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Potential multifaceted agroforestry impacts on farming household's livelihoods in Viet Nam: need to account for agroforestry type, magnitude and maturity for non-biased evaluation

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Abstract Agroforestry is widely recommended in the mountainous areas of Southeast Asia to improve farmers' livelihoods and reverse current land degradation trends. However, studies of the impacts of adoption of agroforestry practices on smallholder farmer livelihoods are limited to field-scale assessments and landscape potential. In this paper, we assess the difference in terms of farming system performance between agroforestry adopters and non-adopters in northwest Viet Nam using propensity score matching (PSM) calculating the average treatment (agroforestry adoption) effect on the treated (adopters) on core economic, environmental, and social indicators. The results of the PSM indicate an increase in revenues of about 8 million VND ha^{-1} yr^{-1} (about 325$) per household when adopting agroforestry, but a counterintuitive outcome regarding erosion. This outcome is likely due to an improperly selected farmer control group, which is located on less erosion-prone land, as well as the presence of immature trees in agroforestry systems, whose canopies have not yet contributed to reducing erosion. A typology of adopters was produced and revealed a wide diversity of agroforestry adoption pathways across the population, which may have blurred the results of the PSM. Six farming household types were obtained ranging from 'Off-farm income-dependent farmers' with low proportion of agroforestry to 'Specialists mixed agroforesters' with higher proportion of agroforestry practices on their farm and different levels of input intensity in their farming systems. This typology highlights the need for greater context awareness in farming system research and proper control of the agroforestry type, the proportion of agroforestry in the farming systems,

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and the maturity of the agroforestry system. This will help to better capture the real-life, farm-scale impacts of agroforestry practices.

Keywords Crop diversification · Diversified farming systems · Household typology · Land degradation · Propensity score matching · Sustainability assessment

Introduction

In Southeast Asia, agriculture with annual crops such as maize or cassava on sloping land is increasing losses of soil (Häring et al. 2014; Do et al. 2023) and depleting soil fertility (Wezel et al. 2002; Nguyen et al. 2008; Valentin et al. 2008). This subsequently leads to decreased yields (Clement and Amezaga 2008), need for intensified input use and loss of revenues thereby trapping farmers in a state of poverty (Zimmer et al. 2018). Despite farmers being aware of these trends and the resulting mid- to long-term threat to their livelihoods, farmers continue cultivating these crops (e.g. maize, rice or sugarcane) because of their knowledge of the cropping practices and the easy access to relevant markets (Zimmer et al. 2018). Alternative management practices with more diverse cropping systems including perennial crops, e.g. agroforestry, have been suggested to replace these unsustainable cropping practices in the upland landscape. Agroforestry refers to land-use systems and technologies that combine woody perennials with non-woody crops and potentially livestock on the same unit of land (Nair 1993).

Agroforestry has been developing in various countries in Southeast Asia and has been promising in contributing to food security and climate-change adaptation and mitigation (Catacutan et al. 2017). Particularly, in the remote mountainous regions of Northwest Viet Nam, agroforestry has been practiced spontaneously by ethnic minorities since the 1960s (Phien and Siem 1999; Simelton et al. 2013). In the last years, the government has strongly promoted fruit-tree based agroforestry systems adoption. Many farming households here combine high-value perennials (fruit or timber) with annual crops. The high value perennials include for instance plum, orange, longan, mango, as well as Son tra (*Docyni indica*) and coffee. The other common crops often grown as sole crops (monoculture or rotation) comprise maize, upland rice, sugar cane, cassava, soybean.

The agronomic performance and delivery of services in the long-term have been confirmed in several studies of agroforestry practices in Northwest Viet Nam. Field trials show that soil and nutrient losses caused by monoculture and intensification are reduced after two years of cultivating agroforestry that includes grass strips and fruit trees along the contour lines (Do et al. 2020b, Do et al. 2023). Furthermore, simulations of economic impacts report substantial long-term returns to agroforestry adoption on maize and rice monocrop plots despite lower returns in the short term (Do et al. 2020a). Agroforestry can also help adapting to climate change while contributing to carbon sequestration (Do and Bui 2023). However, despite the long history of agroforestry in the region, empirical (economic) research is still at the beginning and the high complexity of agroforestry systems and potential returns have yet to be understood for the various practices that have emerged spontaneously among farming households (Hoang et al. 2017). At the household level, impact studies of agroforestry have primarily focused on addressing socio-economic factors influencing farmers' decisions to adopt agroforestry innovations (Simelton et al. 2017; Nguyen 2020). At landscape level, studies have looked at the potential for afforestation, fruit-tree cultivation, and agroforestry with a focus on reducing large scale environmental impacts like erosion or run-off (Nguyen et al. 2022). However, at farm scale, where the agroforestry system plays out its strength, the performance of agroforestry-based farming systems on multiple dimensions of sustainability has not yet been analysed. Based on simulations, the agroforestry systems are expected to have negative impacts in the short-term since perennials require several years to mature, revenues may not compensate for the initial investment within the time of typical end-of project assessments, and the environmental benefits will take time to materialize. Yet, in the long-term, agroforestry has been shown to have positive impacts for food, income, efficiency, welfare, and the environment (Franzel and Scherr 2002; Mercer 2004). Further, all these components are interconnected and show synergistic effects. Hence, it is important to consider these multiple aspects and dimensions of the potential impacts and further assess how the heterogeneous population connects with these changes.

This paper aims to assess the relevance of adopting agroforestry in Northwest Viet Nam. The two specific objectives are to: (i) assess the changes in farming system performance based on agroforestry adoption along economic, environmental, and social indicators and (ii) gain insights into the diversity of agroforestry practices and smallholder farmers by developing a household typology based on a set of factors related to agroforestry adoption as well as economic and social context. Towards objective (i), we used propensity score matching (PSM) and compare adopters and non-adopters with similar characteristics to calculate the average treatment (agroforestry adoption) effect on the treated, i.e., farms that have adopted agroforestry, along each sustainability indicator. A principal component analysis (PCA) combined with ascending hierarchical clustering analysis over socioeconomic and biophysical characteristics of the households is used to classify households into clusters towards objective (ii).

Data and methodologies

Overview of the study areas and data collection

The study area is located in Dien Bien, Yen Bai, and Son La provinces, in Northwest Viet Nam, representing in total 1,320,000 ha of cultivated land, of which more than 75% is located on slopes strongly affected by soil erosion (Duong et al. 2014). The three provinces are among those with the highest poverty rates across the country and have a high degree of reliance on agriculture as 80% of the population lives in rural areas (Bangalore et al. 2019). Recent improvements in infrastructures, which facilitate market access, have increased livelihood opportunities, but the rapid expansion of agriculture coupled with the traditional practice of shifting cultivation have increased land degradation and forest destruction and fragmentation, which threatens environmental sustainability and food security (Zimmer et al. 2018).

Data was collected from 537 households across the three provinces including both adopters and non-adopters of agroforestry practices. The survey was carried out between February and October 2020. Data used here has been collected using household interviews covering socioeconomic and farming characteristics of households (Nguyen et al. 2020a). The data cleaning procedure aimed to remove irrelevant observations, fix structural errors, and filter unwanted outliers for which data would be incomplete for our analysis. Irrelevant observations included farmers whose farming systems could not be definitively classified as agroforestry. Structural errors encompassed issues such as obvious data encoding mistakes by surveyors or missing (estimated) data on key factors related to adoption or impacts, such as farm size or revenue. Outliers were a small number of farmers whose characteristics—such as exceptionally large farm sizes or livestock numbers—significantly deviated from the rest of the sample. After cleaning, a cross-sectional dataset of 397 households was used for the analysis.

Propensity score matching

Matching agroforestry adopters with non-adopters

In this study, propensity score matching (PSM) was used to assess the benefits of agroforestry adoption on twelve household level sustainability indicators. These indicators are comprised of 5 economic indicators (Agricultural income, Non-agricultural income, Crop revenue, Cost of hiring labour, Cost of purchasing seeds), 4 environmental indicators (Dose of fertilizer, Dose of pesticide, Proportion of land with erosion, Level of erosion) and social indicators (Food security and Hired labour). PSM is a quasi-experimental method that aims to create an artificial control group with similar characteristics compared to an intervention group to subsequently estimate the impact of an intervention. The matching process involves pairing each treated unit with one or more untreated units that have similar or identical propensity scores. This helps to create a counterfactual group that closely resembles the treated group along the observed characteristics. This method then allows comparing the performance difference between the adopters and the non-adopters.

A few assumptions need consideration before performing PSM (Rosenbaum and Rubin 1983). The first assumption is the conditional independence assumption (CIA), i.e. the outcome is independent of the treatment assignment after conditioning on the covariates. The second assumption is that an individual has a positive probability of both states, i.e., treated and untreated, if it has the same values of covariates. If the two assumptions are satisfied, the matched control group can be considered as a counterfactual.

The matching is based on the propensity score, computed as the probability of receiving the treatment assignment (i.e., adopting agroforestry) as a function of a set of covariates. The binary model using logistic regression is proposed based on the formula (Eq. 1):

$$e(X) = \Pr[D = 1|X], e(X)\epsilon(0,1) \tag{1}$$

where D takes the value of 1 if the household adopts agroforestry and 0 otherwise, X denotes values of covariates. The selection of covariates is based on the number of significantly meaningful estimated parameters, the characteristics of households driving the agroforestry adoption as provided by the PCA, and some indices, i.e., Akaike information criterion (AIC), percentage of correct predictions, and Likelihood ratio test. Once the best-fitted covariates produce the propensity scores, the matching can be processed based on the distance between the propensity scores of treated variables and those of untreated variables.

We performed the PSM using the package MatchIt in R (Ho et al. 2011) and used the nearest neighbour matching algorithm. Two untreated units were matched with one treated unit with a calliper of 0.2, and the distance was based on Ward's method. The matching process did not consider a replacement. The selection of the relevant model relied on the evaluation of the matching quality, showing the most similar characteristics between the treated variables and the matched untreated variables. The matching quality evaluation is based on the observation of the differences in covariates of each pair before and after the matching (Rosenbaum and Rubin 1983). In this paper, two essential tests of two categories were chosen for the quality evaluation (a) Covariance balancing test (including standardized difference test combined with Mann–Whitney U test) and (b) test for levels of explanation (Pseudo-R-squared). In particular, the covariance balancing test aims to check each covariate's difference pre- and post-matching in matched pairs. The smaller difference gets, the more balanced the groups are. The significance of the difference in pairs is based on the p-value derived from the Mann–Whitney U test. Meanwhile, the Pseudo-R-squared tested the level of explanation. The value was expected to be very small after matching to ensure no systematic differences in the distribution of covariates between the two groups (Conover 1999).

Outcome analysis using linear regression

Once matched, we compared agroforestry adopters with non-adopters in terms of economic, environmental, and social outcomes. The most common parameter to assess these impacts is the average treatment effect on the treated (ATT), which is calculated as the mean difference in the mean outcomes of each pair of treated and untreated individuals generated by PSM (Eq. 2):

$$ATT = E\left(Y^1|D = 1, P(X)\right) - E(Y^0|D = 0, P(X)) \tag{2}$$

We perform the linear regression of each outcome on the treatment variable to obtain the ATT estimator (Eq. 3):

$$y_i = \alpha_0 + \alpha_1 D_i \tag{3}$$

Considering the propensity score matching weights, the estimator of ATT is calculated as follows (Eq. 4):

$$\alpha = \frac{1}{N}\sum_{i=1}^{I\cap S}\left[Y_i^1 - \sum_{i=1}^{I\cap S} W_{ij} Y_j^0\right] \tag{4}$$

where α is the estimator of ATT, S is the common support where the propensity scores of both treated and untreated samples are positive. Treated units receive a weight of 1 and control units receive a weight of $W_{ij} = \frac{e_i}{1-e_i}$. N is the number of treated individuals in the support space (Hirano et al. 2003).

According to the literature, the impacts of agroforestry are emerging across all sustainability dimensions in the economic, environmental, and social domains. These were used as outcome variables for the analysis. The indicators across the three categories have been derived from the household data as well as the household typology. The economic indicators focus on the financial implications, and cover costs and financial benefits. The environmental indicators focus on the primary negative effects of intensified agriculture, which the agroforestry system is expected to overcome, including soil erosion and land degradation. Since most of the households are largely subsistence farmers, food security indicators are included and the degree of reliance on hired labour was included as agroforestry can increase labour demand.

Typology of cropping systems and farmers' households

Classification of cropping system

To gain insights in the characteristics of agroforestry-based cropping systems adopted by farmers, we classified the practices they adopted. Two methods are typically employed: (1) structural classification that account for species, function, economic scale or (2) ecological diversity classification using diversity indices such as Shannon index (Nair 1985; Marcacci et al. 2020). In areas where agroforestry is randomly adopted and trees are combined with various arrangements and for multiple purposes, the classification becomes more complex as is not guided by standard combinations. In this context, types of agroforestry need to be identified with reference to the local cropping systems that are observed. For example, Mulia et al. (2020) classified common agroforestry practices in each region of Viet Nam based on the main perennial crop components such as Acacia-based, Arabica-coffee-based, and Tea-based agroforestry. Other studies focus on a particular economically valuable component of the system to investigate its arrangements and impacts at farm scale in a particular area of Viet Nam (Do et al. 2020b; Nguyen et al. 2020b). We adopted a hybrid approach by combining two classification methods based on dominant tree or crop types and on economic aspects considering the valued added by each component (i.e., high value crop vs. low value crop) (Table 1). This categorization produced 10 cropping systems whose proportion in households' farming system can be compared.

Farmers' household typology

After categorization of the cropping systems, we grouped farming households by combining principal component analysis (PCA) and ascending hierarchical clustering (AHC). After removing correlated variables from the initial 33 variables representing biophysical and socioeconomic resources, the PCA and AHC was performed on 24 variables at farm scale such as the farm size or land tenure. These variables then form the basis to construct household typologies. These variables encompassed household structure (7 variables), farm characteristics (2 variables), the proportion of each cropping systems (10 variables) and the intensity of farming systems (5 variables) (see Table S1). The PCA was used to reduce the dimensionality of the dataset using a small number of uncorrelated variables while preserving as much variability as possible. After

Table 1 Categorization of cropping systems in Northwest Viet Nam. 'AF' in the variable name refer to a cropping system categorized as agroforestry

Cropping systems (variable_name)	Description
Diversified cropping systems (Diversified_CS)	Maize, rice, and/or sugarcane combined with legumes, tubers, timber trees, fruit trees, and/or grass as sub-components
Horticulture based agroforestry (Horticulture_AF)	Legumes and/or tubers as main products are combined with timber trees and fruit trees
Cash crop agroforestry (AF_coffee_tea)	Coffee, tea or cannaceae as cash crops combined with cereal, legumes, tubers, timber trees and fruit trees
Multi-species fruit trees (Orchard AF)	Agroforestry system with fruit trees as main production, sometimes combined with timber trees and crops
Multi-species dominated timber trees (Timber AF)	Agroforestry system with a variety of combinations within timber trees and crops
Cereal and sugarcane (Cereals)	Maize, rice, and/or sugarcane as sole crops, or intercropped crops
Coffee, tea, cannaceae (Sole_cash_crop)	Sole cash crops
Grass	Sole grass
Vegetables	Legumes, tubers, and other vegetables
Fallow	Fallow without trees

Table 2 Selection of treatment and control variables for PSM

ID	Variables	Unit/Implication	Coeff	*p*-value
Treatment variable				
1	Agroforestry adopters (1/0)	Dummy: whether farmers are agroforestry adopters (1) or not (0)		
Control variables				
2	Total farm area	ha	0.0645	
3	Distance to output market	km	0.064	**
4	Security of land rights	Dummy: Whether farmers have a red book (1) or not (0)	0.458	*
5	Rainfall	Dummy: Whether farmers experienced erratic rainfall over the past 5 years (1) or not (0)	1.407	
6	Ethnicity	Dummy variable: Whether farmers are H'mong (1) or not (0)	– 0.744	**
7	Sandy soil	ha	0.331	*
8	Acid soils	ha	1.107	*
9	Humus rich soil	ha	0.336	**
10	Domestic consumption from production	% of production	– 0.006	

Significance. of the *p*-values: '****' 0.001 '***' 0.01 '**' 0.05 '*' 0.1 '' 1

constructing a standardized dataset which was generated from a mean-subtracted data from the original dataset, the covariance matrix of the variables was calculated to compute eigen-vectors and eigen-values. The number of components of interest was determined by eigen-values and percentage of variance explained by the factors in the analysis. Since the eigen-values were proportional to the variance retained, we only selected the top m pairs of eigen-vectors and eigen-values leading to the minimal set of eigen-vectors with the maximum variance. Ideally, components showing eigen-values larger than 1 can be kept for further investigation since they are considered to have significant impacts on the variables. Finally, we reduced the dimensionality of the dataset. This also means that the first component explains the most information of the matrix, followed by the second component moving towards to last one (Verbanck et al. 2015).

An AHC was performed on the principal component retained to categorize households with common characteristics. The AHC algorithms portrays the data as hierarchical tree structures (dendrogram) (Dash et al. 2003). The AHC clustering used the Euclidean metric computing the dissimilarities between observations based on the root-sum-of-squares of differences. This method is commonly used after performing PCA as the first three steps of the AHC algorithm, and PCA algorithm have similar purposes (Blazy et al. 2009; Chopin et al. 2015; Ulukan et al. 2022). Therefore, we could use a transformed matrix from PCA to construct the final dendrogram such as Ward's method (Jafarzadegan et al. 2019). The number of clusters was chosen based on observing the dendrogram and the inertia. Hence, the number of groups was chosen based on the maximum difference in inertia loss between two successive partitions. After the final typology was chosen, the types obtained were described to understand the pathways of adoption of agroforestry within the households' farming systems; which included the characteristics of the different cropping systems and their proportion within the farming system.

Results

Propensity score matching quality evaluation

The PSM showed that tenure security[1] is one important determinant of agroforestry adoption (Table 2). In addition, soil types played essential roles in the likelihood of practicing agroforestry. For instance, having more acid soil type increased the chance of farmers adopting agroforestry. This positive influence also applied to 'sandy soil' and 'humus rich soil'. In addition, farmers' ethnicity was a significant factor, where the H'mong people, one of the

[1] In Viet Nam, red books are official certificates granted by the government to recognize legal ownership of a plot of land. Hence, having a red book positively improves the probability of adoption.

larger ethnic groups in this region of Viet Nam, show a lower probability to adopt. While farm size showed no significance, distance from home to the respective output market does significantly increases the chance of practicing agroforestry.

Following the matching process, each household is considered one unit, assigned with either control unit (non-adopter) or treated unit (adopter). As a result, 36 units are unmatched, including 23 untreated units and 13 treated units. These unmatched units were excluded from subsequent analyses (see Supplementary Material S1 for further explanation).

Impacts of agroforestry

Along the indicators for economic, environmental, and social impacts, we separately calculated each outcome's average treatment effect on the treated (ATT) (Table 3). Overall, five out of twelve sustainability indicators show significant ATT. The farming system performance of agroforestry adopters display a higher on-farm income by 8 million VND per hectare (about 325 USD as of December 2023). This is due to the high market value of most products grown under agroforestry systems. However, in terms of environmental sustainability, farmers that have adopted agroforestry in their farming system exhibit a significantly higher level of soil erosion, approximately 6.9% higher than non-adopters. This result may indicate that recently implemented agroforestry systems have not yet had time to reduce the erosive impact of rainfall through tree cover and soil protection. Alternatively, it could suggest that these systems are being established in areas already prone to higher erosion risk. As for the social aspect, the number of hired labour was lower in the adopters' farms by 1.64 working days per hectare. Agroforestry adopters further report to have one more month of insufficient food for the family which encompasses both the on-farm production and food purchased.

Household typology

The households in Northwest Viet Nam display a wide variety of livelihood systems from large reliance on off-farm income sources to pure farming-based families. Most household heads and decision makers have a relatively low level of education (only attended primary or middle school) and 80% of them are male. Maize and rice are the main crops of the farmers. Besides, coffee and tea, fruit trees of the temperate climate zone are commonly cultivated. Farmers' access to output markets is limited and they tend to save a proportion of crop products for home

Table 3 Average treatment effect on the treated after matching

ID	Indicators	Unit	Control	Treated	Difference (ATT)
Economic					
1	Agricultural income	million VND/ha/year	9.08	17.04	7.96*
2	Non-agricultural income	million VND/year	43.72	39.72	– 4.00
3	Crop revenue	million VND/ha/year	44.29	39.34	– 4.96
4	Cost of hiring labour	million VND/ha/year	1.69	1.43	– 0.26
5	Cost of purchasing seeds	million VND/ha/year	8.54	7.23	– 1.32
Environmental					
6	Dose of fertilizer	kg/ha/year	324.09	323.63	– 0.47
7	Dose of pesticide	litre of sprayed mixture (water and pesticide)/ha/year	2088.19	1942.79	– 145.40
8	Proportion of land with erosion	% of ha	61.45	68.35	6.90**
9	Level of erosion	Scale of 4	1.82	1.97	0.15**
Social					
10	Food security	Number of months in a year with insufficient food (both produced and purchased)	2.75	3.79	1.04*
11	Hired labour	Day's works/ha/year	4.50	2.86	– 1.64*

Signif. codes: '****' 0.001 '***' 0.01 '**' 0.05 '*' 0.1

consumption. Almost half of the household income is derived from off-farm sources.

After applying PCA, the first principle captured 10.2% of the variance and the second axis explained 9.3% of the variance (Fig. 1). Principal component 1 is correlated to the management intensity of cropping systems where the proxies' fertilization cost and workload are driving total income. Principal component 2 was positively correlated to the proportion of cereals and negatively to timber production, education level and to some extent to sole cash crop cultivation. Here, none of the components captured a large share of the variation, which highlighted the high heterogeneity within our data.

After performing the clustering, six differentiated clusters of households were identified (Fig. 2). The resulting six clusters were: (i) Off-farm income-dependent farmers, (ii) Small diversified extensive farmers, (iii) Large extensive high value crop producers, (iv) Specialist mixed agroforesters, (v) Cereal growers, (vi) Intensive market-oriented farmers.

The Off-farm income-dependent farmers households ($n=12$) rely significantly on off-farm activities for their income while agricultural production is largely devoted to household subsistence (Table 4). They have the largest farm area of 3.2 ha among the groups with more than half of the farmed area not cultivated as shown by the average 51% of fallow land and timber production. The rest of the land is shared among cereal and orchard production with 25% under agroforestry production. The Small diversified extensive farmers ($n=39$) have about a third (37%) of their small farm areas (1.5 ha in average) under agroforestry production. Their farming system is diversified as they produce fruit trees on about 34% of their farm and cereals on 43% (of which 55% are home consumed). Large extensive high value crop producers ($n=10$) resemble small diversified extensive

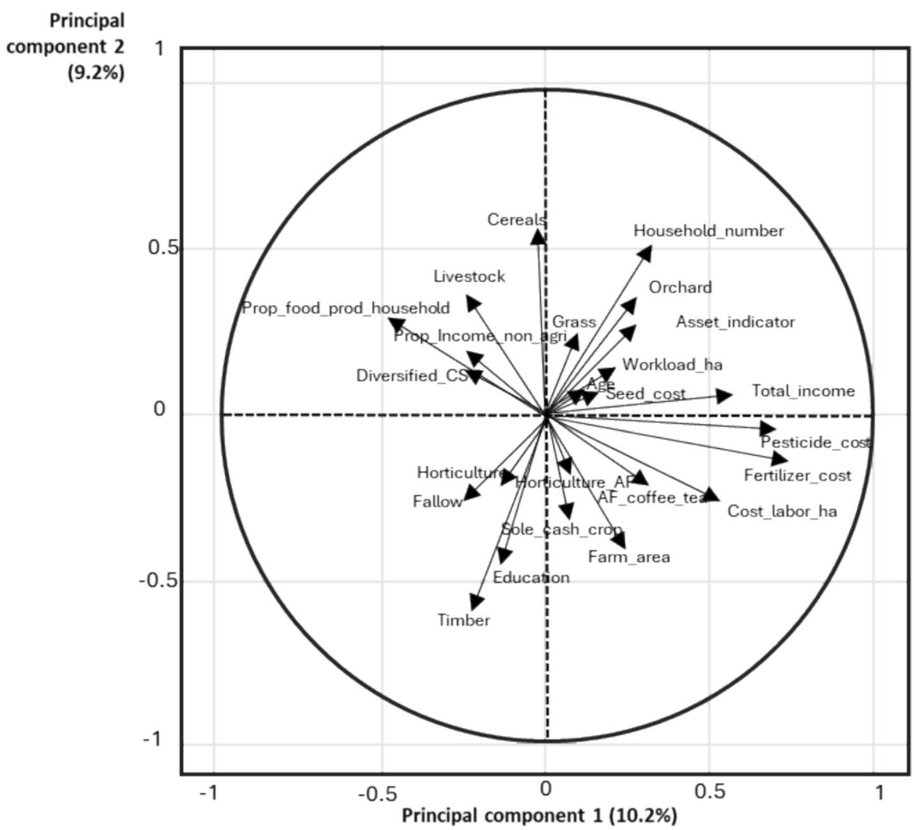

Fig. 1 Projection of the variables used for building the typology in the plane of the first two factors of the principal component analysis

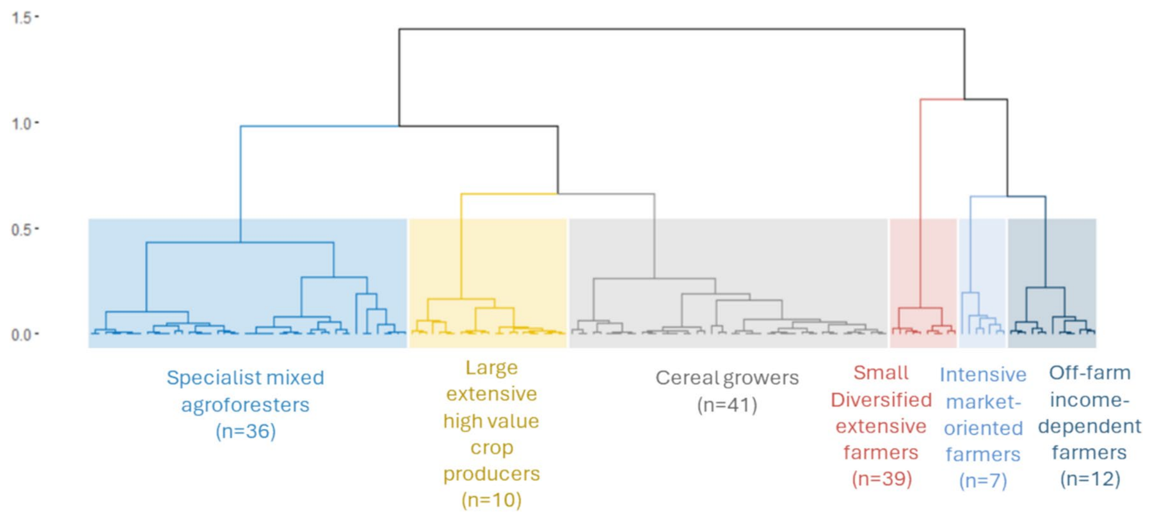

Fig. 2 Classification tree of individuals obtained from an ascending hierarchical clustering performed on the first eleven principal components of the quantitative variables. The classification in 6 groups maximizes the intra group similarity and the inter-group dissimilarity. The tree does not represent the entire population of farmers so some groups may appear smaller than they actually are

farmers but have larger farm areas (2.9 ha) and a higher level of market orientation with only 18% of production for household consumption. Their level of income is slightly higher with 58 million VND.yr^{-1} based on cash crops such as coffee, tea, and perennial medical herbs like cannacea. Specialist mixed agroforesters ($n=36$) represent the second most well-off group with 111 million VND.yr^{-1} and have the highest share of land dedicated to agroforestry with 53% of the total plot area. The central component of their farming systems are fruit and timber trees, and they still have a relatively high share of crop income with 43% of the total household income (agriculture income and off farm income). Additionally, they own significant numbers of livestock with about 12.2 TLU on their farm. The Cereal growers ($n=41$) are mostly growing cereals on 62% of their land with on average 25% agroforestry. Their workload per ha is the second highest among all farmer types. Intensive market-oriented farmers ($n=7$) represent farmers with different farming system orientation but largely market-oriented with only 18% of the food produced for subsistence and lower livestock numbers (1.7 TLU). The workload is the highest of all cluster with 1369 h ha^{-1} yr^{-1} on average (family and labour from employees) and a corresponding high use of fertiliser with 58.000 VND ha^{-1} yr^{-1}.

Discussion

Agroforestry potential in Northwest Viet Nam

Adopting agroforestry in Northwest Viet Nam shows positive signals in terms of improving the livelihoods of the local farmers. Throughout the studied region, agroforestry seems to have positively affected economic aspects, especially income. The results indicated that among adopters, agricultural income is higher by 8 million VND compared to non-adopters. This income effect has also been reported for mature agroforestry systems in other regions of the world (Neupane and Thapa 2001; Cardozo et al. 2015; Phimmavong et al. 2019; Simo et al. 2020). We found that economic benefit probably came with the adoption of agroforestry especially as agroforestry contributes to diversification of livelihood portfolio (Noeldeke et al. 2021) which is a strong motivation to adoption (Magcale-Macandog et al. 2006). Given that none of the agroforestry systems in the sample are mature yet, it is likely that the income will even increase as the system further matures and yields increase, and environmental benefits starts showing effects. Despite seeing positive economic which should offer indirect benefits for food security, such as allowing more off-farm work than traditional agriculture (Duffy et al. 2021), we did not find

Table 4 Descriptive statistics of each group of agroforestry adopters

Variable name (units)	Off-farm income-dependent farmers		Small Diversified extensive farmers		Large extensive high value crop producers		Specialist mixed agroforesters		Cereal growers		Intensive market oriented farmers	
Number of farmers	12		39		10		36		41		7	
Prop of land in Agroforestry (%)	25	26	37	23	37	29	53	30	25	12	31	34
Age (years)	50	10	38	9	51	6	50	11	48	10	44	11
Household_number	3.7	1.2	4.3	1.2	2.9	1	5.1	1.4	5.2	1.6	5.1	1.3
Education (level in school)	2.6	0.8	1.8	0.8	1.9	0.6	1.7	0.9	1	0.9	1.7	1.3
Farm_area (ha)	3.2	1.4	1.5	1.2	2.9	1.2	1.8	1.4	2	1.4	2.8	1.7
Livestock (TLU)	5.9	6.5	5.6	7.8	4.3	3	12.2	14.5	6.1	8	1.7	1.2
Prop_food_prod_household (%)	57	34	55	27	18	19	40	30	53	25	16	19
Total_income (M.VND.yr^{-1})	78	87	42	44	58	34	110	74	105	106	231	140
Prop_Income_non_agri (%)	76	30	34	34	11	21	45	36	36	36	14	24
Workload_ha (h ha^{-1} yr^{-1})	483	362	545	386	274	260	417	300	990	676	1369	1102
Fertilizer_cost (M.VND.yr^{-1})	7	14	4	3	12	8	11	12	13	13	58	38
Pesticide_cost (M.VND.yr^{-1})	0	0	1	1	3	4	2	2	4	3	8	5
Seed_cost (M.VND.yr^{-1})	3	4	2	3	6	8	13	33	3	5	10	11
Cost_labor_ha (M.VND.yr^{-1})	1	1	0	1	6	9	1	2	1	3	10	8
Asset (M.VND)	72	17	58	12	57	11	72	9	69	13	66	9
Orchard (%)	11	12	34	23	7	11	65	26	26	16	39	37
Cereals (%)	10	10	43	24	8	15	19	17	62	21	13	26
Diversified_CS (%)	2	7	3	11	0	0	9	17	2	8	0	0
Sole_cash_crop (%)	5	6	3	8	23	34	1	4	1	6	13	33
Horticulture (%)	2	4	2	5	14	30	1	7	1	5	4	7
Timber (%)	20	30	13	24	39	32	0	3	2	5	11	30
Fallow (%)	51	27	2	7	1	3	2	6	2	6	0	0
Grass (%)	0	0	0	0	0	0	2	4	1	2	0	0
AF_coffee_tea (%)	0	0	0	0	8	24	1	5	2	8	19	34
Horticulture_AF (%)	1	3	0	0	0	0	0	0	0	0	0	1

First column represents the mean value of the variable and the second one the standard deviation

such effect which could be attributable to delayed full benefits of agricultural production from agroforestry systems. When it comes to environmental impacts, it seems highly difficult to draw a strong conclusion from our results. Our analysis shows a higher erosion among adopters which could be due to two aspects namely the biophysical context of adopters and the agroforestry maturity. Indeed, depending on the type of agroforestry system, the tree component may take significant time to fully develop. Hence, benefits of agroforestry may be delayed as it has already been reported for the economic aspects (Cramb et al. 2007). This may be due to the time needed for a full development of the tree canopy and the contribution to the litter layer as agroforestry in Southeast Asia has been unequivocally shown to reduce erosion under different types of tree and crop association (Siarudin et al. 2021; Do et al. 2023, Do et al. 2024; Sittadewi et al. 2024; Gusmao et al. 2025).

Concerning the biophysical context, the analysis could be impacted by the fact that agroforestry adopters are primarily the ones that experienced in the past the most intensive erosion events which acted as a driver of adoption. This suggests that farmers who experienced more erosion before adopting agroforestry were motivated to implement it. However, during the first years of implementation, erosion may not have been significantly reduced to the levels observed among non-adopters. We do not have information regarding the level of erosion experienced before adoption of agroforestry systems. This explanation is only partially dismissed by the fact the PSM analysis controls for the rainfall intensity and soil type within the area, which are two major drivers of erosion but not for the slope level, which is also highly contributing to erosion. This may hide more pronounced potential erosion among agroforestry adopters which could explain the PSM results on this indicator. In the same way, the higher revenue could be a legacy from before adoption and could have been a driver of the initial investment made in adopting agroforestry.

The immaturity of the agroforestry system might also explain the counter intuitive increased erosion level found in the PSM analysis. Here young tree components in agroforestry systems and less root penetration may not have the anticipated effect on erosion. According to the literature (Do et al. 2023), the environmental benefits of agroforestry practices take longer to materialize and may not have taken effects yet. Therefore, it is likely that the causality in this case is reverse, and the observed effect is that farmers facing soil erosion on their farms are more likely to adopt, as the mitigation of erosion is one of the key benefits of agroforestry for upland farmers. In the same way for social impacts, the negative effect found for the food security indicator could potentially also be explained by the important costs involved in establishing and managing agroforestry systems and the delay in production of all components from the agroforestry cropping systems.

Factors to include for in depth study of farm level agroforestry effects

Generally, the adoption of agroforestry and other agronomic innovations is largely driven by multiple farm and household characteristics (e.g., farm size and land tenure) (Zabala et al. 2025). We found similar results in terms of the positive influence of formal land title in Vietnam compared to other case studies (e.g., Saint-Macary et al. 2010). Such land security has often been reported as a major factors for agroforestry adoption as found in Indonesia for multistrata agroforestry systems (Suyanto et al. 2005) or in Bangladesh along, in this last case, with the lack of capital (i.e., limited land area) (Rahman et al. 2017). In our study, we did not find an influence of total farm area on the adoption of agroforestry. This could be due to the diversity of farm types and livelihoods within the typology, which may partially obscure such an effect. Beyond these general household factors, biophysical aspects also play an important role in agroforestry adoption. For instance, in Thailand, highly suitable land is more likely to be cultivated with Eucalyptus tree farming (Boulay et al. 2012). It is generally essential to account for such factors, as comparing adopters and non-adopters without considering these differences may lead to misleading conclusions regarding the potential delivery of multiple services by agroforestry systems. Although our analysis showed some potential impacts of agroforestry, there are additional limitations that prevent confirmation over some observations made across the economic, social, and environmental impacts of agroforestry.

First, we could not control the maturity of the agroforestry-based cropping systems as the information regarding the year of establishment of the agroforestry system or the stage of development of the system is limited. This results have a potential bias in terms of quantification of income change, as economic return becomes positive 3–5 years after adoption and implementation (Wannawong et al. 2004; Do et al. 2020). This return period is also highly dependent on the characteristics of the agroforestry systems with longer delays for some tree species. Moreover, the tree cover can be limited for several years, which can increase erosion if there is no proper cover between the lines of trees. Usually, farmers established grass between the line of trees to cut for livestock feed (or grazing in the case of timber production as grazing with fruits trees can damage trees), but grass cover and grazing were difficult to estimate for farmers.

Second, the diversity of the agroforestry systems is very high and varies across households, limiting appropriate methods to compare the impacts of agroforestry practices. We found very different agroforestry cropping systems with some oriented on cereal production while other were oriented towards high value crops such as coffee. Essentially, those systems represent different innovations that should be studied independently from each other. Our grouping of agroforestry also contributed to obfuscate the effect of the type of agroforestry systems that may have different impacts due to their inherent characteristics. For instance, the cannacea system and the coffee system were grouped together under high value cash crops but the quicker growing cycle of cannacea crops may change impacts—for instance reducing erosion quicker than other cash crops.

Third, agroforestry was adopted to a different extent by farmers with some only adopting agroforestry practices on small parts of their farms and some farmers fully specializing on agroforestry. This also had implications when comparing farmers. Some farmers barely benefit from agroforestry due to their orientation towards off-farm income, for instance in the case of the group ‘Off-farm income-dependent farmers’. A proper selection of farmers that have a similar proportion of livelihood orientation and proportion of agroforestry within their farming system would reduce biases and allow for more thorough estimation of agroforestry impacts, while maintaining a sufficient number of households for the analysis.

Regarding the methodologies, while using the matching scores obtained from the PSM for the entire population to produce ATT, we found that most sampled households were matched and only a small number eliminated (36 unmatched units were dropped). Nevertheless, to preserve the initial number of observations, we need a more flexible propensity score matching approach, allowing the inclusion of non-overlap regions, for example, by using the Bayesian model network as discussed by Nethery et al. (2019). On the other hand, PSM was necessary to reduce the selection bias as much as possible. However, PSM does not allow any conclusion on the mechanisms among variables when the heterogeneity among systems is too large. Another potential approach is to re-run PSM for each cluster generated by PCA; however, this approach could remove considerably more unmatched samples and reduce the statistical power of the sub-dataset.

Conclusion

Based on the current analysis, it is difficult to conclude that agroforestry adopters obtain more sustainable livelihoods than non-adopters—or in fact the other way around as indicated by some of our outcome variable results. Nevertheless, we found significant positive impacts of practicing agroforestry regarding economic benefits. The analysis showed a substantial increase in agricultural income by 8 million VND per hectare and a decrease in the number of hired labour by 1.64 day’s work per ha. The analysis of the other sustainability dimensions reveals that agroforestry could also have unforeseen potential adverse environmental and social impacts even though those may be short term only. These results could partly be due to the early stage of household agroforestry system development, which prevents conclusions on those two dimensions for mature agroforestry practices. Therefore, effects on household food security should be explored more deeply by agroforestry system type and system maturity. Generally, the potential presence of negative effects in the early stages of adoption should be considered in the design of systems promoting agroforestry.

A major shortcoming of our study is the fact that the agroforestry systems implemented by farmers varied a lot regarding (i) the proportion of the farm area cultivated with agroforestry, (ii) the type of agroforestry system that varied from a simple one with two components to multiple components and (iii) the maturity of the system as some surveyed farmers could have implemented agroforestry on their land only shortly before the survey was performed which was not a consistent information provided by farmers. Hence, we recommend that a more robust and detailed monitoring system should be established during future projects that promote agroforestry. Specifically, the temporal dynamics around our outcome indicators could prove to be highly relevant. Furthermore, a more detailed consideration of the establishment time and the specific system and its core components would be essential to improve the understanding of the implications of set-ups of different agroforestry practices. As part of our study, a second survey conducted in the region could help identify new adopters of agroforestry systems who had not previously adopted them and compare them to non-adopters. This would provide a stronger understanding of the short- and long-term effects of agroforestry adoption. We suggest focusing on fruit-based agroforestry systems, as they are more widespread and have demonstrated greater benefits in station experiments. Additionally, we recommend surveying farmers who are significant adopters of agroforestry, meaning, farmers who have converted a large proportion of their land to agroforestry systems.

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Data availability The data that support the findings of this study are available from the corresponding author, P.C, upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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