-farm employment (Martin and Lorenzen, 2016).

In agrarian societies where livelihoods and sustenance are entwined with agriculture, market-driven agricultural transitions would presumably connote economic progress. In reality, the effects of these changes in the GMS on household welfare, and on food security and nutrition specifically, are unclear. Several recent studies in the region, for example, reveal that inadequate nutrition and low dietary diversity remain pervasive (de Sa et al., 2013; McDonald et al., 2015a, 2015b; Nguyen et al., 2013; Talukder et al., 2013). Linkages between agricultural production and dietary diversity as a critical determinant of nutritional outcomes (Lachat et al., 2018; Ruel, 2003) have been studied elsewhere (Dulal et al., 2017; Koppmair et al., 2017; Mulmi et al., 2017), but with the exception of a few studies, e.g. Michaux et al. (2016), associations between agricultural production and dietary diversity in the GMS are largely unexplored. Furthermore, these studies (in the GMS and elsewhere) typically consider only 1 or 2 aspects of the agricultural system such as production diversity (Jones et al., 2014; M'Kaibi et al., 2017; Saaka et al., 2017; Sibhatu et al., 2015; Sibhatu and Qaim, 2018a; Sibhatu and Qaim, 2018b), while robust analysis of agricultural transitions requires a comprehensive view of the agricultural system and of the farm household.

This study attempts to address this gap by quantifying dietary diversity across a spectrum of households in several GMS study sites and linking it to a comprehensive understanding of farm household and agricultural system characteristics. A host of metrics for dietary diversity are available (Ruel, 2003), but this study centers on the Household Dietary Diversity Score (HDDS), a proxy indicator for dietary diversity that tallies the number of different food groups, on a scale of 1 to 12, consumed by a household over a reference period (FAO, 2011; Swindale and Bilinsky, 2006). The study is based on survey data collected using the Rural Household Multi-Indicator Survey (RHoMIS) tool (Hammond et al., 2017), a digital survey platform designed to rapidly gather comprehensive information on not only household welfare indices like HDDS, but farm and household characteristics as well.

The objective of this study is to discern the drivers of dietary diversity in sites at various stages of agricultural transition in the GMS by analysing the association of HDDS to selected household characteristics, livelihood strategies and indicators of farm performance. The study pays particular attention to (1) a set of farm household 'mutable' variables that will likely change as transitions continue, or conversely, could be targets for proposed interventions, and (2) a subset of these mutable variables that are specifically linked to the three key aspects of agricultural transition in the GMS. Such a comprehensive analysis across the different sites can improve understanding of the commonalities and differences in drivers of dietary diversity across the region, clarify the interplay between agricultural transition and dietary diversity, and suggest how ongoing transitions may affect dietary diversity in the region into the future.

2. Materials and methods

We collected primary data for analysing the association of HDDS to key household characteristics, livelihood strategies and indicators of farm performance by implementing household surveys in Cambodia, Laos and Vietnam. Primary data collection supported subsequent household-level statistical analysis.

2.1. Study site description

The localities in the three countries where the surveys were implemented (Table 1) were selected based on expert opinion to capture differences in levels of agricultural transition (CIAT, 2014).

Table 1
Study site descriptions.

Site name	Location	Site characteristics	Households
Cambodia	Ratanakiri Province, northeast Cambodia	Agricultural system: Low-input monoculture Topography: Upland Elevation: 200–400 m Population density*: 17 persons/km^2	631
Laos	Xieng Khouang Province, northern Laos	Agricultural system: Mixed crop-livestock Topography: Upland Elevation: 1200 m Population density**: 16 persons/km^2	365
Vietnam	Dak Lak and Dak Nong Provinces, Central Highlands, Vietnam	Agricultural system: Intensive Topography: Upland Elevation: 400–800 m Population density***: 94–143 persons/km^2	310

* National Institute of Statistics (2013).
** Lao Statistics Bureau (2015).
*** Dak Lak Statistical Office (2016), Dak Nong Statistical Office (2016).

2.1.1. Laos site

Xiangkhouang Province is located in northeastern Laos and is characterised by a plateau surrounded by mountainous terrain. The provincial capital, Phonsavan (19_26’59.30“N, 103_ 13’16.43”E), lies at an elevation of 1095 m.a.s.l. Most farmers are smallholders with mixed crop-livestock systems. Different ethnicities co-exist in the province, with ethnic Lao residing primarily in the lowlands and Hmong in the uplands. Growing seasons for significant crops roughly follow the duration and timing of the wet season, and annual crops are grown from the end of April until the end of October. The main crops are rice (both paddy rice and upland rice), maize for feed, cassava, chili, banana, homegarden vegetables and tea. Animal husbandry focuses on chickens, ducks, cattle, pigs and turkeys. Cut-and-carry forages are collected throughout the year and include *Brachiaria ruziziensis*, *Pennissetum purpureum* and local grass species.

2.1.2. Cambodia site

Ratanakiri Province is remotely situated in northeastern Cambodia and has a population of over 150,000, grouped into twelve ethnic groups including Khmer, Lao Tompoen, and Djarai. Ratanakiri has three main landscape types: a basalt plateau in the geographic centre, an upland region bordering Laos with elevations as high as 1624 m.a.s.l, and flatlands along the Tonle River and in the southern portion of the province. Ratanakiri has a monsoonal climate, with a rainy season extending from April to October that accounts for 99% of the total annual precipitation. The average precipitation and temperature between the years 2005 to 2015 were 2318 mm-yr^{-1} and 26C, respectively. Rice is cultivated for household consumption, and cassava, cashew and rubber are the main cash crops.

Some legume crops, such as soybeans and peanuts, are planted in rotations or intercropped with cashew trees or cassava. Animals are mainly reared for meat production. Ruminants serve as living family savings in case of a sudden need of capital. Pigs and poultry are raised for household consumption or are sold in local or regional markets.

2.1.3. Vietnam site

The Central Highlands of Vietnam have a tropical climate, having an annual average temperature of 24.1C, with heavy rains during the summer (April to September) and minimal precipitation during the winter months (October to March). The main ethnic groups in the area include Ede, Kinh, Mnong and Jarai. Landscapes are characterised by acidic soils, and farming systems are primarily mixed crop-livestock farms. Livestock include cattle, swine and poultry that are primarily raised for meat production. The main staple crop is rice, and feed crops include maize, cassava and forages. Cash crop production focuses on coffee, pepper and cashew nuts.

2.2. Survey implementation

A household survey was implemented in the three sites between December 2015 and March 2016. Respondents were randomly selected from village and commune lists obtained from local authorities by national partners. Cambodian enumerators (the technical staff executing the surveys) conducted the surveys on-farm, while teams of Vietnamese and Lao researchers invited respondents to village meeting halls. Household interviews were conducted in local languages using Android devices. Data automatically uploaded to a cloud server whenever the Android devices successfully connected to the internet and were available for immediate downloading and analysis. The survey instrument used in this exercise was the RHoMIS (Rural Household Multiple Indicator Survey) platform (Hammond et al., 2017).

2.3. The RHoMIS platform

The RHoMIS household survey and analysis tool has been described in detail by Hammond et al. (2017) and has now been applied in more than 17 countries in a series of studies (Fraval et al., 2018; Hammond et al., 2017; Hammond et al., 2018; Ritzema et al., 2017b; Stirling et al., 2018), collecting data on more than 13,000 rural households. Briefly, RHoMIS is a set of carefully designed questionnaire modules that are administered digitally using the Open Data Kit (ODK) software platform, along with an associated set of data extraction and analysis tools written in R. The survey is designed to be both flexible enough to suit local contexts and sufficiently standardised to permit rapid deployment, analysis and comparison between multiple sites. The majority of questions in the survey are used for the estimation of a series of predefined indicators that include:

- The Household Food Insecurity of Access Scale (Coates et al., 2007) for measuring the frequency and severity of hunger.
- The Household Dietary Diversity Score (Swindale and Bilinsky, 2006), providing an indicator of household nutrition status.
- The Progress out of Poverty Index (Desiere et al., 2015; Grameen Foundation, 2015), an asset-based scoring system to estimate the likelihood that a household is in poverty.
- The Potential Food Availability indicator for quantifying the ability of a household to feed itself through both on-farm and off-farm activities (Frelat et al., 2016; Ritzema et al., 2017b).

These indicators are combined with a comprehensive inventory of agricultural crops and livestock including yields, uses, sale prices and inputs, and an assessment of off-farm incomes. The indicators captured in RHoMIS place the farm household along a continuum of household and farm characteristics, performance indicators and welfare indicators (see Fig. 1), not only enabling in-depth analyses of indicators independently, but also integrating analyses of how indicators co-vary and how on-farm and off-farm livelihood strategies correlate to food security, poverty and dietary diversity.

2.4. Description of the key variables

2.4.1. Dependent variable for food security: Household Dietary Diversity Score (HDDS)

HDDS is calculated by tallying the number of food groups consumed by a household over a given reference period. Typical HDDS studies follow the procedure outlined by Swindale and Bilinsky (2006) by using a standardised list of 12 food groups and a 24-h recall period. RHoMIS assesses the same set of food groups and localises typical foodstuffs consumed at each study site but uses a 4-week recall period.

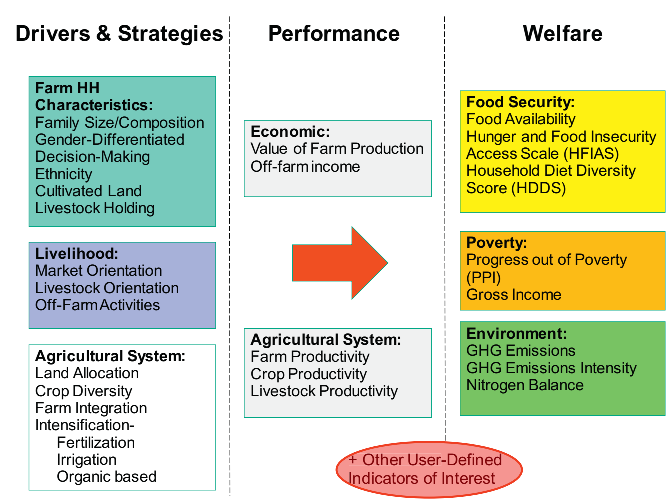

Fig. 1. The structure of the Rural Household Multiple Indicator Survey (RHoMIS): linking drivers and strategies to household-level welfare. Colors denote the different indicator groups.

Fig. 2. Theory of agricultural transition.

Respondents indicate consumption of each food group on a 'daily', 'weekly', 'monthly', or 'never/less than monthly' basis (Hammond et al., 2017). Each food group consumed on at least a weekly basis is given a score of '1'. Food group representation is summed to provide an overall HDDS score between 1 and 12, representing grains, roots and tubers, vegetables, fruits, legumes, meat, fish, eggs, dairy, fats, sweets, and miscellaneous foods, respectively. This adaptation to the HDDS definition means that values of our HDDS score cannot be interpreted in an absolute way (e.g. that 7–8 food groups suggests a diet of sufficient diversity), as it is not calibrated in any standard way to nutritional requirements. Our results therefore only give insight into the variation of dietary diversity encountered in the populations sampled.

We nevertheless chose this approach of measuring dietary diversity to enable comparison of surveys conducted at different points during the agricultural year, as seasonality typically strongly affects dietary diversity scores. With this approach our results are independent of the timing of the single survey application, a factor that in multi-site analyses, as in our case, is otherwise difficult to control. Analyses have shown that our method was highly correlated to 'gold standard' 24-h recall results when both methods were implemented in the same survey and captured similar ranges in dietary diversity (Martin-Prével et al., 2015). Fraval et al. (submitted) showed a strong association between an adapted dietary diversity score and micronutrient gaps when performing detailed food consumption analyses, further confirming that the indicator conveys key information about food security and also showing that recall length did not affect the HDDs results.

2.4.2. *Independent variables*

A simplified and generalized theory of agricultural transition (Fig. 2), similar to e.g. Turner and Ali (1996) and alluding to Boserup (1965), forms a backdrop for the identification of independent variables for this study. With increases in regional population density, and accompanying urbanisation and higher demand for labour, both food demand and labour factor prices increase, leading to an agricultural system that garners higher output prices in the context of increasing prices for productive resources. As forwarded in CIAT (2014), the agricultural system transitions away from subsistence-oriented and diverse production activities toward a system that aims to sell farm produce, specialises in profitable production activities and intensifies production (indicated as three aspects of Production System Transition in Fig. 2). The sites considered in this study are seen to be at different states of on-going agricultural transition: for example, the Laos sites are still significantly subsistence-oriented, while the sites in Vietnam have largely completed this transition. Furthermore, transition trajectories, as described by differing mixes and degrees of market orientation, production specialisation and intensification, may not be similar across sites. The core of the analysis in this study, therefore, focuses on a selected set of independent variables that represent the three aspects of Production System Transition (Fig. 2) in the GMS, rather than the drivers of agricultural transition (i.e. population density, price increases, etc.), to capture the effects of contrasting transition levels and trajectories on dietary diversity.

However, this study does not consider the key transition variables exclusively, but takes a broader view by combining the key transition variables with a set of other 'contextual' variables that describe household characteristics and livelihood strategies, forming a comprehensive set of independent variables with potential association with dietary diversity (Table 2). Some of these variables are essentially 'immutable', i.e. they are fixed and therefore less subject to changes due to agricultural system transitions, or by extension, cannot be readily

Table 2
Explanatory variables for Household Dietary Diversity Score.

Variables	Description	Type[a]	Units
Household characteristics			
Ethnicity	Self-identified ethnicity of household.	Cat	n/a
Household Type	Five types of household heads are possible: both parents, single parent, parent working away from home, non-parent, child.	Cat	n/a
Livelihood strategies and farm performance			
Female Decision-Making Control	Female control over potential food energy available, on a scale (0–1): 0 = male-controlled, 0.5 = egalitarian, 1 = female-controlled.	Cont	Dimensionless
Off-Farm Income	Income from off-farm activities.	Cont	$USD.yr^{-1}.person^{-1}$
Market Orientation for Food Availability	Relative importance of crop and livestock sales in generating potential food energy available.	Cont	%, 0–100
Value of Crop Production (per person)	Monetised value of crop production, normalised by household size.	Cont	$USD.yr^{-1}.person^{-1}$
Value of Livestock Production (per person)	Monetised value of livestock production, normalised by household size.	Cont	$USD.yr^{-1}.person^{-1}$
Land Owned (per person)	Household land area, normalised by household size.	Cont	$ha.person^{-1}$
Crop Diversity	Number of crops.	Count	Dimensionless
N Fertiliser Use	Ratio of amount of N fertiliser applied to land cultivated.	Cont	$kg\,N.ha^{-1}$
Land Irrigated	Approximate percentage of land area that is irrigated.	Cont	% (0, 17, 33, 50, 75, 100)
Crop Productivity	Ratio of monetised value of crop production and land area cultivated.	Cont	$USD.ha^{-1}$
Livestock Holdings (per person)	Livestock holdings in Tropical Livestock Units (TLU), normalised by household size.	Cont	$TLU.person^{-1}$
Livestock Diversity	Number of livestock types.	Count	Dimensionless
Livestock Contribution to Food Availability	Percentage of food availability ($kcal.MAE^{-1}.yr^{-1}$) that is traceable to livestock production, either through direct consumption or from proceeds when livestock are sold.	Cont	%, 0–100
Livestock Productivity	Ratio of monetised value of livestock production and livestock holdings.	Cont	$USD.TLU^{-1}$

[a] 'Cat' = categorical variable, 'Cont' = continuous variable, 'Count' = count variable.

addressed by interventions. Therefore, variables and indicators distilled from the RHoMIS survey were grouped into two sets of independent variables to compare against HDDS. The Household Characteristics Group (Table 2) contains categorical variables that for the intent of this analysis are considered to be immutable, e.g. ethnicity and household type. Conversely, the Livelihood Strategies and Farm Performance group (Table 2) is a collection of continuous and count variables that are considered to be 'mutable' farm household characteristics and strategies.

Within the Livelihood Strategies and Farm Performance variable group (Table 2), specific variables were selected to represent the three key aspects of production system transition (Fig. 2). Market orientation was represented by the 'Market Orientation for Food Availability' variable, a weighted indicator of the proportion of farm produce that is sold vs. consumed. The weighting uses the 'Food Availability' indicator to account for the importance of each farm product to each household's livelihood. The indicator has been tested and applied in a series of recent studies (Frelat et al., 2016; Hammond et al., 2017). 'Food Availability', while not specifically considered as a variable of interest in this study, is a key indicator in RHoMIS and is embedded in the definition of several other variables (Table 2). 'Food Availability' is the food energy, expressed in kilocalories per male adult equivalent per day, potentially available to a household through both on-farm agricultural production and markets (Frelat et al., 2016; Hammond et al., 2017; Ritzema et al., 2017a). Production specialisation is quantified by two indicators: crop diversity (number of different crops grown) and livestock diversity (number of different livestock species kept). Intensification of production is described using several variables as well: N (nitrogen) applied as mineral fertiliser and land under irrigation.

Other 'contextual' independent variables (Table 2), considered together with the key transition variables, include key farm and livelihood characteristics that may be associated with dietary diversity such as farm size, livestock holdings and household size. Several key parameters that would typically be included in the Household Characteristics Group, namely Household Size and Gender Decision Type, were incorporated into the Livelihood Strategies category to enhance quality of the results. The Gender Decision Type variable quantifies the relative control of women over the benefits of on-farm and off-farm activities (Van Wijk et al., 2016), and has a continuous value between zero (women have no role in decision-making) and one (women control all decisions related to the benefits of on- and off-farm activities). Tavenner et al. (2019) describes a recent detailed study of this indicator. Though this variable is descriptive of cultural contexts, it is not considered an immutable descriptor and can be influenced through gender-based interventions. To account for high variability in household size and its effects on household resource endowments and farm productivity, appropriate variables were normalised by the number of household members, including Off-Farm Income, Land Owned, Livestock Holdings, Value of Crop Production, and Value of Livestock Production.

2.5. Analysis approach

The RHoMIS survey differentiated farmer responses on food groups consumed between food purchased from the market and food produced on-farm. HDDS values are thus partitioned by source, forming three distinct dependent variables for statistical analysis: Total HDDS, HDDS from purchased food ($HDDS_{pur}$), and subsistence HDDS ($HDDS_{sub}$). All data preparation, outlier testing, and statistical analysis were performed in R (R Core Team, 2014).

Aiming to retain the maximum number of households in the dataset, we identified outlier households based on two criteria. First, we manually screened all dependent and independent variables for unreasonable values. Second, we tested the remaining variable values for excessive influence on parameter values by using DFBETA plots in R (Fox and Weisberg, 2011). Households with DFBETA data points having an absolute value $> 2/\sqrt{n}$, where n is the number of households, were labeled as outliers and removed from the dataset. From both outlier criteria, 12, 8, and 3 households were removed from the Cambodia, Laos, and Vietnam datasets, respectively.

Quantitative analysis of HDDS association with categorical and immutable Household Characteristic variables used Kruskal-Wallis testing to identify whether statistically significant differences were apparent between factor levels, and visual inspection of boxplots to discern where differences were most evident. Analysis of HDDS vs. the Livelihood Strategies and Farm Performance Group (Table 2), a collection of mutable continuous and count variables, centered on negative binomial regression, a generalized linear model (Venables and Ripley, 2002). HDDS is an over-dispersed count variable (Koppmair et al., 2017) and correlation between independent variables is evident due to overlapping variable definitions, e.g. Off-Farm Income and Value of Crop Production are addends in the Food Availability indicator calculation. All models started with a full set of independent variables, and we used the 'step' function in R (Hastie and Pregibon, 1992; Venables and Ripley, 2002) to sequentially remove the most insignificant terms from the regression model using Akaike's Information Criterion. Terms remaining with $p > 0.1$ were then manually removed to leave the most parsimonious model.

Results from the Household Characteristics group analysis did not subsequently inform analysis of the Livelihood Strategies and Farm Performance group. Statistically significant differences in the former would be important to consider if formulating interventions or discerning how cultural differences or resource endowments affect dietary diversity. However, in this study, comparisons within and between the sites are the primary focus. Thus, we opted to identify Household Characteristics differences as an area for further study and important criteria for in-depth analysis and intervention strategy. Subsequent regression analysis of the Livelihood Strategies and Farm Performance group is thus performed across the entire sample population in each site.

3. Results

3.1. Farm characteristics

A listing of selected farm and household characteristics provides context for subsequent analysis (Table 3). Median values and interquartile ranges are indicated for continuous and count variables of interest.

Five household types were reported across the 3 sites: (1) two parents, (2) single parent, (3) non-parent household head, (4) household head working away from home, and (5) child household head. Not all household types were reported in each site, and low-frequency household types were consolidated into an 'Other' category in the analysis. The number of distinct ethnicities reported in the Cambodia, Laos, and Vietnam sites were 6, 2, and 6, respectively, though Cambodian survey enumerators used a generic 'Other' ethnic category as a sixth ethnicity during data collection.

The Cambodia site exhibits larger farm sizes and cultivation area than either the Laos or Vietnam sites, but similar livestock holdings to the Vietnam site. The Laos site has larger family sizes and a greater diversity of household types, and also places greater emphasis on livestock production (via quantity and diversity) than the other sites.

Levels of agricultural intensification, i.e. as reflected by nitrogenous fertiliser input rates and use of irrigation, differ markedly between sites. The Cambodia site is the least intensified of the 3 sites, with negligible N fertiliser use and a median value of the percentage of land irrigated being zero, with an interquartile range of only 17%. The Laos site reflects slightly more irrigation usage, but the overall intensification level remains low. Conversely, intensification levels in the Vietnam site reflect the prevalence of intensified agriculture and high market connectivity.

Table 3
Selected farm household characteristics.

	Values: Median (Interquartile Range)		
	Cambodia	Laos	Vietnam
Household characteristics			
Family size	5 (3)	6 (3)	4 (2)
Ethnicities represented[a]	6	2	6
Number of household types[a]	4	5	3
Livelihood strategies and farm characteristics			
Female decision-making control (0–1)	0.50 (0.083)	0.5 (0)	0.5 (0)
Total income (USD.yr^{-1})	1890 (2640)	250 (1270)	3270 (4390)
Off-farm income (USD.yr^{-1}.person^{-1})	14 (98)	0 (11)	79 (318)
Market orientation for food availability (%, 0–100)	80 (49)	9.1 (42)	74 (43)
Value of crop production (USD.yr^{-1}.person^{-1})	340 (420)	194 (195)	558 (966)
Value of livestock production (USD.yr^{-1}.person^{-1})	0.67 (5.2)	4.0 (10)	12 (37)
Land owned (ha)	3.5 (3.6)	1.2 (1.3)	1.2 (1.5)
Land cultivated (ha)	3.5 (3.5)	1.5 (1.7)	1.3 (1.5)
Crop diversity (# of crops produced)	5 (3)	4 (3)	4 (2)
N fertiliser use (kg N.ha^{-1})	0 (0)	0 (0)	34 (38)
Land irrigated (%, 1–100)	0 (17)	0 (50)	75 (83)
Crop productivity (USD.ha^{-1})	500 (420)	890 (740)	1680 (1700)
Livestock holdings (TLU)	0.63 (2.7)	3.7 (5.8)	0.7 (1.9)
Livestock holdings (TLU.person^{-1})	0.13 (0.55)	0.56 (0.91)	0.16 (0.49)
Livestock diversity (# of livestock types produced)	2 (1)	3 (2)	2 (1)
Livestock contribution to food availability (%, 0–100)	0.027 (1.3)	3.7 (8.1)	1.4 (5.8)
Livestock productivity (USD.ha^{-1})	2.5 (32)	5.0 (17)	37 (220)

[a] A simple count, thus not a median value.

3.2. Household Dietary Diversity Score

Reported HDDS values cover the entire range of possible values on a scale from 1 to 12. Sample sizes were uneven across the 3 sites, with the Cambodia site having a sample size more than double that of the Vietnam site (Fig. 3). The Laos site reports the lowest mean and median HDDS value (Fig. 3).

A Kruskal-Wallis test result of $p = 4.9\text{e-}13 < 0.05$ confirms visual inspection (Fig. 3) that the central tendency between the 3 sites is not identical. Shapiro-Wilk values and skewness/kurtosis tests (Fig. 3), along with visual inspection of HDDS histograms (Fig. 4) confirm that, in each site, HDDS values are not normally distributed. A substantial group (~10–15%) of households consumed only 1–2 food groups (normally grains plus either fats or vegetables). This diet information is based on the month of the year when farmers recalled consuming the fewest number of food groups.

We considered the fraction of HDDS attributable to purchased food vs. food produced on-farm. Households were grouped into 3 categories at each site: those with HDDS < 5, those with 5 < HDDS < 8, and those with HDDS > 8. These tertiles are subjective, as no guidelines have yet been formulated for the number of food groups considered to be adequate or inadequate (FAO, 2011), and are thus intended to show food purchase trends across an HDDS spectrum. Box plots (Fig. 5) show that in Cambodia and Vietnam, purchased food groups are most important for overall HDDS, while in Laos the farm-based groups are most important. In all sites, trends suggest that households with low HDDS (Group 1) showed a lower fraction of HDDS from purchased food.

3.3. HDDS vs. household characteristics

Examination of Household Characteristics centered on 2 variables: Household Type and Ethnicity (Fig. 6). Respondents typically self-identified as 'Single [Parent]' or '[Parents] Together'. Frequency of the three other household types was low across all 3 sites, necessitating consolidation into a generic 'Other' household category. Similarly, in the Cambodia and Vietnam sites, ethnicities represented by only a few households were consolidated into an 'Other' ethnicity category.

No statistically significant differences in HDDS are evident for the

	Camb	Laos	Vietnam
n*	607	334	295
Mean	6.4	5.3	6.8
Median	6	5	7
Minimum	1	1	2
Maximum	12	12	11
Skewness	-1.0	0.58	-1.55
Kurtosis	-3.0	-3.0	-1.23
Shapiro-Wilk	2.1E-08	2.8E-07	3.2E-06

* Number of households after outliers were removed.

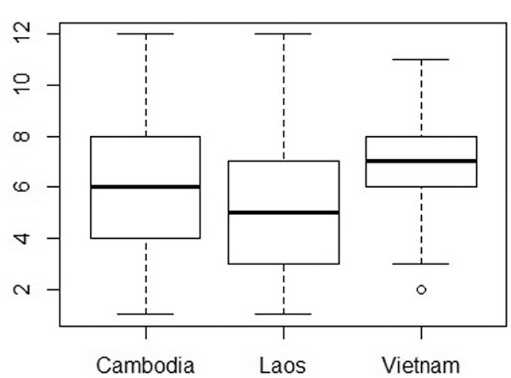

Fig. 3. Descriptive statistics for Household Dietary Diversity Score, per site.

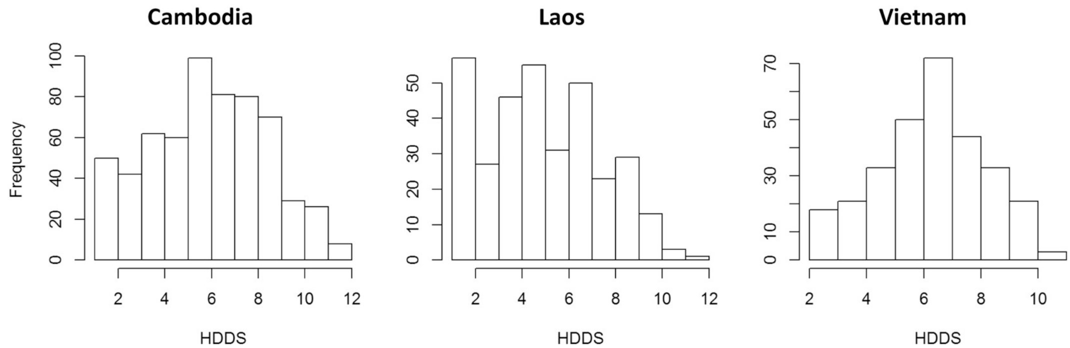

Fig. 4. Household Dietary Diversity Score histograms.

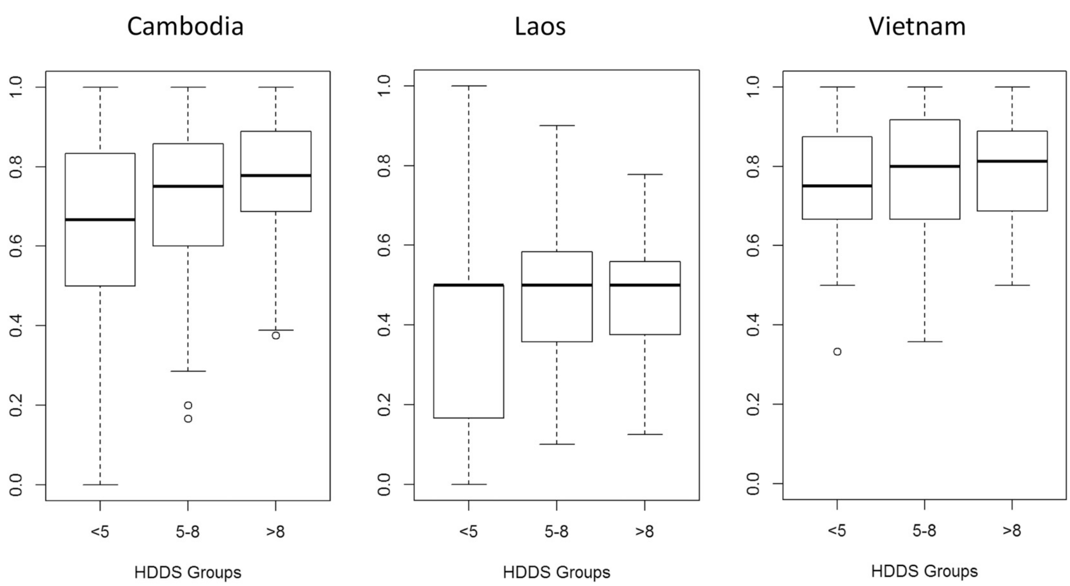

Fig. 5. Fraction of Household Dietary Diversity Score from purchased food, by groups.

Household Type variable, in any of the 3 sites, as indicated by Kruskal-Wallis *p*-values greater than the 0.05 significance level. Household Type results contrast sharply with the Ethnicity variable, as differences in HDDS values between ethnicities are statistically significant in all 3 sites.

Pairwise Wilcoxon tests reveal more detail on HDDS differences across ethnicities within each site. In the Cambodia site, Khmer HDDS values are significantly greater than the Cha Rey ($p \leq 0.001$), Tom Poun ($p < 0.01$), and Other ($p < 0.001$) ethnicities. Aside from the Khmer group, the Cha Rey HDDS values are significantly lower than the Lao ($p < 0.01$) and Tom Poun ($p < 0.01$) ethnic groups. Of the two ethnicities in the Laos dataset, the Hmong HDDS scores are significantly lower than the Lao ethnic majority ($p < 0.01$). In the Vietnam site, the Kinh majority ethnic group shows significantly higher HDDS scores than the Ede ($p < 0.05$) and Mnong ($p < 0.01$) groups, but not the 'Other' ethnic group, a small collection of Nung, Tay, and Thai ethnicities that outperform only the Mnong ethnicity ($p < .05$). These results suggest that ethnicity, in all three sites, is an important element to consider when targeting dietary diversity as a key development outcome in agricultural interventions.

3.4. HDDS vs. livelihood strategies and farm performance indicators

The second stage of the HDDS analysis focused on assessing the association of a set of 14 mutable 'Livelihood Strategies and Farm Performance' indicators (Table 2) with HDDS for each study site. A minimal set of significant regressor variables (with significance levels $p < 0.10$) were assumed to identify key variables associated with HDDS variability. Negative binomial regression coefficients represent log differences in the expected count of HDDS for a unit change in each regressor variable, while holding other regressors constant (Table 4), meaning that an increase in the value of these variables leads to a negative effect on the expected HDDS score, and therefore a decrease in dietary diversity.

A cross-site comparison reveals several commonalities between sites (Table 4). Value of Crop Production is the only variable that is statistically significant for Total HDDS in all 3 sites, while Crop Diversity, Livestock Holdings, Value of Livestock Production, and Crop Productivity variables are insignificant in all sites for Total HDDS. Accordingly, an increase in crop production may lead to higher dietary diversity in all three sites, while other variables might lead to improved dietary diversity in one or more sites, but not all. A positive association between Off-Farm Income and HDDS in the Laos and Cambodia sites shows the importance of off-farm income in purchasing diverse foods from the market. A strong negative association between Market Orientation for Food Availability vs. HDDS in the Laos and Cambodia sites indicates that increased use of crop and livestock sales to access food energy is matched with a loss of dietary diversity. Otherwise, results differ markedly across the 3 sites (Table 4) in both complexity and content. A minimal set of 2 regressor variables for the Vietnam site contrasts sharply with 8 significant variables for the Laos site.

Associations between key indicators and HDDS are further clarified by analysis of marginal effects. The key indicators presented in Fig. 7 are limited to the strongest associations with the lowest relative

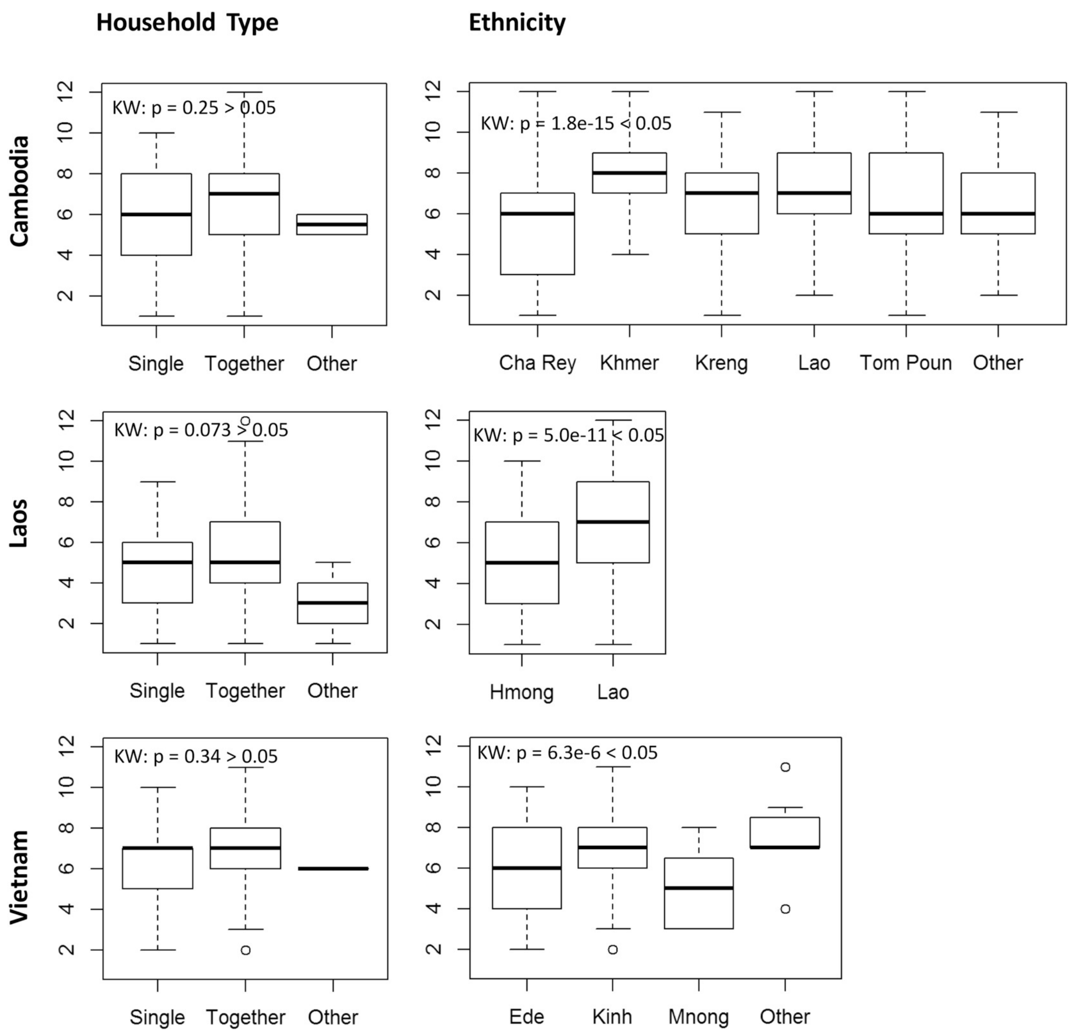

Fig. 6. Household Dietary Diversity Score by key household characteristics.

uncertainty as reflected in the *p*-value (indicated in Table 4). Holding all other regressors at their mean, we see that in the Cambodia site, Female Decision Making Control has a small but highly certain positive association with HDDS (increasing at most by 1 food category across the range of possible values). Conversely, Market Orientation has a small negative association with HDDS. Livestock Contribution to Food Availability has a stronger but more uncertain positive association with HDDS (increasing by a minimum of 1 to a maximum of 6 food categories). In the Laos site, the Value of Crop Production and Land Owned variables are positively associated with HDDS with a high degree of uncertainty. The Land Irrigated variable has a small but highly certain positive association with HDDS. In the Vietnam site, the Value of Crop Production has a less uncertain, positive association with HDDS when compared to Laos, but the association between Livestock Diversity and HDDS is positive with a high degree of certainty.

3.4.1. Cambodia site

Reliance on markets for dietary diversity (Fig. 5) is further reflected in synchrony between $HDDS_{pur}$ and Total HDDS regressor variable sets, and dissimilarity between $HDDS_{sub}$ and Total HDDS. Variables associated with increased dietary diversity coming from on-farm produce are thus different from those that positively affect purchased dietary diversity. Though $HDDS_{sub}$ plays a minor role in the Cambodian household, Value of Livestock Production, Crop Diversity, Land Irrigated and Livestock Holdings are linked to $HDDS_{sub}$, and increases in these variables lead to increased dietary diversity. Only the Cambodia site indicates linkages between Female Decision-Making Control and Total HDDS: increased decision power of women leads to increased diversity in the food purchased, and thereby to increased overall dietary diversity.

3.4.2. Laos site

Households in the Laos site rely on both markets and consumption of farm products for dietary diversity (Fig. 5), differing from the predominant market orientation of the other 2 sites, and further evidenced by the strong synchrony in regressor variables between purchased and subsistence HDDS and Total HDDS. Whereas in Cambodia total dietary diversity is in most cases only affected positively if a positive relationship between the independent variable and purchased HDDS is evident, in Laos total HDDS can be affected positively (and negatively) by both the farm-based and purchased HDDS routes. Of the 3 sites, the Laos site shows the strongest linkage between HDDS and agricultural intensification strategies, i.e. N Fertiliser Use and Land Irrigated. N Fertiliser Use is positively related to purchased HDDS (more mineral fertiliser use means more production, more sales and thereby more cash available to buy diverse food), whereas irrigation leads to positive effects on dietary diversity based on both purchases and consumption of farm-based production.

3.4.3. Vietnam site

Regression results forward only 2 significant variables for Total HDDS, and as such, the Vietnam site has the simplest statistical model

Table 4
Regressor variables of significant livelihood strategies and farm performance for Household Dietary Diversity Score.

	Cambodia			Laos			Vietnam		
	HDDS	HDDS pur	HDDS sub	HDDS	HDDS pur	HDDS sub	HDDS	HDDS pur	HDDS sub
Female Decision-Making Control (0-1)	0.22 **	0.28 ***							
Off-Farm Income (USD.yr^{-1}.person^{-1})	5.0e-5 *	6.5e-5 *		1.1e-4 *	2.9e-4 ***				
Market Orientation for FA (%, 0-100)	-2.2e-3 ***	-1.8e-3 *	-4.1e-3 ***	-2.6e-3 *		-3.7e-3 **			
Value of Crop Prod (USD.yr^{-1}.person^{-1})	7.1e-5 *	1.2e-4 ***		2.0e-4 **		4.8e-4 ***	6.9e-5 ***	6.2e-5 **	
Value of Livestock Prod (USD.yr^{-1}.person^{-1})			2.7e-4 *			6.8e-3 **			
Land Owned (ha.person^{-1})	3.2e-2			0.36 **	0.38 **				
Crop Diversity (# of crops)			0.062 ***		-0.053 *				0.091 **
N Fertiliser Use (kg N.ha^{-1})				3.7e-3	5.2e-3				
Land Irrigated (%, 0-100)			4.2e-3 ***	2.5e-3 ***	2.0e-3 *	3.0e-3 ***			
Crop Productivity (USD.ha^{-1})						-4.7e-5			
Livestock Holdings (TLU.person^{-1})		-0.037	0.09 ***						
Livestock Diversity (# of livestock types)				0.049 **	0.086 **		0.068 **		0.33 ***
Livestock Contribution to FA (%, 0-100)	4.5e-3 **	6.1e-3 **							
Livestock Productivity (USD.ha^{-1})				-1.1e-3		-1.8e-3 *			5.1e-4 ***

*** p<0.001, ** p<0.01, * p<0.05, ' ' p<0.1

***$p < 0.001$.
**$p < 0.01$.
*$p < 0.05$, '$p < 0.1$'.

of the 3 sites. The most significant regressor variable for Total HDDS is the Value of Crop Production, matched by a similar value for the same variable for $HDDS_{pur}$, with higher value of crop production leading to higher purchased dietary diversity, and thereby also to higher total dietary diversity. The relatively small proportion of HDDS from on-farm sources is correlated to Crop and Livestock Diversity as well as Livestock Productivity. All of these variables have a positive effect on farm-based dietary diversity, with Livestock Diversity (the number of different livestock species raised on-farm) not only leading to an increase in farm-based dietary diversity, but also to an increase in total dietary diversity.

To frame subsequent discussion, Table 5 summarises the statistical results by regrouping the set of 14 Livelihood Strategies and Farm Performance variables (Tables 2-3). The three transition aspects of market orientation, production specialisation, and intensification are defined in simple terms using 5 of the 14 regressor variables. The market orientation indicator is the Market Orientation for Food Availability variable. The specialisation aspect is comprised of the 'inverse' of the Crop Diversity (e.g. low crop diversity indicates high specialisation) and Livestock Diversity variables. Intensification is reflected by N Fertiliser Input and Irrigation variables. The remaining nine regressor variables place results within the wider farm household context, i.e. Farm Characteristics, Farm Performance, and Other Household Characteristics categories. Variable medians and interquartile range results (Table 3) are subjectively interpreted as Low, Med[ium], or High, and regression results against Total HDDS (Table 4) are indicated by sign and significance. Results therefore summarise whether a variable has a high or low value and whether it has a large effect on HDDS. For example, nitrogenous fertiliser use is typically an important determinant of production and an entry point for production intensification. However, it is not identified as a significant variable in any of the sites. In Cambodia and Laos, the use of mineral fertiliser is low while in Vietnam it is high, but results show little variation in intra-site mineral fertiliser use. So though mineral fertiliser would be

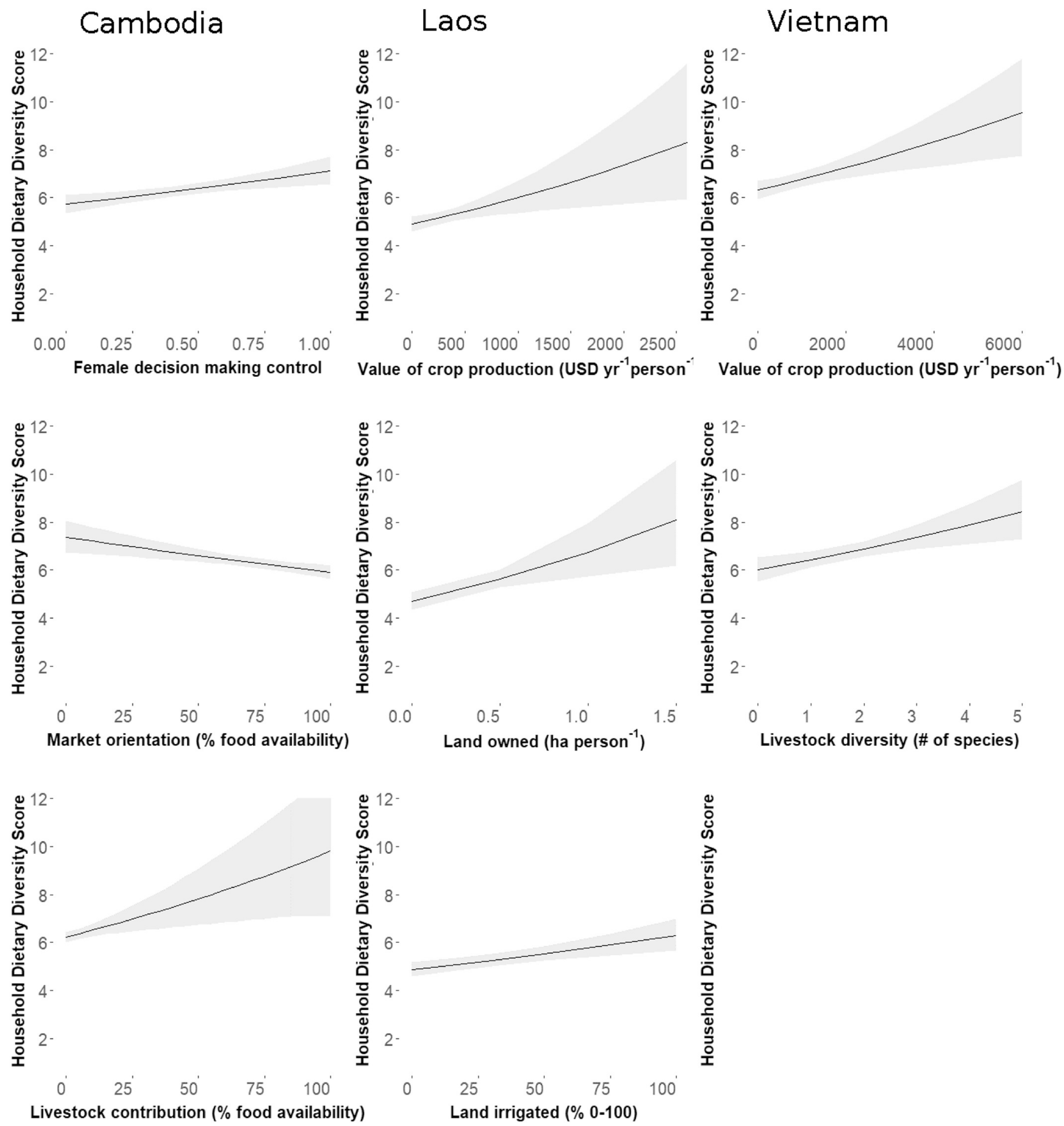

Fig. 7. Marginal effects plots of key indicators.

expected to affect production positively, it does not have large within-site variation and therefore in analyses at the integration level does not arise as a key variable.

3.5. Food group differentiation with HDDS

Fig. 8 displays food group composition for each HDDS value across the full HDDS range within each site. Charts reveal the distinctions between sites and shifts in food groups as HDDS scores increase, for Total HDDS as well as its purchased and subsistence components. The differences between the sites in the dietary diversity represented in the purchased and subsistence components of HDDS reflect results displayed in Fig. 5: the diversity of the purchased portion of HDDS dominates in the Cambodia and Vietnam sites, while the food group diversity originating from on-farm production and purchasing are roughly equal in the Laos site.

Examination of one food category illustrates the utility of food group disaggregation. The 'fruits' category becomes prevalent in each of the sites when HDDS values reach a value of approximately '7', as shown in the Total HDDS charts in Fig. 8. Further information can then be gained through close examination of the 'HDDS purchased' and 'HDDS subsistence' charts. In the Laos site, for example, the 'fruit'

Table 5
Levels of independent variables and interpreted correlated variation to Household Dietary Diversity Score.

		Cambodia		Laos		Vietnam	
Household Dietary Diversity Score (median):		6		5		7	
Agricultural Transition		Level	CV*	Level	CV*	Level	CV*
Market Orientation	Market Orientation for FA	High	(-)***	Low	(-)*	High	
Specialisation	Crops	Low		Med		Med	
	Livestock	High		Med	(-)**	High	(-)**
Intensification	N Fertiliser	Low		Low	(+)	High	
	Irrigation	Low		Low	(+)***	High	
Farm Characteristics	Land Owned	High	(+)	Low	(+)**	Low	
	Livestock Holdings	Low		High		Low	
Farm Performance	Value Crop Production	Med	(+)*	Low	(+)**	High	(+)***
	Crop Productivity	Low		Med		High	
	Value Livestock Production	Low		Med		High	
	Livestock Productivity	Low		Med	(-)	High	
	Livestock Contribution to FA	Low	(+)**	Low		Low	
Other HH Char's	Female Decision Control	Med	(+)**	Med		Med	
	Off-farm Income	Med	(+)*	Low	(+)*	High	

*CV = Correlated Variation

*, **, and *** indicate significance levels for variables.
[a]CV = Correlated Variation.

category is insignificant below 'HDDS purchased' scores of 6. As the maximum allowable HDDS score for a farm household is 12, an 'HDDS purchased' score of 6 corresponds to an 'HDDS subsistence' score of 6 or less. These results therefore suggest that Lao site households consume what little fruit they produce on-farm. Households with a Total HDDS score of roughly 6 or above then increasingly turn to market sources.

Households in the Laos site clearly produce rice for consumption and purchase little grain from the market, while the inverse is true for the Vietnam site. As in the case of fruit, consumption of dairy and legumes is negligible in all sites below Total HDDS = 7, but above this threshold, dairy products are typically purchased and legumes are produced on-farm. Fats and sweets are consumed by almost all households and are already present in diets of low diversity. In the Vietnam site, eggs and vegetables, and to a smaller extent meat and fruits, originate on-farm, while in the Cambodia site, grains, roots and tubers, eggs, fruits and fish originate from on-farm production. In the Laos site, virtually all crop-based food groups originate from on-farm production.

4. Discussion

Results establish that dietary diversity, as measured using HDDS, varies between three GMS study sites that are perceived to be in various phases of agricultural transition (Table 5). A key component of the analysis is associating HDDS to a simple but comprehensive set of mutable farm, livelihood, and household characteristics, as mutable characteristics are likely to change as agricultural systems undergo further change. Forging these links requires an understanding of 2 factors for effective interpretation of results within and across sites: (1) the levels of each variable, at each site, representing those characteristics, and (2) the variation of those variables within each site and the significance of the association of that variation with HDDS. For example, the Value of Crop Production variable in the Vietnam site has high variation that is significantly correlated to HDDS, around a high median production value relative to the other sites. Both data provide meaningful information. On the other hand, a lack of correlated variation in N fertiliser use rates to HDDS in the Vietnam site does not reflect its unimportance as a 'driver': high crop production levels in the Vietnam site in fact depend upon fertiliser inputs. Rather, there is little variation in N fertiliser input rates correlating to HDDS because fertiliser use is high across the spectrum of farm households in the Vietnam site. Interpretation of the data within its site context is therefore a key component of the analysis.

4.1. Laos site

Relative to the other two sites, the Laos site is positioned at the lower end of the spectrum in terms of income (Table 3) and dietary diversity (HDDS, Fig. 3). Following Boserup's theory of agricultural intensification via induced innovation (Boserup, 1965) and as outlined in Herrero et al. (2014), the Laos site appears to be in only the initial phases of agricultural transition (Table 5). Livelihood strategies have a strong subsistence orientation, particularly in production of grains, roots and tubers, and some vegetables (Fig. 8). Households are more dependent on on-farm production in terms of HDDS than the Vietnam or Cambodia sites, as reflected in the fraction of HDDS that is purchased (Fig. 5), and significant synchrony between $HDDS_{sub}$ and Total HDDS regression terms (Table 4).

Agricultural transition variables (i.e. those representing market orientation, intensification, and specialisation shown in Table 5) are key drivers of dietary diversity, though not all in the same direction.

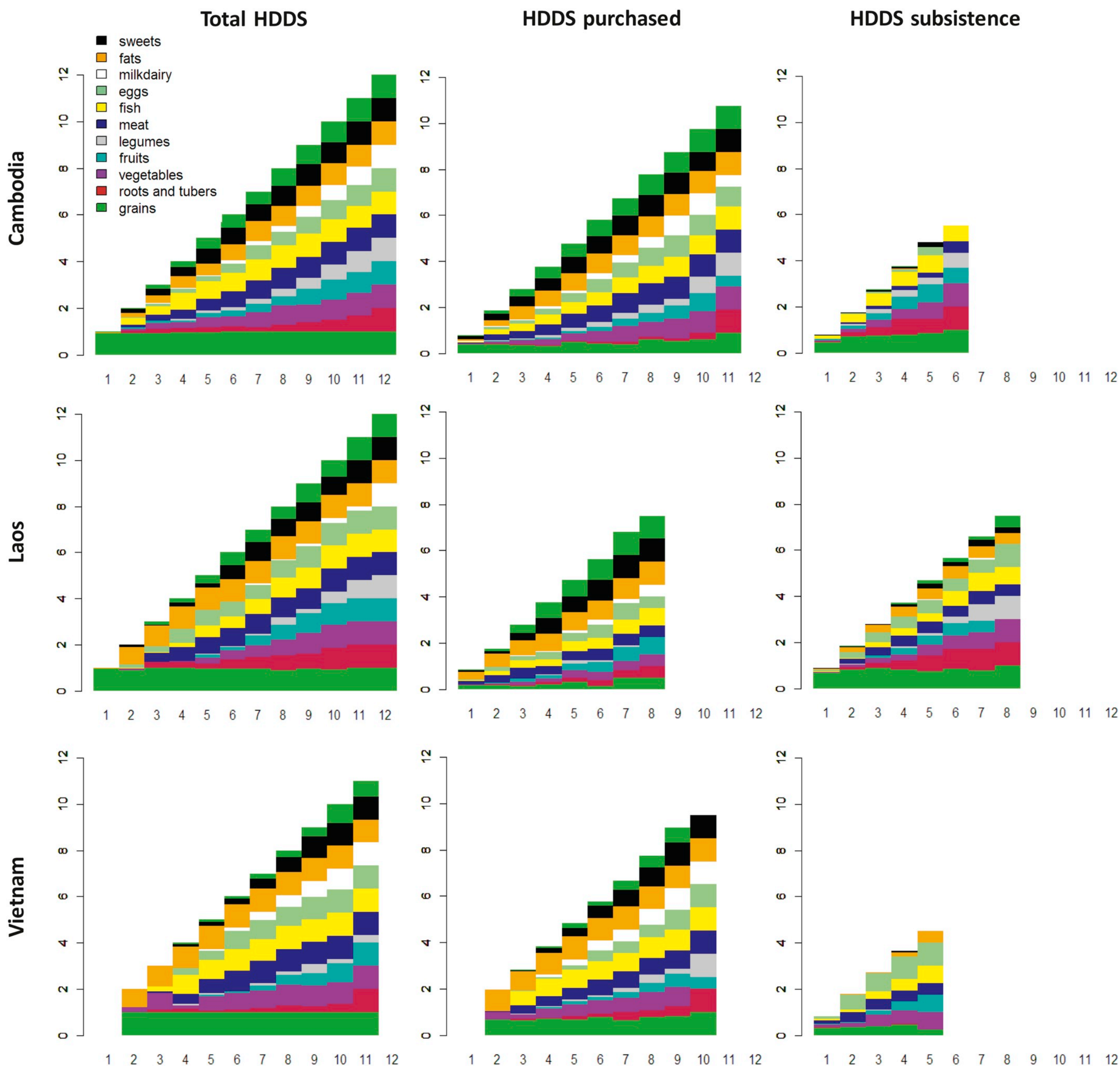

Fig. 8. Dietary diversity: proportion of households consuming specific food categories by farm type and period. Both the horizontal and vertical axes show the total dietary diversity scores. On the vertical axis, the composition of household diets are shown using colour-coded food categories. The vertical axis thereby shows the proportion of households consuming each category at specific dietary diversity levels.

Intensification influences HDDS positively, but intensification is currently evident only through limited irrigation (Table 3), primarily for subsistence paddy rice production (Fig. 7). Furthermore, irrigation expansion is the most significant driver of HDDS, through both market and subsistence pathways (Table 4). Fertiliser use is limited, though regression results indicate that as application of fertiliser increases, HDDS improves through marketing of produce (Fig. 5).

However, HDDS also trends negatively against other transition aspects. The significant negative correlation with livestock specialisation (Table 5) reflects a subsistence orientation toward livestock production (also reflected through high livestock holdings), thus enhancement of livestock diversity would presumably lead to higher dietary diversity. However, increased livestock diversity is associated with higher HDDS through market connectivity (Table 4), so a fuller understanding of market interactions is needed to more fully interpret this dynamic.

Agricultural transition is not the only driver of dietary diversity in the Laos site, though it is arguably the dominant influence. Though off-farm income is negligible, regression results show a dramatic effect on dietary diversity through market purchases when off-farm income becomes available. Overall, with increased crop production, through either more land or through intensification, households first diversify diets via on-farm production, with some shift in orientation toward markets (Fig. 5).

These findings may suggest that the linkage between ongoing agricultural transition, or perhaps interventions, to improved dietary diversity may be somewhat predictable, but would depend on the balance between what are currently positive intensification influence vs. negative specialisation and market orientation influences. Production intensification shows a clear positive HDDS trend but coupling intensification with market connectivity that is conducive to HDDS enhancement, within a context that is still strongly subsistence-oriented, would be critical. Improvement in off-farm income and maximising the value of crop production are important ‘non-transition’ farm household characteristics to consider.

4.2. Cambodia site

The Cambodia site is positioned between the Laos site and the Vietnam site in terms of HDDS (Fig. 3) and all forms of income (Table 3). The site presents a mixture of agricultural transition traits that differ from those of Laos, i.e. along the trajectory of increased market orientation, intensification, and specialisation. Agricultural systems appear to be focused on specialised and non-irrigated cash crop production, with relatively low crop production levels that are nonetheless primarily intended for the market, especially across the border with Vietnam. HDDS is primarily associated with food purchases (Fig. 5), a finding supported by the lack of synchrony between the significant factors for $HDDS_{sub}$ and Total HDDS (Table 4). High market connectivity is a prerequisite condition for this to be true. At the same time, the intensification strategies of fertiliser use and irrigation are nearly absent. Livestock production is de-emphasised, with the Cambodia site having the lowest livestock holdings of any site. Despite being a market-oriented site, crop diversification, irrigation, and increased livestock production, when present, produce foodstuffs that are primarily consumed by the household (Table 4) including rice, roots and tubers, and vegetables (Fig. 8). Some food groups, i.e. dairy, fats, sweets, and eggs are obtained only from the market (Fig. 8).

Unlike the Laos site, agricultural transition characteristics appear to have little bearing on dietary diversity, which is instead associated with non-transition farm and household aspects. However, keeping in mind that levels of associated variables are important to consider along with the variables' correlated variability, the lack of significance for e.g. fertiliser or irrigation, may be explained by the lack of any variation to correlate against HDDS. There may simply be too little fertilisation or irrigation utilised among the surveyed households to be measurable against HDDS, but introduction of intensification strategies may well have a positive (albeit unknown) effect on dietary diversity.

Strikingly, the variable with the most significant correlation to HDDS, Market Orientation for Food Availability, is negatively correlated, as in the case of the Laos site. This variable indicates the degree that crop and livestock production sales are used to obtain potential food energy (Table 2). This result appears counter-intuitive, as increasing market orientation in an agricultural context having strong market connectivity would seem to give farm households the opportunity to purchase a diverse basket of food groups, as is in fact reflected in Cambodia's purchase food group distribution (Fig. 8). However, this result may reflect a changing attitude toward dietary diversity as farm revenues increase, or may indicate that farm proceeds may be used for other non-food purposes such as school fees. Furthermore, some farm households in remote areas may be far from markets, but are still highly market-oriented through traders. For these households, market access to a diversity of purchased foodstuffs may be limited, and income from farm sales thus may not necessarily translate to higher dietary diversity.

Association of dietary diversity with non-transition variables (e.g. productive resources such as land and livestock holdings, and productivity and household characteristics such as female decision control and off-farm income) is more prominent for the Cambodia site than the Laos site (Table 5). Livestock holdings are low, yet production is relatively market-oriented (Fig. 7). Conversely, farms are larger relative to the other sites, but increased farm size remains positively correlated to HDDS. Cambodia is the only site where Female Decision-Making Control has non-trivial variation and is significantly associated with HDDS. As in the Laos site, off-farm income is low, but is associated with increasing HDDS when it is accessible.

The Cambodia site presents a different picture of early-stage agricultural transition (market orientation, intensification and specialisation as shown in Table 5) than the Laos site, where market orientation is less prominent. Specialisation and intensification traits reflect pre-transition conditions, while livelihoods are dependent on cash crop production on larger farms. It is therefore uncertain how further agricultural transition will affect dietary diversity. However, based on results from Laos and Vietnam, introduction of even small intensification measures will likely correlate to improved dietary diversity. The importance of non-transition aspects must not be ignored in the transition process, and improved female decision-making over food purchases along with greater off-farm income could produce large HDDS gains.

4.3. Vietnam site

Vietnam presents the lowest poverty (as expressed by income, Table 3) and highest HDDS of any of the 3 sites (Fig. 5). Farms have seemingly undergone the transition to commercialisation and specialisation (Table 5), and are small but highly intensified (Table 3 and Table 5). A high percentage (75%–80%) of HDDS is purchased, rather than produced on farm (Fig. 5). Food groups are well-represented, with the exception of roots and tubers, which are consumed typically only by high-HDDS households (Fig. 8).

Low correlated variation of post-transition market orientation, specialisation, and intensification variables to HDDS (Table 5) is likely due to uniformity across the sample population: most households are already highly connected to markets, with highly specialised and intensified agricultural systems. Despite high market orientation, livestock diversity still plays a role in increasing dietary diversity through on-farm consumption of livestock products, highlighting the potential role of livestock to support dietary diversity in post-transition households. Otherwise, variations in the value of crop production are the predominant driver of HDDS, as crop production equates to cash resources for purchasing diverse foodstuffs (Fig. 8).

4.4. Cross-site trends

Though limited in farm size, the Vietnam site has transitioned to highly market-oriented, specialised, and intensified agricultural systems, unsurprisingly matched with high farm performance indicators (Table 5). The Cambodia and Laos sites are at different positions in the transition space but have markedly different transition pathways in terms of market orientation, specialisation, and intensification. The Cambodia site, with low fertiliser and irrigation usage, is nonetheless highly market oriented. The Laos site shows a different trend, with some crop specialisation and irrigation (primarily for rice production), but with low market orientation and emphasis on subsistence production. These results illustrate transition processes in the GMS may be multi-dimensional rather than linear.

HDDS appears to be more related to cropping system transitions than to livestock systems, whether crops are consumed on-farm or sold in the market. Interestingly, crop diversification shows little effect on Total HDDS: gains in $HDDS_{sub}$ are matched with losses in $HDDS_{pur}$ (Table 4). These contrasting effects might be one explanation why the literature on the link between crop diversity and dietary diversity shows confusing results, with limited effects of crop diversity on dietary diversity at best (Cook, 2018; Waha et al., 2018). Livestock diversification may be associated with higher HDDS, but pathways differ between sites. Our results on the contrasting effects of diversification on $HDDS_{sub}$ and $HDDS_{pur}$ show that crop and farming diversification need to be understood as part of overall livelihood diversification strategies (Mortimore and Adams, 2001; Newsham and Thomas, 2011).

Analysis of household characteristics reveals that though significant differences in dietary diversity are not apparent between household types, ethnicity was a major driver of HDDS scores in each site (Fig. 6), and therefore should be considered in further studies, farming systems analysis or intervention design. This study focused on variability within each site to give indications of drivers of dietary diversity, and thus the site populations were not disaggregated by ethnicity. Further research is needed, however, to understand the nature of dietary diversity differences between ethnic groups, and to understand how agricultural transition trajectories and potential interventions could be shaped by ethnicity.

The disaggregation of the food groups by origin (Fig. 8) gives key information on how continuing agricultural transition may result in transitions within specific food groups, or potentially for projects that try to improve dietary diversity through on-farm interventions. This information can also give insights into possible policy recommendations. In the Vietnam site, only eggs and vegetables originate on-farm, and to a smaller extent meat and fruits, while in the Cambodia site grains, roots and tubers, eggs, fruits and fish originate from on-farm production. These food groups and their corresponding products could be targeted to directly improve dietary diversity through home consumption of production. Other production interventions that would potentially increase production would indirectly improve dietary diversity if farmers use the extra income to buy diverse foods. The fact that appreciable amounts of fats and sugars are consumed by households with low dietary diversity scores suggests that this is unlikely to be a viable pathway to diverse diets unless these undesirable consequences are countered. Policies that support further production intensification should therefore be paired with nutrition education; otherwise, improved incomes will likely not result in improved diets. In the Laos site, essentially all crop-based food groups originate from on-farm production, thereby suggesting that production intensification options could directly result in more diverse diets.

5. Conclusions

The objective of this study was to discern key drivers of dietary diversity, as measured by an adapted implementation of the Household Dietary Diversity Score, in three study sites in the Greater Mekong Subregion that represent different stages of agricultural transition from subsistence to commercialised production. Characteristics differ between the sites as indicated by levels and trends in indicators representing 3 primary transition descriptors: market orientation, specialisation, and intensification. Agriculture in the Vietnam site has essentially transitioned, while the Laos and Cambodia sites display divergent combinations of transition traits. These results suggest that agricultural transformation in the context of the GMS is best described in terms of multiple pathways rather than a linear progression.

Dietary diversity, as measured using HDDS, varies in a statistically significant manner between three GMS study sites that roughly follows that commercialisation transition. However, drivers of dietary diversity differ markedly between the sites. In the Laos site, HDDS is most closely correlated to a set of variables closely linked with agricultural transition, while in the Cambodia site it follows other farm and household characteristics. In the Vietnam site, dietary diversity is closely correlated to the overall value of crop production. These findings show that continuing agricultural transitions will exhibit differing trajectories between the sites, with concomitant impacts on dietary diversity.

Agricultural transition pathways are site-specific, and therefore contextualised policies and approaches are needed to ensure that agricultural transitions do not occur at the expense of dietary diversity. Though findings cannot be translated directly to intervention recommendations in this study, they do provide indications of where interventions might be needed to support or potentially offset the effects on dietary diversity from ongoing agricultural transition processes. Cambodia and Laos show much potential for input-driven intensification, while in Vietnam diversification is a key policy entry point, as well as further diversification of livestock production. This will lead to increased market orientation, but it must be accompanied by nutrition education to stimulate diversification strategies. Future research can focus on discerning the linkages between dietary diversity and key drivers in greater detail, perhaps in conjunction with household analysis and modeling to formulate specific interventions. These efforts should carefully consider the differentiating role of ethnicity as a driver of dietary diversity.

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