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Assessing the sustainability of agricultural production - a cross-sectoral comparison of the blackberry, tomato and tree tomato sectors in Ecuador

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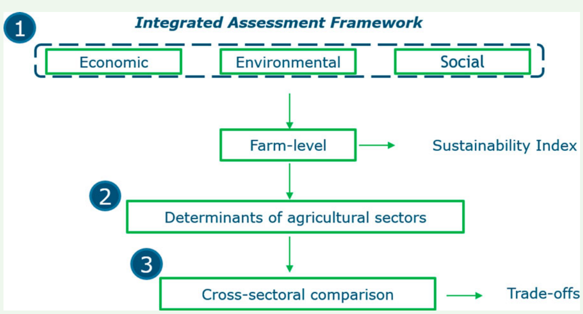
ABSTRACT

Achieving a sustainable agricultural system requires an effective assessment of economic, environmental, and social conditions. Existing research has mainly focused on a single sector and lacks critical comparisons of determinants and trade-offs between sustainability dimensions. This study adopts a cross-sectoral perspective to assess and compare the sustainability performance of fruit and vegetable farms in Ecuador. Furthermore, the study analyzes the relation between sustainability outcomes on the one hand and farm resources, farmer demographics, and farm size on the other. Principal Component Analysis and a General Linear Regression model are used in the analysis. The results show that clear disparities in sustainability performance exist between different fruit and vegetable sectors. Furthermore, on average, farms with a higher social- and economic-oriented sustainability performance are more proficient in exploiting conventional resources (land and labour). In contrast, farms with a higher environmental-oriented performance display better handling of ecological resources such as water and forests. A sustainable use of resources is needed to prevent conflicts between sustainability dimensions. The research provides novel insights to stakeholders on the integrated assessment of agricultural sustainability and its results.



KEYWORDS
Agricultural sustainability; performance assessment; principal component analysis; utility theory; farmer preferences

1. Introduction

A growing world population, adverse effects from climate change, and heightened global competition exert increasing pressure on agriculture and the use of natural resources (Antle et al., 2017; McNeill, 2019; Slapø & Karevold, 2019). In turn, intensive agricultural production methods have caused widespread environmental pollution and ecological degradation,

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triggering habitat destruction (Kurgat et al., 2018; Martey & Kuwornu, 2021; Teklewold et al., 2013). Moreover, there is increasing concern over adverse work conditions, child labour, and other social issues in large agricultural exploitations around the world, leading to calls for appropriate measures at the international level regarding the sector (Pandey, 2019; Srivastava et al., 2016). Hence, the urgency of developing sustainable, resilient and adaptable agricultural production systems is widely acknowledged (Porcuna-Ferrer et al., 2020).

While sustainability is high on policy and research agendas in recent years, applications in the agri-food sector are still in their early stages. Sustainability encompasses different, often conflicting, goals of a social, economic, and environmental nature (Rodrigues et al., 2018; Santika et al., 2020; Seghezzo et al., 2020). Balancing these goals means to satisfy human food needs, preserve natural resources, enhance actors' and rural communities' welfare and sustain economic viability without compromising current or future generations' ability to meet their needs (Darnhofer et al., 2011; Ehgartner, 2020; Erbaugh et al., 2019; Gritten et al., 2013). The accomplishment of sustainability in agricultural production systems requires a comprehensive assessment of environmental, social, and economic conditions and will raise awareness about how production systems could be reoriented towards improved sustainability (Jacobi et al., 2020; Malak-Rawlikowska et al., 2019; Tiwari & Khan, 2019; Veisi et al., 2013; Yu & Wu, 2018). However, existing research primarily focuses on only one agricultural sector and lacks critical comparisons of the determinants of sustainability and trade-offs between sustainability dimensions across different sectors (Hahn & Kühnen, 2013; Osabohien et al., 2019).

This paper will assess and compare the sustainability performance of different agricultural sectors. Furthermore, we analyze potential determinants that can explain differences in sustainability performance across sectors. A cross-sectoral comparison may provide valuable insights for the identification of sustainable practices and the development of synergies in agricultural systems. Moreover, results from the cross-sectoral analysis may boost the quality and effectiveness of sustainability performance assessments. The sectors used for the analysis are the blackberry, tomato, and tree tomato production sectors in Ecuador. These sectors are of interest because more than fifty percent of primary production in these sectors is performed by peasant households (Houtart, 2018; Lechón & Chicaiza, 2019). Furthermore, several studies have reported that these sectors have significant levels of social inequality and struggle with the appropriate use of natural resources such as water for irrigation (Astier et al., 2011; INEC, 2016; Medina, 2017). In addition, each of these sectors has attracted government support to create partnerships between agronomic research centres, academia and industry stakeholders to diversify portfolios towards more sustainable products.

Several sustainability assessment approaches exist. Examples include hierarchy evaluation, critical points identification, spatial models, product lifecycle analysis, and integrated assessments (Cristóbal et al., 2015; Huyard, 2020; Nchanji et al., 2017; Rebs et al., 2019; Thies et al., 2019). This research adopts an integrated approach to tackle the multidimensionality of agricultural sustainability. More specifically, we apply the integrated sustainability performance assessment framework (ISPA) that was developed by Moreno-Miranda and Dries (2022). The framework covers the three sustainability dimensions through qualitative and quantitative indicators that were validated by experts who assessed their feasibility and practical relevance. In the current paper, the ISPA indicators will be combined into one measure of sustainability following a principal components analysis (PCA). This will allow the comparison of sustainability across different sectors for evaluation purposes.

The research contributes to overcoming the methodological and empirical challenges of sustainability assessments of agricultural systems. Deytieux et al. (2016) and Moreno-Miranda et al. (2020) point out that a clear challenge in assessment approaches is to solve apparent conflicts between the sustainability dimensions and how to incorporate this in the weights of different indicators. The first contribution of this paper is to use an integrated assessment framework and a quantitative approach that combines indicators of each of the sustainability dimensions, without pre-assigned weights, for calculating sustainability measures. In a next step, we explicitly study potential trade-offs that exist between the three sustainability dimensions. Boas et al. (2016) argue that standardized measures in agricultural systems are necessary for evaluation, while Halbe and Adamowski (2019) claim that there are limitations in the simultaneous handling of large numbers of variables in sustainability assessments. Our second contribution is to apply principal components analysis to standardize variables, and handle relatively large multi-variable data sets. A final criticism of the existing research is that the lack of comparison in practices and the verification of results reduces the credibility of sustainability assessments (Doré et al., 2011). The third contribution of this research is therefore the cross-sectoral analysis of sustainability performance indexes and the investigation of the determinants of sustainability performance.

The paper is structured as follows. Section 2 provides the theoretical framework and hypothesis. Section 3 outlines the research design and methodology. Section 4 provides a description of the data. Section 5 focuses on the research findings. Section 6 presents the discussion of the findings. In the final section, we discuss the research implications and conclusions.

2. Theoretical framework and hypothesis development

The problem of sustainability has long been an essential part of economic research. Most research has focused on the (in)efficiency of using common-pool natural resources, the so-called 'tragedy of the commons' (Hardin, 1968), and the negative externalities associated with economic activities (Pigou, 1920). Linking sustainability and optimality goes back to Ramsey's classical work examining growth constraints (Ramsey, 1920). For Heal (2001), optimality is a refined form of sustainability, while Doyen and Martinet (2012) expand this idea by using utility theory as a basis to explore optimal growth paths for economies (Fleurbaey, 2015). Some authors (see, e.g. Cairns & Martinet, 2014; Martinet & Doyen, 2007) have explored the use of the maximin value of utility to measure what is sustainable and what is the limit to growth or development. Recent work has turned to the nexus between sustainability, utility, and preferences at the farm level. For instance, Weltin and Hüttel (2019) observed differences in ecological performance between farms and argued that this could be related to differences in environmental preferences (Kassie et al., 2015) and awareness of adopters and non-adopters of certain ecological practices.

In line with Mayen et al. (2010), we assume that farmers derive utility (e.g. ecological or social benefits) from sustainability via preferences for a particular type of practice (economic, environmental, and social-oriented). An example of a sustainable practice is the responsible use of water, while a potential benefit could be continued food production and the absence of social conflicts. This can be interpreted by utility scores, as mentioned by other authors (e.g. Hong et al., 2021; Lutta et al., 2020; Wang et al., 2020).

The utility theory (von Neumann & Morgenstern, 1953) serves as a basis which we apply to frame the farmer through a choice set based on economic, environmental, and social preferences (Muñoz-García, 2005). The choice set represents all the alternatives of resource usage (e.g. higher water use and less capital use) that a farmer can conceive – whether these will be achievable in practice or not (Jehle & Reny, 2010, p. 9). Besides the choice set, farmers are bound by constraints in farm resources (e.g. Marra & Carlson, 1987). Therefore, agricultural sustainability preferences and resource constraints together form the optimality problem. For simplicity of representation, we consider only the economic and environmental sustainability dimensions of a farmer in the following.

Consider a farmer that maximizes utility '*max U*', where utility is derived from economic and environmental sustainability, and given the resources available on-farm. The level of economic resources is denoted by x_{ec} and the level of environmental resources is denoted by x_{en}. The utility function is assumed to be concave, and increasing levels of either resource increase the farmer's utility (sustainability oriented towards a certain sustainability dimension). The farmer's sustainability problem can then be formulated as Equations (1) and (2):

$$\max_{x_{ec},x_{en}} U(x_{ec}, x_{en}) \tag{1}$$

$$\text{subject to} \;\; P_1 x_{ec} + P_2 x_{en} \leq Y \tag{2}$$

where P_1 is the monetary value incurred for buying/hiring the economic resource and P_2 the monetary value for buying/hiring the environmental resource. The constraint in (2) shows that the farmer who wants to buy/hire the two resources cannot spend more than the total budget Y. In Figure 1, we exemplify the case of two farmers (utility maximizers), where each solid black line represents a constraint (budget line) in the two resources available on-farm, economic versus environmental. Besides, each indifference curve represents those combinations of the two resources that leave the farmer equally well off or equally satisfied – hence indifferent – in having any combination on the curve. Farmers have the same preferences (parallel utility curves), and

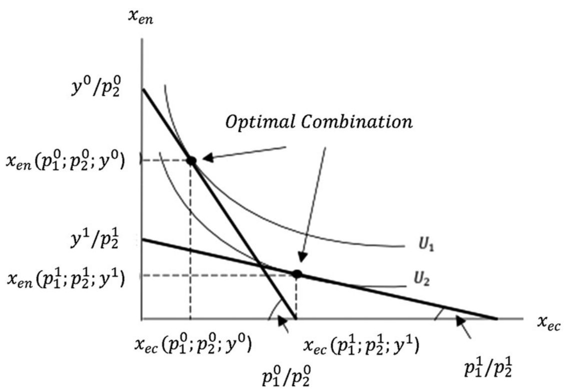


Figure. 1. Utility (sustainability) maximization of two farmers based on economic x_{ec} and environmental x_{en} resources. Source: Authors' own representation.

the optimal point of utility (sustainability) of each farmer is the point of tangency between the budget line and the indifference curve. The region below each budget line represents the set of feasible combinations of resources but with inferior utility to any point on the indifference curve.

Figure 1 shows that the farmer that is subject to the steeply sloping budget line will have higher access to x_{en}, while the farmer subject to the flatter budget line will operate with higher accessibility to x_{ec}. Furthermore, we see that different constraints in resources will lead to different levels of utility (sustainability), as the farmer that can achieve U_1 reaches a higher utility than the farmer with U_2. We frame the effect of the resource restrictions in the following hypothesis:

> **Research hypothesis:** Differences in resources between farmers will lead to different performance outcomes related to economic, environmental, and social-oriented sustainability.

3. Assessment framework, research design and methodology for analysis

3.1. Sustainability assessment framework

Figure 2 represents the Integrated Sustainability Performance Assessment (ISPA) framework (left side of the figure), based on Moreno-Miranda and Dries (2022) in combination with the cross-sectoral analysis (right side of the figure). The development of the ISPA framework was based on a structured literature review to derive sustainability indicators and validation of the indicators by sector representatives and experts based on criteria of relevance and operational

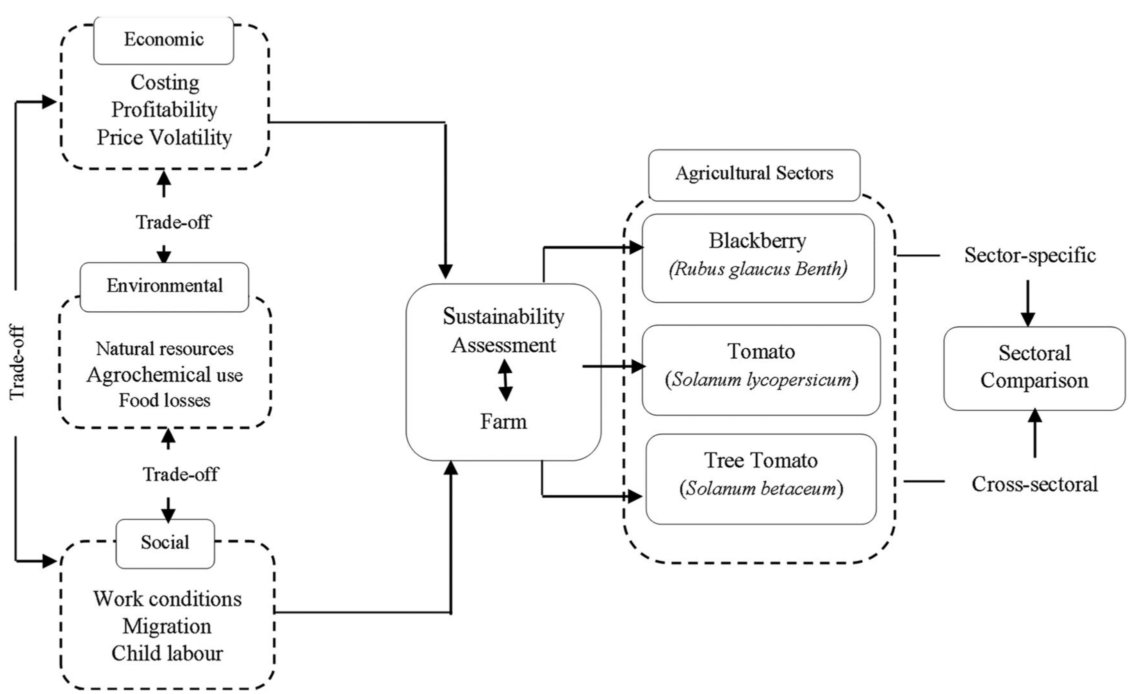


Figure. 2. An integrated assessment framework and cross-sectoral comparison. Source: Authors' representation based on Moreno-Miranda and Dries (2022).

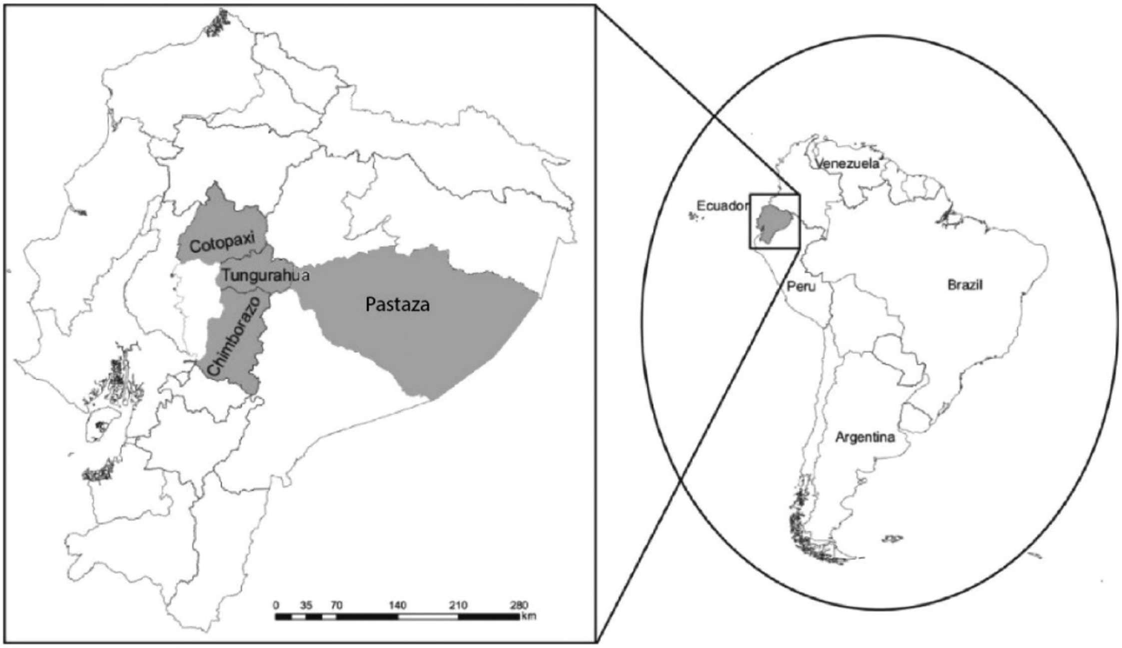


Figure. 3. Location of the study area in Ecuador. Source: Authors' representation.

feasibility. De Olde et al. (2016) consider similar aspects for evaluating farm sector sustainability in Denmark. The framework includes *costing*, *profitability*, and *price volatility* categories for the economic dimension, *natural resource consumption, agrochemical use* and *food losses* categories for the environmental dimension, and *work conditions, migration,* and *child labour* categories for the social dimension. Indicators of each category are described in Appendix A1.

3.2. Methodology for data collection

3.2.1. Study area

The study area is the Inter-Andean zone of the central region (Figure 3; center-east Ecuador–between 1 14 00 S and 78 37 W). The region includes Cotopaxi, Tungurahua, Chimborazo, and Pastaza provinces. The cultivated area is around 700,000 ha. In the warm-rainy season (December-May) the temperatures range from 11 to 25 °C. In the cold-dry season (June-November) temperatures range from 5 to 14 °C. Agriculture is extensive and conventional, and is focused on the production of feed for livestock and food for people. Tubers-, cereals-, fruits- and vegetables-based farming systems are the most important; the most widely cultivated crops are maize (Zea mays L.), potato *(Solanum tuberosum)*, blackberry *(Rubus glaucus Benth)*, tree tomato *(Solanum betaceum)*, quinoa *(Chenopodian quinoa)*, and tomato *(Solanum lycopersicum)* (INIAP, 2018). Production in these sectors is mainly based on peasant family farming.[1] The well-being of peasant producers is vital in the public policies of the country and programmes of multilateral organizations (Moreno-Miranda et al., 2019). These policies and programmes seek to stimulate the family economy, revalue the rural environment, strengthen food sovereignty and promote sustainability.

3.2.2. Survey design

A survey to gather the necessary information to apply the ISPA framework was designed with questions in English, translated to Spanish (respondents' native language), and checked by three experts to make sure that all terms were easy to understand. Cronbach's alpha coefficient validated the survey (Chan & Idris, 2017). We pilot-tested the survey through exploratory interviews with smallholders from 15 farms (blackberry, tomato, and tree tomato) and five representatives of agricultural associations chosen from the sample randomly. Some questions were adapted to the nature of the production sector, for example, packages and weights used to trade products (e.g. blackberry in buckets of 6.7 kg, tomato in boxes of 20.5 kg, and tree tomato in bags of

38.5 kg). The final survey consists of four major sections. The first section captures farmer and farm characteristics. The second section collects information on the economic performance of the farm in production and market activities. The third section tackles environment-related activities that respondents carry out on the farm. The last section examines the social conditions of workers and family members that operate on the farms.

3.2.3. Sample selection

The study population consists of all farms belonging to the blackberry, tomato, and tree tomato sectors registered by the Ministry of Agriculture of Ecuador on the 31st of December 2019. Registered farms are subjected to the authorities' requirements, such as the peasant health insurance and taxpayer registry (Molina-Vera, 2021). In cooperation with a group of technicians of the Ministry of Agriculture, we randomly selected 1800 farms for the initial sample. The final sample included 1443 farms as personal and labour-related reasons impeded some farmers from participating in the interviews. The sample distribution is described in Table 1.

The crop sectors in Ecuador can be classified as emerging or conventional sectors. According to Cruz et al. (2017), emerging sectors are those that experiment with a transition phase and grow at a good pace. These sectors do not yet make a considerable contribution to the country's gross domestic product. Aspects such as a well-known local product, high growth rates, and expansion at the regional level, progressive industrialization, profound social changes, and growth potential are common in these sectors.

Herger et al. (2008) point out that conventional sectors have an economic activity characterized by the ease of doing business, leading to larger volumes being traded than in emerging sectors. These sectors make a significant contribution to a country's gross domestic product. Often these sectors are prioritized to add value to raw materials and boost innovation. Besides, these sectors have more workforce available because agricultural high schools focus heavily on students' skills development for these sectors. Aspects such as local and regional recognition, developed infrastructure, and technological transfers are features of these sectors. The three sectors in our study include one conventional and two emerging sectors (see Table 1).

3.2.4. Pilot-test and data collection

The pilot-test showed that an in-situ visit is the best method for the survey distribution. The survey target was farm owners or family farm heads, who were asked to respond on behalf of their business. To encourage response, we contacted representatives of organizations that farmers belong to (e.g. associations, cooperatives, unions, and guilds). These representatives encouraged farmers to participate in the study and agree to a visit. Visit dates often coincided with member meetings for the convenience of the respondents. After obtaining representatives' permission and visit dates, a team of 4 people conducted the survey iteratively in three waves over several months. All interviews were conducted with individual farmers and in a private space. On average, each interview took around 10 min. Twenty percent of the meetings were rescheduled due to a low attendance rate of farmers. In total, 90 percent of responses were collected from individual respondents during group meetings, and farm visits completed the remaining 10 percent.

3.3. Methodology for analysis

3.3.1. Principal components analysis and sustainability index

A common characteristic of sustainability assessment approaches is the use of several indicators simultaneously. According to Nardo et al. (2005), the calculation of indexes based on indicators is a helpful tool for transferring multi-dimensional information on the performance of economic sectors. Principal Component Analysis (PCA) is a multivariate technique

Table 1. Distribution of farms per crop sector in the study sample.

Code	Crop Sector	Type	Category	Location	Sample size	%
BL	Blackberry	Conventional	Fruit	Ch / Tg	561	38.9
TM	Tomato	Emerging	Vegetable	Ch / Tg	480	33.3
TT	Tree tomato	Emerging	Fruit	Ct / Tg	400	27.8

Note: Ch = Chimborazo province; Tg = Tungurahua province; Ct = Cotopaxi province
Source: Authors' survey

that is frequently used to construct indexes in exploratory data analysis and predictive models (Krishnan, 2010; Kristjanpoller & Minutolo, 2018). The main objective of PCA is to minimize the dimensionality of a data set consisting of interrelated variables while conserving variation (Doukas et al., 2012). This is achieved by transforming the indicators in the data set into a new set of variables, the Principal Components (PCs), which are uncorrelated, orthogonal, and ordered (Ghorbani & Chong, 2020). PCA has the advantage of being sensitive to the relative scaling of the original variables (Stock & Watson, 2002). These characteristics of PCA are advantageous for index construction.

PCA has been used in a wide range of applications in various research fields: to characterize populations in urban areas; to identify agricultural trends; to evaluate regions' industrial capabilities; to analyze resource costs; and to construct socio-economic indicators (Chan & Park, 2005). In the agricultural sector, authors have used PCA in the context of water waste in irrigation schemes (Dearing et al., 2019; Muema et al., 2018); pollution in vegetable supply chains (Sawut et al., 2018); adaptability of production systems to variable weather conditions (Abi Saab et al., 2019); agricultural development based on cultivation technologies (Rasmussen & Reenberg, 2014); and the impact of value chains on farmers' livelihoods (Kousar et al., 2019). To the best of our knowledge, PCA has not yet been used to assess the sustainability performance of different fruit and vegetable sectors. We will use PCA to calculate indexes of the economic, environmental, and social sustainability of farms in the three production sectors, blackberry, tomato, and tree tomato.

The steps in the calculation of the Sustainability Index (ξ) are: (i) applying PCA on the economic (x_n), environmental (r_d) and social (w_a) indicators; and (ii) combining the corresponding PCs for the estimation of separate sustainability indexes (ξ, economic, environmental, and social indexes).

Step 1: PCA application. The application of PCA consists of multiple stages. In the first stage, normalization of the selected indicators of the three sustainability dimensions is carried out by using Equation (3):

$$X_{ik\ normalized} = \frac{X_{ik} - Min(X_k)}{Max(X_k) - Min(X_k)} \quad (3)$$

where X_{ik} is the value of farm i for indicator k, $Min(X_k)$ is the lowest value of indicator k, and $Max(X_k)$ is the highest value of indicator k. Equation (3) transforms all the selected indicators to a 0–1 scale. The value of 0 is assigned to the farm with the lowest value of the sustainability indicator. A value of 1 is assigned to the farm with the highest value of the selected indicator.

In the second stage, the correlation matrix (R) is calculated, which depicts the interrelations between the indicators. A value close to 1 (or −1) means that indicator k is strongly correlated positively (or negatively) with other indicators. A value close to 0, means that indicator k is uncorrelated with other indicators. If an indicator is uncorrelated with the rest of the indicators, then the method will exclude it from the analysis.

In the third stage, eigenvalues and eigenvectors of the correlation matrix are calculated. The calculation is based on Equation (4):

$$(R - \lambda I) = 0 \quad (4)$$

where R is the correlation matrix ($n \times n$), λ is the symbol for eigenvalues, and I is the unit matrix. Solving for λ, a nth degree polynomial equation is obtained, and n eigenvalues are calculated. The eigenvalues with higher scores (greater than 1) are used for calculating the indexes, while eigenvalues with small scores are ignored. The eigenvectors are derived from Equation (5):

$$(R - \lambda_j I)F_J = 0 \quad (5)$$

where R is the correlation matrix, λ_j is the eigenvalue of the estimated Principal Component j, I is the unit matrix and F_J is the matrix of the eigenvector corresponding to the λ_j eigenvalue.

Finally, a matrix of vectors is derived based on the calculated eigenvectors. The matrix of vectors is transposed and multiplied by the original normalized indicators. This results in the transformation of the original set of indicators into Principal Components (PCs). The PCs are normalized linear functions of the indicator variables and are mutually orthogonal. The first PC accounts for the largest proportion of total variation of all indicator variables. The second PC accounts for the second-largest proportion and so on.

Step 2: Estimation of separate Sustainability Indexes. The Sustainability Index (ξ) is calculated based on Equation (6).

$$\xi_i = \frac{\lambda_1 C_1 + \lambda_2 C_2 + \ldots + \lambda_j C_j}{\lambda_1 + \lambda_2 + \ldots + \lambda_j} \quad (6)$$

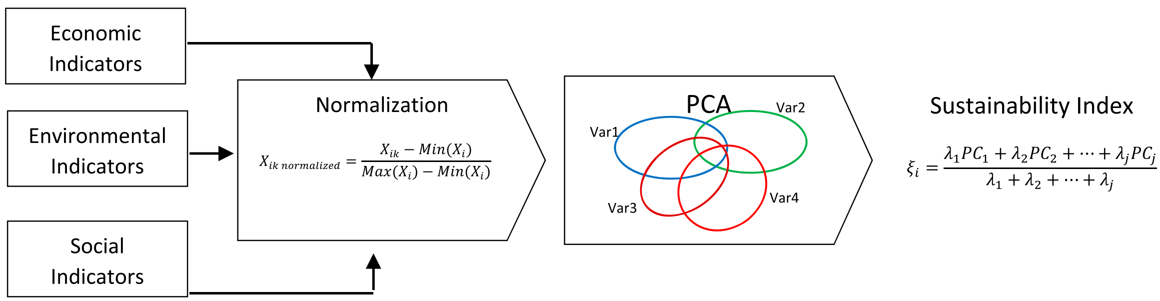


Figure 4. Steps for the estimation of the Sustainability Index. Source: Authors' own representation.

where ξ_i is the economic, environmental or social sustainability index of farm *i* and $\lambda_j C_j$ is the multiplication of eigenvalue *j* with its corresponding Principal Component. $\lambda_j = varC_j$ and $\lambda_1 + \lambda_2 + \ldots + \lambda_j$ is the total variation of an index, hence the variances are used as weights. Sustainability Index components are ranked based on their eigenvalues (from the highest to the lowest value) which helps to express the index as a weighted sum of the normalized version of the indicators. Figure 4 shows an overview of the estimation process of the Sustainability Index.

Furthermore, a cut-off point is used to denote the boundary between sustainable and unsustainable performance. The study adopts the Gomez et al. (2015) approach, which uses the community average as a primary basis to establish the cut-off point instead of an absolute value for all situations. This seems reasonable since farmers commonly judge their state of well-being on the basis of their position relative to their neighbours.

3.3.2. Econometric model

To examine the determinants of the sustainability performance of farms we will estimate an econometric model using the generalized linear model – GLM. In line with our theoretical framework, we include farm resources as key explanatory variables of farm sustainability in our model. Previous studies (e.g. Brown et al., 2019; Ebel, 2020) have also incorporated farm and/or farmer characteristics as potential determinants of sustainability. The econometric model is presented in equation (7):

$$Farm\ Sustainability\ (\xi_i) = f(\ farm\ resources_i,\ \ farmer\ demographics,\ \ farm\ size) \quad (7)$$

where *farm resources*$_i$, *farmer characteristics* and *farm size* are vectors of the economic, ecological, and social resources owned by farm *i*, the characteristics of the farmer and farm household; and characteristics of the scale of the farm operation. Note that, to reduce the potential for spurious correlation, the estimation with the economic performance as a dependent variable has environmental and social resources as explanatory variables; the model with environmental performance as dependent variable has economic and social resources as explanatory variables; and the model with social performance has economic and ecological resources as independent variables.

3.3.3. Cross-sectoral analysis

Sustainability performance is expected to differ between agricultural sectors. Our analysis therefore compares the ξ_i of farms across different sectors. The cross-sectoral analysis aims to identify cross-sectoral sustainability relationships and trade-offs (Philipp et al., 2012). To represent the sectoral ξ_i, scores are illustrated through scatter plots. Furthermore, we use a robust ANOVA and multiple comparison test to identify significant differences in sustainability scores and determinants between sectors.

4. Data

4.1. Sustainability indicators

The *costing*, *profitability*, and *volatility* categories examine six (from x_1 to x_6), two (x_7 and x_8), and one (x_9) variable, respectively. The *natural resource consumption*, *agrochemical use*, and *food losses* categories evaluate three (from r_{10} to r_{12}), three (from r_{13} to r_{15}), and one (r_{16}) variable, respectively. The *work conditions* category assesses seven variables (from w_{17} to w_{23}), and *migration* and *child labour* categories consider one variable, w_{24}, and w_{25}, respectively. Table 2

Table 2. Descriptive statistics of sustainability indicators.

Category	Code	Variable		Unit	Blackberry		Tomato		Tree tomato	
					Mean	s.d.	Mean	s.d.	Mean	s.d.
Costing	Economic									
	x_1	Labour use		laborers / kg	0.024	0.020	0.004	0.001	0.005	0.003
	x_2	Labour cost		USD / kg	0.995	0.740	0.170	0.114	0.169	0.104
	x_3	Production cost		USD / kg	1.157	0.437	0.238	0.045	0.055	0.040
	x_4	Agricultural input cost		share	27.213	16.275	23.368	15.389	33.390	15.384
	x_5	Transport cost		share	19.764	15.970	16.871	12.656	27.946	20.186
	x_6	Self-Consumption		share	27.432	17.302	15.813	11.523	9.170	6.792
Profitability	x_7	Price		USD / kg	1.492	0.321	0.566	0.095	0.725	0.092
	x_8	Gross margin		USD / kg	0.426	0.313	0.327	0.104	0.631	0.102
Price volatility	x_9	Farmer perception		score [1-10]	5.271	1.990	5.797	1.569	5.778	1.359
Natural Resource consumption	Environmental									
	r_{10}	Water use		m^3 / kg	0.480	0.289	0.045	0.023	0.038	0.014
	r_{11}	Fossil fuel use		gal / kg	0.335	0.108	0.026	0.0063	0.042	0.022
	r_{12}	Crop rotation		number	1.280	1.141	1.555	1.360	1.069	0.921
Agrochemical overuse	r_{13}	Fertilizer use		share	24.915	14.892	25.924	19.997	17.489	13.121
	r_{14}	Pesticide use		share	17.967	10.998	12.492	10.324	17.062	12.910
	r_{15}	Bioproduct use		share	23.382	15.510	31.358	23.831	50.083	16.408
Food losses	r_{16}	Farmer perception		score [1-10]	7.685	1.494	4.772	2.102	6.698	1.970
Work conditions	Social									
	w_{17}	On-farm	overload	h / worker	0.701	0.612	1.767	1.433	1.569	1.363
	w_{18}		underemployment	h / worker	0.853	0.632	2.601	1.288	2.143	1.643
	w_{19}	Off-farm	overload	h / worker	0.182	0.137	0.797	0.449	0.988	0.514
	w_{20}		underemployment	h / worker	2.720	1.369	3.489	1.924	3.369	1.272
	w_{21}	Health Insurance Satisfaction		score [1-10]	5.878	1.726	3.061	1.590	2.402	1.086
	w_{22}	Training level	Ecology	score [1-10]	5.148	2.152	6.866	2.203	6.077	2.515
	w_{23}		Entrepreneurship	score [1-10]	5.072	1.845	5.555	1.952	5.936	1.694
Migration	w_{24}	Rural-to-urban		household share	20.938	8.267	24.401	2.857	19.155	3.853
Child labour	w_{25}	Child labour			20.105	7.284	15.017	2.901	16.436	3.753

Note: s.d. is standard deviation
Source: Authors' own representation

Table 3. Descriptive statistics of agricultural determinants and sustainability indicators.

			Blackberry		Tomato		Tree tomato	
Code	Variable	Unit	Mean	s.d.	Mean	s.d.	Mean	s.d.
Farm resources								
Income	Farm income	USD	2805	1439	2925	1722	9500	1933
Workforce	Perception of workforce availability (1 unavailable – 10 available)	score [1-10]	7.20	2.29	3.14	1.74	5.31	2.05
Land	Land	m^2	2055	1462	1870	920	3464	1590
Organic matter	Organic matter	Ton/season	18.33	12.22	11.60	6.90	25.08	16.40
Forest	Forest	Tree number	19.50	10.50	75.60	29.70	68.50	20.30
Water	Irrigation water	m^3/season	238.50	107.30	210.10	99.30	422.10	174.90
Farmer demographics								
HH_size	Household size	number	3.30	1.70	4.10	1.30	4.50	1.50
Age	Age	year	49.70	12.90	46.0	12.40	39.10	11.0
Edu	Education	year	6.90	2.90	8.0	2.50	8.0	2.20
Farm size features								
Area	Acreage	m^2	1759	1525	1513	1351	3465	4590
Density	Crop density	plant/m^2	0.11	0.01	1.11	0.21	0.26	0.04
Harvest	Harvest	kg / plant	5.63	1.06	3.35	0.56	23.98	10.91
Yield	Yield	kg / m^2	0.46	0.19	3.04	0.42	5.24	0.84

Note: s.d. is standard deviation
Source: Authors' own representation

summarizes summary statistics for the sustainability indicators for the sample of blackberry, tomato, and tree tomato farms.

4.2. Variables in the regression model

Table 3 summarizes summary statistics of variables corresponding to farm resources, farmers' characteristics and farm size characteristics. The table shows standard deviations to illustrate the extent to which variables vary within the sample of blackberry, tomato, and tree tomato farms.

4.2.1. Farm resources

On-farm resource availability influences preferences for on-farm management (Dogliotti et al., 2006). For instance, a greater land/labour ratio of a farm may lead to a greater emphasis on mechanization; on the other hand, when the ratio tends to be small, a farmer might focus on intensive labour use (Nziguheba et al., 2021). Key farm resources that are considered in the analysis are farm income (*Income*), workforce (*Wkforce*), land (*Land*), organic matter (*Orgmat*), forest (F*orest*), and water (*Water*).

4.2.2. Farmer characteristics

Previous studies (e.g. Burton, 2014) have identified a link between the farmers' behaviour and characteristics. Demographic features such as age and education can influence farmers in adopting sustainability schemes (Lambert et al., 2007). Better educated farmers are found to have a higher preference for environmental enhancement of the farm and inclusive practices (Anwarudin & Dayat, 2019), whereas traditional farmers tend to prefer more intensive production and land use (Bernard et al., 2014; Wilson & Tisdell, 2001). Understanding how demographic factors influence sustainability preferences is essential for determining trade-offs. The *farmer characteristics* that are included are the farm household size (*HH_size*), age of the head of the household (*Age*), and the education level of the household head (*Edu*).

4.2.3. Farm size characteristics

The link between farm size and sustainability in agriculture has been found in various contributions. For example, smaller farms are widely advocated as being more appropriate for implementing ecologically beneficial farming practices (Woodhouse, 2010); and the productivity on larger farms may suffer from less efficient labour supervision, compared to smaller farms that use a higher proportion of family labour (Garzón Delvaux et al., 2020). We therefore consider farm size characteristics and how they influence farms' economic, environmental, and social performance. For this purpose, farm size includes acreage (*Area*), crop density (*Density*), harvested volume (*Harvest*), and yield (*Yield*) variables.

A possible concern for our empirical approach is that of endogeneity. Endogeneity may occur because unobserved variables can affect both independent and dependent variables. For instance, we miss a good indicator for farmer skills, but farmer skills may affect both yield and sustainability performance. We have tested for endogeneity in the econometric model but could not resolve it fully; therefore, we consider our results to indicate correlations rather than causal effects.

5. Results

5.1. Selecting principal components

Based on the methodology described in Section 3.4.1 and using the Statistical Package for Social Sciences Amos (IBM SPSS Amos software), the twenty-five selected indicators are analyzed to extract principal components. These principal components are subsequently used to estimate economic, environmental, and social performance indexes (ξ_i) per farm. Indicators must be correlated to make PCA feasible. Appendix A2 shows that the indicators present significant coefficients of correlation in absolute terms. Table 4 shows the eigenvectors and eigenvalues with their cumulative variability resulting from PCA. PCA was applied on the indicators per sustainability dimension. The cumulative variances of the eigenvalues show that the first three principal components per dimension include the majority of the information (between 63.88% and 83.72% of the total variance).

The eigenvectors between indicators and performance components show differences and similarities across sectors (numbers in bold). On the side of the economic dimension, the agricultural input cost, output price, and gross margin correlated with the performance of all sectors, while the transport cost mostly loaded for blackberry and tree tomato farms. In the

Table 4. Principal components of sustainability.

		Blackberry			Tomato			Tree Tomato		
Variable		C1	C2	C3	C1	C2	C3	C1	C2	C3
Economic										
Labour use		**0.33**	0,18	−0,04	0.29	0.07	0.27	**0.34**	0.05	0.01
Labour cost		0.29	0.17	0.01	0.11	0.05	**0.55**	0.33	0.03	0.00
Production cost		0.29	−0.17	0.01	**0.38**	0.01	−0.15	**0.34**	0.03	0.01
Agricultural input cost		0.03	0.01	**−0.57**	−0.11	−0.09	**0.41**	0.02	0.00	**−0.54**
Transport cost		−0.03	−0.07	**0.58**	−0.04	0.03	**0.39**	−0.01	0.00	**0.52**
Self-Consumption		**0.33**	−0.11	0.00	**0.40**	0.06	−0.11	0.00	−0.19	−0.07
Price		0.20	**0.48**	0.03	0.07	**0.53**	−0.04	0.13	**0.52**	−0.02
Gross margin		−0.08	**0.47**	0.01	−0.10	**0.48**	0.03	−0.01	**0.46**	−0.02
Farmer perception on volatility		0.03	0.12	0.26	0.05	0.09	0.00	0.02	0.03	0.19
Eigenvalue		2.58	1.74	1.37	2.50	1.72	1.32	3.23	1.75	1.66
% Variance		32.70	24.21	18.19	31.72	23.73	17.22	38.87	23.40	20.46
Cumulative %		32.70	56.91	75.10	31.72	55.45	72.67	38.87	62.27	83.72
Environmental										
Water use		0.07	**0.64**	−0.12	0.01	−0.15	**0.64**	**0.51**	0.01	0.06
Fossil fuel use		−0.11	**0.48**	0.28	−0.05	0.16	**0.57**	**0.50**	−0.02	0.01
Crop rotation		0.08	0.32	−0.25	**0.54**	−0.03	0.02	0.07	0.31	0.26
Fertilizer use		**0.55**	0.05	**−0.33**	−0.02	0.42	0.05	−0.08	**0.46**	−0.25
Pesticide use		0.14	−0.03	**0.73**	−0.40	−0.29	0.11	−0.01	**−0.53**	−0.06
Bioproduct use		**−0.56**	−0.02	−0.18	−0.02	**0.44**	−0.04	−0.01	−0.16	**0.69**
Farmer perception on food loses		−0.05	−0.03	0.15	**0.44**	**−0.45**	0.04	0.06	0.10	**0.51**
Eigenvalue		2.39	1.57	1.20	1.87	1.50	1.33	1.99	1.62	1.11
% Variance		27.71	24.63	18.76	30.77	22.60	19.61	32.36	27.16	17.90
Cumulative %		27.71	52.34	71.10	30.77	53.37	72.98	32.36	59.52	77.42
Social										
On-farm	overload	**0.40**	−0.11	0.12	**0.58**	−0.03	0.00	0.05	**−0.57**	−0.08
	underemployment	−0.03	**0.55**	0.04	−0.31	0.34	−0.01	−0.06	**0.49**	0.01
Off-farm	overload	−0.36	0.16	0.15	**−0.34**	−0.08	0.03	−0.31	0.21	−0.10
	underemployment	**0.48**	0.07	−0.04	0.10	0.39	**0.43**	0.15	0.31	−0.10
Training level	Ecology	0.06	−0.13	0.35	0.32	**0.55**	−0.20	**0.45**	0.07	0.60
	Entrepreneur	−0.17	**0.51**	−0.14	−0.06	**0.42**	0.01	**0.47**	0.11	−0.03
Rural-to-urban		−0.04	0.13	**0.49**	−0.11	0.00	0.40	−0.34	0.08	0.03
Child labour		−0.06	−0.03	**0.59**	0.02	−0.09	**0.53**	0.02	−0.04	**0.59**
Health Insurance Satisfaction		−0.24	−0.38	−0.07	0.29	0.00	0.31	0.04	0.05	**0.60**
Eigenvalue		1.96	1.39	1,21	1.79	1.31	1.25	1.86	1.37	1.19
% Variance		27.53	22.31	17.43	25.55	22.50	15.82	25.53	21.31	17.13
Cumulative %		27.53	49.84	67.27	25.55	48.06	63.88	25.53	46.84	63.97

Note: Numbers in bold are the highest eigenvectors (loadings) between indicators and components for each sustainability dimension
Source: Authors' own representation

environmental dimension, the water, fossil fuel, and bioproducts use correlated with the scores of the three sectors. At the same time, crop rotation is mainly correlated with the performance of the tomato farms. For the social performance, the importance of the on-farm overload of work and training level is common in the three sectors, while rural-to-urban migration mostly correlates with blackberry farms.

5.2. Estimating sustainability indexes

Table 5 shows the share and the absolute number of farms per sector and per interval of scores for ξ_i (sustainability indexes). The results show heterogeneity in the three sustainability dimensions across sectors. The average indexes for economic and social performance are the lowest of the three evaluated dimensions; on average, they score 0.86 and 0.91, respectively. The average index of environmental performance has the highest score, 1.32. In the economic dimension, 60% of tree tomato farm scores are in the 1.0 - 1.2 interval, and at least 15% of farms score above the sector cut-off point (1.11); while blackberry and tomato farms are more concentrated in lower intervals, but at least 23% and 19% of farms, respectively, are above their cut-off points (0.94 and 0.62). For the environmental index, tomato farms are highly concentrated in the 1.4–1.6 and 1.6–1.8 intervals, with 40% and 20%, respectively, and at least 25% of farms are above the cut-off point (1.53), while farms in the other two sectors score lower and less than 17% of farms of each sector is above the cut-off points. For the social index, blackberry farms are more concentrated in the higher intervals, 1.0 - 1.2 (44% of farms) and 1.2–1.4 (18% of farms) and at least 28% are above the sector cut-off point (1.12). Appendix A3 summarizes these findings through histograms and parametric density functions for each sector.

5.3. Cross-sectoral comparison

5.3.1. Determinants of sector-specific performance

Table 6 shows results for the generalized linear model – GLM regression. Appendix A4 shows the correlation coefficients for the independent variables.

The analysis of farm resources shows that households with higher income perform better economically and socially in the blackberry and tree tomato sectors. Farms with better access to the workforce have better socio-economic performance, but farms with higher land ownership (owned or rented) perform worse socially. The higher on-farm use of organic matter in different cropping activities is positively correlated with ecological sustainability. Forest-rich farms have better environmental performance but lower economic outcomes. Better access to water shows higher financial results but a lower ecological effect.

Farmer demographics show that younger farm heads with larger households do better economically; instead, older farm heads do better in environmental terms. More educated and trained farm heads achieve higher socio-economic scores.

Concerning the farm size characteristics, small-scale farms perform better than large-scale farms in all dimensions. Whereas high yields in production

Table 5. Number and share of farms per sustainability index interval for 1442 farms in the blackberry (561), tomato (481), and tree tomato (400) sectors.

Sustainability Index interval	ξ^{bl}_{ec}	ξ^{tm}_{ec}	ξ^{tt}_{ec}	ξ^{bl}_{en}	ξ^{tm}_{en}	ξ^{tt}_{en}	ξ^{bl}_{so}	ξ^{tm}_{so}	ξ^{tt}_{so}
<0.2	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
0.2-0.4	0 (0)	10 (46)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	7 (34)	0 (0)
0.4-0.6	5 (26)	28 (135)	4 (18)	0 (0)	3 (14)	0 (0)	0 (0)	21 (99)	1 (1)
0.6-0.8	19 (108)	43 (210)	5 (19)	3 (16)	3 (14)	4 (15)	5 (30)	41 (198)	15 (58)
0.8-1.0	53 (300)	14 (67)	16 (59)	9 (53)	4 (16)	5 (18)	23 (129)	16 (79)	47 (193)
1.0-1.2	18 (100)	5 (22)	60 (241)	39 (221)	7 (33)	15 (60)	44 (248)	6 (28)	26 (105)
1.2-1.4	5 (27)	0 (0)	11 (45)	34 (197)	18 (92)	57 (229)	18 (102)	4 (16)	6 (23)
1.4-1.6	0 (0)	0 (0)	4 (18)	9 (53)	40 (193)	12 (49)	6 (34)	3 (14)	5 (20)
1.6-1.8	0 (0)	0 (0)	0 (0)	4 (21)	20 (96)	4 (15)	3 (17)	2 (13)	0 (0)
1.8-2.0	0 (0)	0 (0)	0 (0)	0 (0)	5 (22)	3 (14)	1 (1)	0 (0)	0 (0)
Cut-off point per dimension and sector	0.94	0.62	1.11	1,22	1,53	1,30	1.12	0.71	0.93
Average Index per dimension		0.86			1.32			0.91	

Note: $\xi^{bl\ tm\ tt}_{ec\ en\ so}$ is the economic, environmental and social Sustainability Index in the blackberry, tomato and tree tomato sectors, respectively. xx (xx) – percentage of farms (number of farms)
Source: Authors' own representation

Table 6. Regression results for the econometric model, determinants of ξ_i sustainability performance indexes per sector.

	Blackberry			Tomato			Tree tomato		
Dependent	ξ_{ec}	ξ_{en}	ξ_{so}	ξ_{ec}	ξ_{en}	ξ_{so}	ξ_{ec}	ξ_{en}	ξ_{so}
Intercept	0.832***	1.231***	0.991***	0.319***	1.611***	0.604***	0.936***	1.305***	0.902 ***
Income	2.01e^{-5} ***	−4,25e^{-6} *	1.83e^{-6} ***	−2.37e^{-5} *	0.001*	−4.67e^{-5} *	6.88e^{-5} *	−4.02e^{-6} *	2.82e^{-5} ***
	(0.04)	(−0.11)	(0.37)	(−0.05)	(0.02)	(−0.06)	(0.16)	(−0.08)	(0.53)
Workforce	0.001**	−4.87e^{-6}	0.001**	0.001**	6.62e^{-5}	0.001*	0.001**	4.47e^{-5}	0.001
	(0.08)	(−0.06)	(0.11)	(0.09)	(0.01)	(0.03)	(0.106)	(0.01)	(0.01)
Land	5,6e^{-6}*	−2.28e^{-6}	−1.12e^{-5}*	−2.1e^{-6}	−1.13e^{-5}*	−4.08e^{-5}*	−1.77e^{-5}**	−2.31e^{-5}*	−1.46 e^{-5}*
	(0.11)	(−0.04)	(−0.16)	(−0.27)	(−0.14)	(−0.05)	(−0.84)	(−0.09)	(−0.55)
Organic matter	−0.001**	6.63e^{-6}*	−0.001	0.001**	0.003***	−0.001	0.001	0.004***	−0.001
	(−0.11)	(0.03)	(−0.06)	(0.12)	(0.22)	(−0.01)	(0.01)	(0.61)	(−0.01)
Forest	−0.001***	0.001**	0.001	−0.002*	8.06e^{-5}*	−5.94 e^{-5}***	−3.95e^{-5}*	2.76e^{-5}	2.98e^{-5}*
	(−0.55)	(0.24)	(0.21)	(−0.11)	(0.05)	(−0.47)	(−0.48)	(0.03)	(0.29)
Water	0.001**	−0.001***	−0.002**	0.001*	−3.09e^{-5}	0.001*	0.001**	−1.72e^{-5}**	2.15e^{-5}**
	(0.19)	−0.32	(−0.22)	(0.17)	(−0.04)	(0.19)	(0.31)	(−0.19)	(0.22)
HH_size	0.005**	0.004**	−0.008*	0.001	−0.004**	−0.013**	0.011***	0.004*	−0.013***
	(0,07)	(0.05)	(−0.08)	(0.01)	(−0.03)	(−0.11)	(0.16)	(0.05)	(−0.16)
Age	−0.001**	0.001**	0.001*	0.001	0.004***	−0.001	−0.001*	0.034*	−7.3e^{-5}
	(−0.08)	(0.05)	(0.05)	(0.02)	(0.23)	(−0.02)	(−0.08)	(0.03)	(−0.01)
Edu	0.003*	0.0005	0.002	0.005**	−0.003*	0.01**	0.004**	−0.025	0.004**
	(0.06)	(0.01)	(0.039)	(0.08)	(−0.04)	(0.06)	(0.09)	(−0.01)	(0.07)
Area	−2.1e^{-6}	−5.1e^{-6} **	−9.8e^{-6} ***	−2.4e^{-5} ***	−9.4e^{-5}	−3.5e^{-5} ***	−5.5e^{-6}	−2.5e^{-6} **	−6.2e^{-7} *
	(−0.03)	(−0.08)	(−0.12)	(−0.22)	(−0.001)	(−0.294)	(−0.026)	(−0.11)	(−0.02)
Density	−2.418***	0.677	−0.137	0.07**	−0.006*	−0.057*	−0.037	0.032*	−0.013
	(−0.21)	(0.06)	(−0.01)	(0.09)	(−0.01)	(−0.07)	(−0.02)	(0.01)	(−0.004)
Harvest	−0,048***	0.016*	0.013*	0.024*	−0.027*	−0.058***	0.001**	−0.001*	0.001
	(−0.37)	(0.12)	(0.08)	(0.09)	(−0.07)	(−0.19)	(0.118)	(−0.03)	(0.025)
Yield	0.643***	−0.169***	−0.309***	0.243***	−0.065**	0.099***	0.021***	−0.045***	−0.01*
	(0.87)	(−0.226)	(−0.344)	(0.67)	(−0.13)	(0.25)	(0.176)	(−0.34)	(−0.07)
ξ_{ec}	–	−0.015*	0.358***	–	0.069*	0.296***	–	−0.207***	0.063*
	–	(−0.01)	(0.29)	–	(0.05)	(0.28)	–	(−0.18)	(0.051)
ξ_{en}	−0.003*	–	0.01*	0.02**	–	−0.012	−0.171***	–	−0.072**
	(−0.004)	–	(0.008)	(0.03)	–	(−0.015)	(−0.21)	–	(−0.07)
ξ_{so}	0.183***	0.011*	–	0.14***	−0.021	–	0.037*	−0.051*	–
	(0.22)	(0.01)	–	(0.16)	(−0.02)	–	(0.05)	(−0.055)	–
Goodness of fit D^2	0.542	0.432	0.481	0.695	0.496	0.474	0.602	0.513	0.421
χ^2 **Sig. 0.05**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DW	1.716	1.928	1.691	1.669	1.859	1.773	1.896	1.822	1.728
$S(x_n, r_d, w_a)$		1.09			0.95			1.11	

Note: *, **, *** denote coefficient significant at 0.10, 0.05 and 0.001 level. ξ_{ec} (ξ_{en}) [[ξ_{so}]is the index of economic (environmental) [social] performance. D^2 is the proportional reduction in deviance (R^2 homologue), χ^2 Sig. 0.05 is the Omnibus test and F-value homologue, and DW is the Durbin-Watson statistic.
Source: Authors' own representation

Table 7. ANOVA results and multiple comparison test for sustainability performance per sector.

	One-way F (2, 1438)	Tukey test- multiple comparison Blackberry	Tomato	Tree tomato
ξ_{ec}	958.52 ***	$S_2 = 0.94$	$S_3 = 0.62$	$S_1 = 1.11$
ξ_{en}	315.69 ***	$S_3 = 1.22$	$S_1 = 1.53$	$S_2 = 1.30$
ξ_{so}	692.97 ***	$S_1 = 1.12$	$S_3 = 0.71$	$S_2 = 0.93$

Note: *** denotes a coefficient significant at 0.001 level, S_i is a statistically different sector
Source: Authors' own representation

favour economic outcomes but lower environmental performance.

By nature, sustainability objectives provoke conflicts and automatically invoke trade-off situations aimed at exposing improvement opportunities. Our assessment of farm sustainability identifies that trade-offs exist between economic, social, and ecological sustainability, and they differ between sectors. For example, the tree tomato sector has a relatively low environmental and high economic performance, suggesting an economic-environmental trade-off. In contrast, the tomato sector obtains high environmental and poor socio-economic performances and calls for socio-environmental trade-offs.

5.3.2. Cross-sectoral comparison

Table 7 shows results from the one-way ANOVA employed to determine differences between sustainability indexes (economic, environmental, and social performance) for the blackberry, tomato, and tree tomato sectors. A multiple comparison test complements the findings by ranking sectors that are statistically similar.

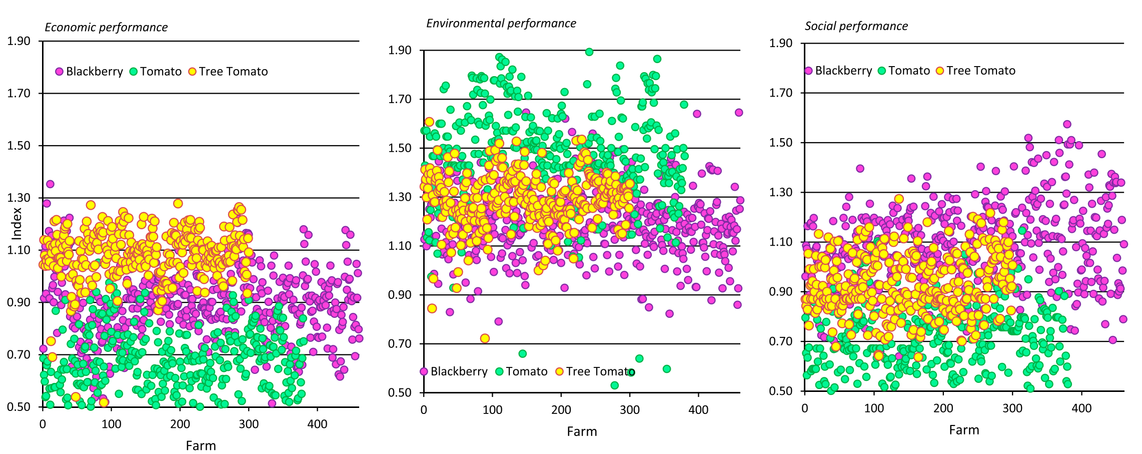
Results for the economic, environmental, and social indexes show significant differences ($p < 0.001$) between the three sectors. The tree tomato farms (an emerging sector) offer better economic sustainability, tomato farms (an emerging sector) present the highest environmental performance, and blackberry farms (a conventional sector) have the highest performance in the social dimension, on average. Figure 5 summarizes these findings through scatter plots.

6. Discussion

6.1. Indicators and differences in sustainability performance

This section will discuss the findings in light of the existing literature. We start with the relationship between indicators and performance components. The economic performance was highly influenced by components related to costs (e.g. labour and production) and margins. The components about work conditions and training were of the highest impact on social performance. The component related to the use of natural resources (e.g. water, fuels) highly impacted farms' environmental performance. These findings complement Heredia-R et al. (2020), who show that profitability indicators represent most of the economic dimension of farms while confirming that natural resources and welfare indicators are crucial for farm sustainability (Viteri Salazar et al., 2018).

The sustainability assessment also shows clear differences in performance between the economic,



Note: the scale of scores has been adjusted to a scale of 2:1

Figure 5. Scatter plots of blackberry, tomato and tree tomato sustainability index scores. Note: the scale of scores has been adjusted to a scale of 2:1. Source: Authors' own representation

ecological, and social dimensions for the three sectors. The economic and social performances are, on average, the lowest of the three dimensions, and the environmental performance has the highest share of farms above the cut-off point per sector. This is consistent with findings from Bonisoli et al. (2019), who claim that the ecological dimension of agriculture is reinforced thanks to environmental certifications and the strong promotion of agro-ecology (-forestry). Ramírez-Orellana et al. (2021), instead, mention that the lack of adequate legislative protection and aid aggravates the socio-economic conditions of farms.

6.2. Relation between farm resources, farmer characteristics and farm size and sustainability performance

In terms of the determinants of sustainability, we find that farms with higher incomes, workforce availability, and water for production activities show a higher economic and social performance. This confirms that increasing incomes and employment can form pathways out of weak socio-economic conditions (Haggblade et al., 2010). On the other hand, it contrasts the ecological perspective of McGuire et al. (2013) and Gaitán-Cremaschi et al. (2020) who advise farmers to prefer water conservation (use minimization) rather than seeing it as a purely economic resource.

Furthermore, farms owning higher forest resources have higher social and ecological performance. This finding is consistent with the double role of farmers as forest users and custodians (Meyfroidt, 2013). The use of forest resources (e.g. biodiversity, organic matter, biofuel) supports farms economically, while forest custodians help to sustain environmentally benign practices, thus building socio-ecological resilience.

A higher use of organic matter in cropping activities positively impacts economic-ecological sustainability. This is in line with the results of Fageria (2012) and Reeves (1997). These authors claim that organic matter content in soils is crucial to ensure the long-term environmental sustainability of agricultural ecosystems and productivity of farming systems for improving economic sustainability. Moreover, we found that larger households with more educated, younger farm heads deliver better economic results, while older heads seem to be more oriented towards environmental performance. In fact, for May et al. (2019), younger heads make farms more sustainable financially compared to conventional farmers. Ghosh and Hasan (2013) state that larger families perform better both financially and environmentally. On the other hand, Malak-Rawlikowska et al. (2019) found that educated farm heads did not lead to an increase in overall labourers' wellbeing, nor improving ecological management of crops.

Finally, large-scale farms have a significantly lower performance than small-scale farms in all three sustainability dimensions. Low sowing densities and low yields may weaken farms economically. However, moderate density and production yields could significantly improve farms ecologically (e.g. soil restoration) and socially (e.g. prevention of work overload). Our findings contrast some studies (e.g. Ren et al., 2019) that consider large-scale farms superior in sustainability performance. On the other hand, they are in line with findings of the contribution of small-scale farms to the sustainability of agricultural systems (Tavernier & Tolomeo, 2004).

6.3. Sectoral comparison and trade-offs between sustainability dimensions

In the cross-sectoral analysis, we find substantial sectoral variation. The relatively higher economic performance of tree tomato farms can be explained by larger households, more educated farm heads, and better access to economic resources (e.g. land). The environmental-oriented performance of tomato farms seems to be leveraged by access to the forest, organic matter, relatively older farmers, and the moderate density of sowing and yield per plant. The social-oriented performance of blackberry farms is leveraged by moderate household income, a small household size and older heads. These findings are consistent with studies on the impact of demographics and farm size on the sustainable well-being of agricultural sectors (Burton, 2014; van der Meulen et al., 2014). Moreover, D'Annolfo et al. (2020) argue that sustainability of an agricultural sector depends on its autonomy in resources and farmers' preferences for territorial sustainability.

Approaches exist to improve the balancing between financial return, social well-being, and ecological resilience of farms. Most of the discussed trade-offs in the literature on agriculture point to the balancing of the economic-environmental dimensions. For example, as Kanter et al. (2018) point out, improved agroforestry management positively affects production efficiency, or as Lu et al. (2015) stresses, economic-environmental trade-offs can be overcome by optimizing water through irrigation. Our study confirms these potential trade-offs and expands them by considering trade-offs with the social dimension. We find the following potential ways of overcoming trade-offs and boost agricultural sustainability: sustainable management of forest resources can help to expand production and household welfare (socio-environmental), sustainable management of water can help to avoid social conflicts due to scarcity (socio-environmental); and diversified agricultural production can minimize monocultures, improve yields and provide ecosystem services (e.g. pollination) (economic-environmental).

6.4. Practical implications

The study uses a theoretical framework based on the utility (preferences) theory and resource restrictions to assess farmer/farm sustainability performance. For scholars, this perspective provides insights that could strengthen the research and teaching of sustainability science. Practitioners can use the assessment framework to incorporate indicators that are appropriate for the context under study. It may also aid farmers and policymakers in identifying priorities and regulative developments. Principal component analysis helps in increasing interpretability and minimizing information loss. The cut-off points relative to each sector are estimates that allow farms to be easily distinguished into low and high sustainability groups. The analysis of determinants (resources, demographics, and farm size) allows to identify groups with similarities and differences in performance. Based on this, policymakers may direct policies focused on the dimensions and farmers most affected.

6.5. Limitations and future work

The study presented several limitations in its development. The use of PCA (factor analysis) is limited to exploratory factorial analysis. Some resources of importance for the good performance of the farms, such as soil resources, were not considered in the examination of sustainability determinants. The research was conducted for farms in specific agricultural sectors and with similar agro-climatic conditions; this may limit the generalizability of the findings to other sectors and regions.

Our findings leave room for future work. One major shortcoming that could be addressed in future research is an improved understanding of the impact of farmer demographics and farm size features on sustainability. Appealing aspects are, for instance, gender, race, homeownership, farming type (e.g. subsistence or commercial), farm type (e.g. marginal, small, medium, or large). These aspects would provide insights into how farmers may effectively improve sustainability performance. Our assessment framework models sustainability performance as an array of ex-ante outputs conditional upon the states of nature; therefore, potential stakeholders could reinforce many of the insights gleaned from our work through the use of longitudinal data and to identify how different sustainability conditions affect farmers in conceiving risk.

7. Conclusion

This paper assessed three agricultural sectors' economic, environmental, and social performance, namely, blackberry, tomato, and tree tomato. The study took place in the Inter Andean region of Ecuador. It adopted an integrated approach to assess the sustainability of sampled farms by applying the indicators of the ISPA framework. PCA converted these indicators into one measure of sustainability for the three sustainability dimensions: economic; ecological; social. It also analyzed determinants of performances to identify differences and potential trade-offs across sectors. An econometric model examined the determinants, namely, farm resources, farmer demographics, and farm size using a GLM regression model. A robust ANOVA and multiple comparison tests examined differences in performance scores and determinants between sectors. The study found that farms that differ in resources, such as income, workforce, forest, and water owned, also show different performances in the dimensions of sustainability. Specifically, younger and older farm heads perform better socio-economically and environmentally, respectively, and small-scale farms perform better than large-scale farms in all dimensions. Trade-offs exist between economic and social dimensions and between socio-economic and environmental dimensions, respectively. Overcoming socio-economic and socio-environmental trade-offs is possible through sustainable management of forest and irrigation water, to expand the welfare of farming households and to avoid social conflicts due to potential scarcity.

Note

1. The peasant family farm is an organizational form in agricultural, forestry, fisheries, pastoral, and aquaculture production which is managed and operated by a family and predominantly reliant on family labour, including both women and men. The family and the farm are linked, and combine economic, environmental, social, and cultural functions.

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Appendix A1: Description of sustainability indicators present in ISPA framework

Dimension	Category	Attribute	Definition	Relevance Scale
Economic	Costing	Labour use	The amount of physical, mental, and social effort used to produce goods and services	Local
		Labour cost	The wage paid to employee, and the cost of employee benefits.	Local
		Production cost	All the costs incurred by a farm from cultivating a product or providing a service.	Regional
		Agricultural input cost	The cost of overhead items used exclusively in the cultivation of agricultural products.	Regional
		Input cost	The costs internally assumed by the farmers of transport the production to the sell point.	Regional
		Self-Consumption	The producers themselves consume the entire or part of output they produce.	Farm
	Profitability	Price	The amount of money expected, required, or given in payment for something.	Regional
		Gross margin	The difference between revenue and cost of goods sold.	Farm
	Volatility	Price volatility perception	Dispersion of price about their central tendency (i.e. mean), measured by the standard deviation.	Regional
		Related-factors of price volatility	Factors closely related to price dispersion.	Regional
Environmental	Natural resources consumption	Water use	The amount of water used for agricultural purposes	Local
		Fossil fuel use	The amount of fossil fuel used for agricultural purposes	Local
	Sustainable practice	Crop rotation	The practice of planting different crops sequentially on the same plot of land.	Local
	Agrochemical usage	Fertilizer use	The amount of fertilizer used for agricultural purposes	Farm
		Pesticide use	The amount of pesticide used for agricultural purposes	Farm
		Bioproduct use	The amount of biofertilizer used for agricultural purposes	Farm
	Food losses	Food losses perception	The decrease in the quantity or quality of the harvest.	Farm
Social	Work conditions	Time-related Overload	The amount of work time considered as labour overutilization when exceeding the limit established by law.	Local
		Time-related Underemployment	The amount of work time considered as labour underutilization because it does not approach the threshold established by law.	Local
		Health insurance satisfaction	Level of satisfaction of public health insurance use.	Regional
		Training level	The level of knowledge on certain topics of relevance for the farming activity.	Local
	Migration	Rural-to-urban migration	The number of household members that move outside the farm to urban areas.	Regional
	Child labour	Child labour	The number of household members between 5 and 15 years that work on agricultural activities.	Regional

Source: Authors' representation based on Moreno-Miranda and Dries (2022)

Appendix A2: Pearson correlation coefficients between sustainability indicators

Economic indicators									
	x1	x2	x3	x4	x5	x6	x7	x8	x9
x1	1	0.541****	0.266***	0.008	−0.005	0.353***	0.159***	−0.141***	0.045
x2	0.541****	1	0.174***	−0.081	−0.015	0.258***	0.095*	−0.118**	0.027
x3	0.266***	0.174**	1	−0.023	0.072	0.817**	0.072	−0.59****	−0.04
x4	0.008**	−0.081	−0.023	1	−0.34***	−0.004	−0.001	−0.002	−0.08
x5	−0.005	−0.015	0.072	−0.34***	1	0.062	−0.09**	−0.086	0.110**
x6	0.353***	0.258***	0.817*****	−0.004	0.062	1	0.167**	−0.55****	0.008
x7	0.159***	0.095*	0.072	−0.001	−0.009	0.167**	1	0.612****	0.084
x8	−0.14**	−0.18**	−0.59****	−0.002	−0.086	−0.55****	0.612****	1	0.074
x9	0.045	0.027	−0.041	−0.058	0.110**	0.008	0.084	0.074	1

Environmental indicators							
	r10	r11	r12	r13	r14	r15	r16
r10	1	0.342***	−0.02	−0.03	−0.00	−0.01	0.128***
r11	0.342***	1	−0.138***	0.132***	0.092*	0.020	−0.00
r12	−0.02	−0.18***	1	−0.09	−0.47****	−0.03	−0.02
r13	−0.03	0.132***	−0.09	1	−0.39***	0.010	−0.00
r14	−0.000	0.092*	−0.473****	−0.39***	1	−0.01	0.007
r15	−0.01	0.132***	−0.138***	0.010	−0.01	1	0.128***
r16	0.128***	−0.000	−0.02	−0.00	0.07	0.032	1

Social indicators									
	w17	w18	w19	w20	w21	w22	w23	w24	w25
w17	1	−0.00	−0.06	0.307***	−0.26***	0.007	−0.119**	0.027	0.03
w18	−0.00	1	0.016	0.109**	−0.25***	−0.01	0.089	0.043	0.01
w19	−0.06	0.016	1	−0.35***	−0.02	−0.01	−0.02	−0.02	0.06
w20	0.307***	0.109**	−0.35***	1	−0.39***	−0.00	0.027	0.07	−0.00
w21	−0.25***	−0.255***	−0.02	−0.32***	1	−0.07	−0.07	0.019	−0.00
w22	0.007	−0.01	−0.01	−0	−0.07	1	−0.08	0.074	0.08
w23	−0.19**	0.089	−0.02	0.027	−0.07	−0.08	1	0.10*	−0.1

Note: **, * the correlation is significant at 0.01, 0.05 level (bilateral).
Source: Authors' own representation

Appendix A3: Histograms with overlaid density estimates for the different SI scores.

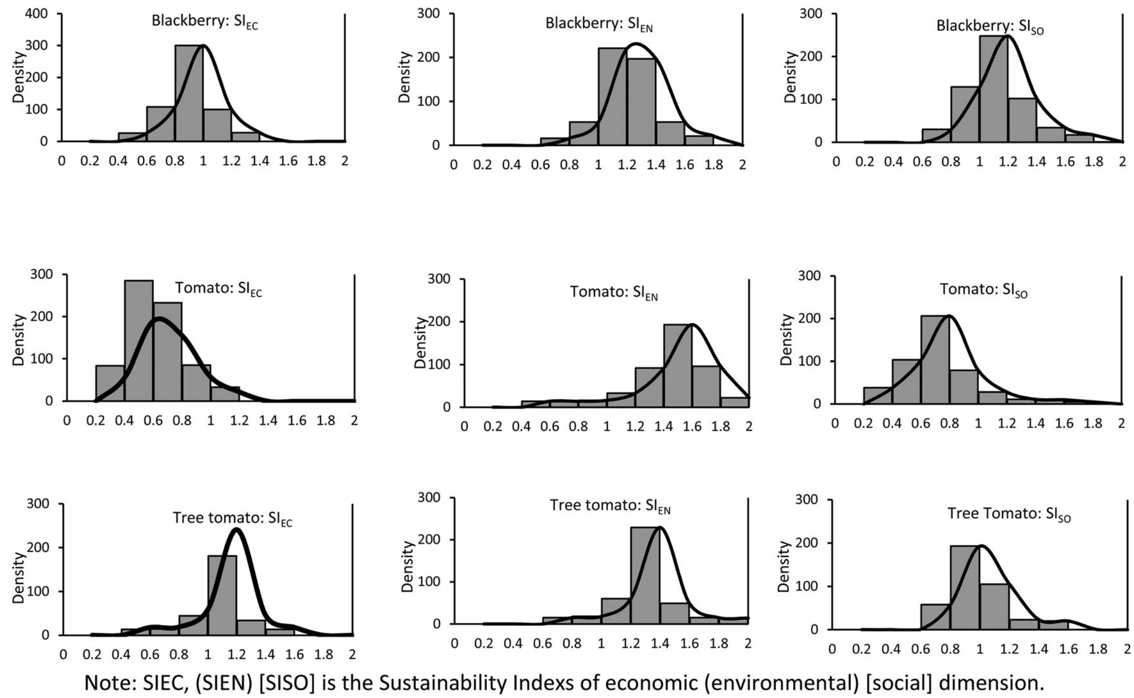

Figure A1. Note: SI_{EC}, (SI_{EN}) [SI_{SO}] is the Sustainability Indexs of economic (environmental) [social] dimension. Source: Authors' own representation

Appendix A4: Pearson correlation coefficients between determinants and performance indexes of sustainability

	Blackberry			Tomato			Tree Tomato		
	ξ_{ec}	ξ_{en}	ξ_{so}	ξ_{ec}	ξ_{en}	ξ_{so}	ξ_{ec}	ξ_{en}	ξ_{so}
Income	0.343**	−0.107*	0.223**	−0.264*	0.129*	−0.105*	0.435**	−0.398**	0.486**
Wkforce	0.099*	−0.123*	0.102*	0.118*	0.029	0.102*	0.120*	0.126*	0.024
Land	0.399*	0.103*	−0.134**	−0.363**	−0.142**	−0.352**	−0.245**	−0.392**	−0.235**
Orgmat	−0.141**	0.099*	−0.095*	0.446**	0.244**	−0.122*	0.030	0.626**	−0.016
Forest	−0.331**	0.514**	0.194*	−0.257*	0.108*	−0.401**	−0.224**	0.385**	0.055
Water	0.241**	0.672**	−0.225**	0.164*	−0.243*	0.379*	0.116*	−0.321**	0.216**
HH_size	0.389**	0.065*	−0.448**	0.102*	−0.103*	0.118*	0.114*	−0.022	−0.353**
Age	−0.094*	−0.100*	0.033	0.026	0.263**	−0.122*	−0.079	0.126*	−0.005
Edu	0.030	0.094*	0.061	0.122*	−0.126*	0.114*	0.184**	−0.245**	0.390**
Area	−0.473**	−0.465**	−0.384**	−0.377**	−0.184*	−0.402**	−0.183**	−0.492**	−0.050
Density	0.406**	0.027	−0.116*	0.335**	−0.284**	0.261**	−0.611**	0.356**	−0.245**
Harvest	−0.217**	0.421**	0.236**	0.113*	−0.108*	−0.232**	0.130*	−0.009	0.611**
Yield	0.455**	−0.128*	−0.181*	0.588**	−0.103*	0.044*	0.231**	0.395**	−0.245**
ξ_{ec}		−0.517**	0.257**		0.346**	0.201**		−0.270**	0.626**
ξ_{en}	−0.517**		−0.028*	0.346**		−0.263**	−0.270**		−0.114*
ξ_{so}	0.257**	−0.028*		0.201**	−0.263**		0.626**	−0.114*	

Note: **, * the correlation is significant at 0.01, 0.05 level (bilateral).
Source: Authors' own representation