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Agroecology for sustainable development: evidence on multidimensional performance from a cross-country TAPE assessment in Africa

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Introduction: Agroecology is increasingly recognized as a pathway for transforming agrifood systems and advancing progress toward the SDGs. Yet, large-scale, cross-context evidence on its multidimensional performance as framed holistically by the FAO's 10 Elements remains limited.

Methods: The Tool for Agroecology Performance Evaluation (TAPE) and the Land Degradation Surveillance Framework (LDSF) were applied on 839 farming households in Benin, Ethiopia, Kenya, and Madagascar. Correlation analysis was used to quantify relationship between agroecological integration and multidimensional performance key drivers were identified through regression analysis.

Results and Discussion: Higher levels of agroecological integration are significantly positively correlated with higher performance across economic, environmental and social domains. This implies that the environmental benefits of agroecology do not come at the cost of reduced productivity and profitability and suggests that agroecology significantly contributes to sustainable development in Africa. Sociocultural Elements of Agroecology, including human and social values, culture and food traditions, and knowledge co-creation, emerged as key drivers of agroecological transitions and multidimensional performance. However, barriers remain, such as high input costs, insecure land tenure (particularly for women), and low youth engagement in farming. The study emphasizes the need for enabling policies that support agroecological business models, secure tenure rights, and foster equitable, labor-saving innovations. By providing multi-country evidence, it underscores the value of systemic, holistic food system assessments to guide agroecological transitions.

KEYWORDS

biodiversity, food security, income, productivity, soil health, transition

1 Introduction

The growing recognition of the adverse impacts of agricultural and food systems on environmental, human, economic, and social wellbeing has sparked a global movement towards transitioning to more sustainable and equitable food systems (Benton and Harwatt, 2022; Kaljonen et al., 2023). This momentum has inspired food systems transformation through sustainable approaches like regenerative agriculture, organic farming, climate-smart agriculture, and agroecology (Muhie, 2022; Tuttonell et al., 2021). Considering the interconnected nature of food systems with social, economic, political, and environmental dimensions, adopting a systemic approach is essential for holistically addressing food systems challenges and enabling integrated decision-making (Lamanna et al., 2024; United Nations Environment Programme (UNEP), Food and Agriculture Organization of the United Nations (FAO), & United Nations Development Programme (UNDP), 2023). In this context, agroecology is gaining prominence in attaining food sovereignty while addressing externalities associated with agroecosystems (Fernandez and Ernesto Méndez, 2018; Fiore et al., 2024). One of the core features that sets agroecology apart from other forms of sustainable agriculture is its holistic approach in simultaneously addressing multidimensional aspects of food systems (Fernandez and Ernesto Méndez, 2018; Fiore et al., 2024; Geck et al., 2023; Scherf, 2018). In this regard, agroecology is grounded in the 10 elements of agroecology (FAO, 2019b) which were formally adopted by the FAO Council representing all member states and therefore hold normative value as a global reference framework. These elements provide a comprehensive vision of agroecology, enabling food system actors to operationalize and evaluate agroecological transitions. In parallel, the 13 principles of agroecology (HLPE, 2019) are closely aligned with the 10 elements and serve as a science–policy interface that facilitates debate, bridges diverse knowledge systems, and informs policymaking (Bicksler et al., 2023; Wezel et al., 2020). Together, the 10 elements and the 13 principles complement one another and are acknowledged as frameworks that capture the holistic nature of agroecology; one providing normative legitimacy, the other fostering policy dialogue and scientific engagement (Wezel et al., 2020; Wezel et al., 2020; HLPE, 2019). According to Erica and Dario (2022) agroecology offers the most promising strategy for transforming food systems by applying ecological principles to agriculture and ensuring the regenerative use of natural resources and ecosystem services, while also promoting socially equitable food systems.

Despite its growing momentum, a key barrier to fully understanding agroecology's potential lies in the limited assessment of its holistic, multidimensional performance. Critics of agroecology often narrow their focus on its economic viability, questioning its profitability. For instance, Fiore et al. (2024) argue that agroecological practices may prioritize environmental goals over economic outcomes like productivity and profitability, making them less appealing to farmers. Similarly, Falconnier et al. (2023) highlight that while agroecology emphasizes on input reduction through farm diversification, recycling, and efficiency, the African-specific context characterized by heavy reliance on rain-fed agriculture, dominance of small-holder farming systems, high vulnerability to land degradation and soil nutrient mining, often leads to soil nutrient depletion, thereby undermining soil health and long-term productivity. However, these critiques frequently stem from

evaluations of isolated agroecological farm practices—such as intercropping, agroforestry, or the use of animal manure—conducted on small-scale experimental plots. While the mentioned agroecological practices are individually important, collectively contributing to agroecological transitions, farmer interests, values, and choices in the African context are shaped by a wider set of factors beyond farm practices. Socio-cultural norms often linked to environmental stewardship, sustained farmer experience through peer learning and intergenerational knowledge transfer, as well as dynamics of localized market systems all play a central role in shaping food systems (Andrieu et al., 2025). This underscores the need for systemic evaluations that account for these contextual dimensions. The prevailing practice-based, piecemeal focus of many studies therefore overlooks the broader, integrative benefits of agroecology across multiple sustainability dimensions. Moreover, the predominantly short-term focus of many studies highlights the importance of assessing the long-term effects of agroecological investments to ensure reliable and proven conclusions. To address potential biases and enhance meaningful decision-making, it is equally important to compare agroecology's performance across multiple dimensions with the performance of alternative approaches (Geck et al., 2023).

To provide evidence for a holistic assessment of agroecology and support the transition toward sustainable food systems, various tools and frameworks have been developed (Geck et al., 2023). Among these, the FAO's Tool for Agroecology Performance Evaluation (TAPE) stands out for its ability to link the level of agroecological integration to performance across key criteria (Mottet et al., 2020) aligned with the Sustainable Development Goals (SDGs). TAPE evaluates food system performance across five dimensions—environment, economy, governance, health and nutrition, and society and culture—which are closely tied to critical SDGs, including: ending poverty in all its forms (SDG 1), achieving food security and improved nutrition through sustainable agriculture (SDG 2), ensuring healthy lives and wellbeing for all (SDG 3), promoting gender equity and women empowerment (SDG 5), reducing inequalities within and among countries (SDG 10), ensuring sustainable production and consumption patterns (SDG 12), and protecting, restoring, and promoting the sustainable use of terrestrial ecosystems (SDG 15). However, with regards to measuring agroecological impacts on soil health, the current TAPE questionnaire relies on qualitative data, which may be influenced by respondents' subjective biases. While (FAO, 2019a; Mottet et al., 2020) highlight the value of soil sampling and testing in assessing soil health within TAPE and recommend their use where feasible, the practical application of this approach has often proven challenging in existing TAPE studies due to associated costs and technical requirements. To address this gap, this study introduces an advanced methodological approach for the soil health criterion of TAPE. By integrating household survey data with soil sample analyses using the global Land Degradation Surveillance Framework (LDSF). This integration provides a more objective basis for evaluating agroecology's impact on soil health. Moreover, combining biophysical and physicochemical soil health indicators is essential, as soil health is highly sensitive to the nature of farming practices and serves as a key measure of agroecological performance (Cárceles Rodríguez et al., 2022; Sharma et al., 2024).

To address these challenges, the study aimed to provide evidence on the level of agroecological integration and assess how varying

degrees of agroecological integration correlate with multidimensional performance. This research combines TAPE findings with more comprehensive soil sampling and analysis techniques, utilizing the Land Degradation Surveillance Framework (LDSF) to integrate biophysical soil health assessments with physio-chemical evaluations. The LDSF is a framework that offers a hierarchical soil sampling design, along with statistical analysis and inference, achieving high accuracy for local relevance while developing predictive models with global applicability (Winowiecki et al., 2016; Winowiecki et al., 2021).

Our study, to the best of our knowledge, is the first multi-country assessment applying the two globally relevant tools to evaluate the multidimensional performance of agroecology, while also advancing the TAPE framework with an improved soil health criterion assessment. This evidence is crucial for informing policies and initiatives that drive agroecological transitions, particularly in the context of sustainable development and soil health. By offering actionable insights, the research empowers policymakers and land users to promote agroecological practices that are environmentally sustainable, socially acceptable, and economically viable. Spanning diverse contexts across four countries, the study generates representative evidence of agroecological performance in varied settings. Additionally, it introduces significant enhancements to the TAPE tool, including a robust online data management platform and an integrated soil health analysis component, ensuring improved accessibility and utility for future users.

2 Materials and methods

2.1 Scope of the study

This research was conducted in the context of the global programme *Soil Protection and Rehabilitation for Food Security* (ProSoil) and Enhancing soils and agroecology for resilient agri-food systems in Sub-Saharan Africa (ProSilience). Implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, ProSoil has since 2015, supported the adoption of agroecological farming practices to restore degraded soils sustainably. The program trained farmers and agricultural advisors, collaborates with government and private sectors, and integrated agroecological soil management into education while facilitating knowledge exchange (GIZ, 2023) across different stakeholders. In the context of this study, the selection of the study sites was guided by the programme's priority countries, which defined the scope of the research and limiting it to four preselected countries in sub-Saharan Africa namely Benin, Ethiopia, Kenya, and Madagascar. Table 1 provides a brief overview of the context of study sites in each of these four countries.

2.2 Data collection and analysis

The Tool for Agroecology Performance Evaluation (TAPE), developed by the Food and Agriculture Organization of the United Nations (FAO) was tailored integrating an advanced soil health criterion as recommended by (Mottet et al., 2020) and applied on 839 farms across Benin, Ethiopia, Kenya, and Madagascar. To ensure the sample size remained manageable within the available resources, the assessment concentrated on three comparable administrative units per country—three communes in Benin, three counties in Kenya, and

three districts each in Ethiopia and Madagascar—spanning diverse agroecological zones. A total of 839 households were selected by assigning randomly generated numbers to census lists, with the number of respondents in each administrative unit proportionate to the target population.

TAPE is a global analytical tool structured into four main steps, providing complementary insights into the degree of agroecological integration and its multidimensional impacts on farming systems (Mottet et al., 2020). The preliminary step of TAPE (Step 0) assesses the socio-economic, demographic, and biophysical aspects of the farming system. It identifies farming typologies and factors influencing agroecological transitions. Secondary data contextualizing the study site was obtained through desk reviews at broader scales, while additional details like farm size and household characteristics were gathered via the TAPE surveys. Identified information gaps were filled by conducting key informant interviews. A total of 54 key informant interviews were conducted in this regard.

Step 1, also known as the Characterization of Agroecological Transition (CAET), evaluates the level of a farm's transition to agroecology as reflected by their integration of the 10 elements of agroecology, each element being evaluated against 4 indicators (Table 2). The results reveal the level of agroecological integration, highlighting the strengths and weaknesses of each farm, as well as the interactions between different agroecological elements. Scores for each indicator were aggregated and standardized using a percentile scale from 1 to 100%, based on a Likert scale ranging from 0 to 4. The average scores for all agroecological elements were used to calculate the total CAET score, and correlation coefficients were computed to examine the relationships between the CAET score and individual agroecological elements.

Step 2 assesses agroecological performance against sustainability indicators aligned with the Sustainable Development Goals (SDGs). Correlating results from Steps 1 and 2 provides insights on how various agroecological elements contribute to sustainability. Finally, Step 3 contextualizes TAPE findings through participatory interpretation by stakeholders. This step validates previous results, evaluates contributing factors, and offers practical recommendations in advancing agroecological transitions.

The Spearman's rank correlation test was used to assess the relationship between the total CAET score with performance indicators and each of the 10 agroecological elements. The Spearman's correlation coefficient (r) ranges from -1 to 1 , with $\rho = 1$ indicating a perfect positive correlation (where one variable increases as the other increases, and vice versa), $\rho = -1$ indicating a perfect negative correlation (where one variable increases as the other decreases, and vice versa), and $\rho = 0$ indicating no correlation between the variables. The associated p -value determines the statistical significance of the correlation, with a small p -value (typically ≤ 0.05) indicating strong evidence against the null hypothesis, and a large p -value (> 0.05) indicating weak evidence against the null hypothesis.

Given the complexity of the dataset, a principal component analysis (PCA) was applied to identify the key drivers of agroecological transition. The PCA simplified the large number of variables per observation by transforming them into a smaller set of principal components, highlighting the most influential factors shaping the transition. K-means clustering was used to assess optimal number of clusters that can be extracted from principal components scores and their typologies evaluated using selected soil variables – soil organic carbon and total nitrogen.

TABLE 1 Brief overview of the study sites in the four countries.

Country	Context summary of study sites
Benin	The study included 240 households in Borgou, Collines, and Zou, spanning the Sudanian, Sudano-Sahelian, and Sudano-Guinean ecoregions, with annual rainfall of 800–1,500 mm. Mixed farming systems predominate, with average farm sizes of 5 ha for crops, 2 ha of natural vegetation, and 0.6 ha for pasture. Key crops are rice, sorghum, and cotton, with sheep and cattle as primary livestock. ProSoil interventions focused on soil fertility techniques, agroecological practices, legume rotations, and organic inputs.
Ethiopia	The study involved 198 households across Hula, Sodo-Zuria, and Walmara districts in Ethiopia's midland and highland areas, with altitudes of 1,500–3,190 m, annual rainfall of 800–1,900 mm, and temperatures of 16 °C–19 °C. Farming systems are mixed subsistence, with crops like cereals, pulses, coffee, and livestock. Key challenges include soil acidity, limited inputs, and market access. Population growth drives land shortages, deforestation, and degradation. Soil acidity, low organic matter, scarce inputs, limited market accessibility, and a centralized public extension system that restricts access in remote areas are some of the production constraints. Although there are policies that promote agricultural development, there are still issues with their coordination and gaps in their application. ProSoil interventions majorly focused on training in integrated soil fertility management, crop-livestock-forestry synergies, farm diversification, water management, improved fodder, livestock breeds, biogas, mechanization, and liming.
Kenya	The study included 201 households across Bungoma, Kakamega, and Siaya counties in western Kenya. Located in lower midland zones, the region has a reliable annual rainfall of 650–1,900 mm, altitude 790–1,500 m, and temperatures averaging 21.8 °C–24 °C. Smallholder mixed subsistence farming is typical, with average farm sizes of 0.77 ha for domestic consumption with surplus produce being sold locally. Key crops include maize, beans, vegetables, bananas, and sweet potatoes, while primary livestock are cattle, chickens, and goats. Challenges limiting agroecological transitions in the study area include advanced land degradation, high poverty levels (68% of farmers below the poverty line), limited access to market and infrastructure and unfavorable policies promoting subsidies on external farm inputs. ProSoil interventions begun in 2018 to promote agroecological practices, focusing on training, soil rehabilitation practices, and farmer-led research. The project supports policy development for agroecology, advocates for soil management reforms, and ensures knowledge-sharing to foster implementation.
Madagascar	The study involved 200 households across Belobaka, Katsepy, Manerinerina, and Tsaramandroso in Madagascar's Boeny region, a semi-arid area with annual rainfall of 1,200–1,300 mm over 5 months. The landscape includes plateaus under 800 m, plains along rivers, and a low population density with many rural migrants. Subsistence farming dominates, with small farms (1.5 ha on average) focusing on rice (50% of land), pulses in flooded areas, and common fruit trees like mango. Cattle are used for fieldwork and transport, with pesticide use prevalent for cash crops. Infrastructure and institutional support are limited. ProSoil's efforts, which started 3 years later than in other regions, include training on soil protection, promoting agroecology, supporting tree planting, securing communal land tenure, and networking for soil management knowledge.

2.3 Soil sampling and analysis

To generate a more robust and multidimensional assessment of agroecology's impact on soil health, the TAPE methodology was strengthened through the integration of the Land Degradation Surveillance Framework (LDSF) developed by World Agroforestry Center (Vägen and Winowiecki, 2023). While soil health is already one of TAPE's criteria, this study is the first to operationalize it at such a large scale by combining household survey data with comprehensive soil analyses in 4 countries. The LDSF framework offers a hierarchical, spatially explicit, and systematic sampling design that ensures local relevance while enabling global comparability through predictive modeling (Winowiecki et al., 2016; Winowiecki et al., 2021). Across the 839 selected farms, a 1,000 m² plot was established at each site where composite soil samples (topsoil: 0–20 cm and subsoil: 20–50 cm) were collected from four subplots per plot. Each sample was air-dried and sieved to 2 mm and sub-sampled for laboratory analyses at the CIFOR-ICRAF Soil and Land Health laboratory. Key soil health indicators, including soil organic carbon, pH, total nitrogen, texture and base cations were analyzed and systematically matched with farm-level management data and the soil health responses from the TAPE household survey. This integrated, multi-criteria approach represents a methodological advance that enhances the objectivity of agroecological performance evaluations. It bridges the gap between physiochemical and biophysical soil health dimensions providing a good evidence base.

2.4 Limitation of the study

The manuscript recognizes several limitations in combining qualitative and quantitative soil health assessments. Although this integrated approach strengthens analysis and enhances scientific rigor, it also presents challenges. Aligning farmers' perceptions with scientific measurements is methodologically complex, as indicators like soil color used as a proxy for SOC do not always correspond with laboratory results. Qualitative insights, while valuable, may be influenced by subjective judgments, socio-cultural contexts, or short-term experiences that do not always align with measured soil properties. On the other hand, quantitative data typically represent conditions at a single point in time and space, which can be difficult to reconcile with broader, experience-based knowledge. Such discrepancies across sites complicate interpretation and limit comparability. Moreover, the dual approach is resource-intensive, requiring additional time, expertise, and funding, which constrains scalability in larger initiatives.

The study was also limited by its relatively short duration, which provided only a snapshot of agroecological status rather than capturing transitions over time. A longitudinal study would be especially valuable for indicators like soil health, where changes manifest gradually. Additionally, the study applied FAO's standardized thresholds to interpret levels of agroecological integration. While these benchmarks provide consistency, context-specific interpretations of CAET scores would enhance local relevance. However, such localized standards remain

TABLE 2 Elements of agroecology and their associated indicators used in the characterization of agroecological transitions (CAET).

No.	Dimension	Element of agroecology	Indicators
1	Agroecological practices	Diversity	Crop diversity
			Animal diversity (including fish and insects)
			Tree diversity (including other perennials)
			Diversity of activities generating income
2		Synergy	Crop/livestock integration
			Soil management system
			Integration of trees (agroforestry, silvopastoral, agrosilvopastoralism)
			Connectivity between elements of the agroecosystem and the landscape
3		Recycling	Recycling of biomass and nutrients
			Waste production and management
			Water recycling and saving
			Energy reduction and renewable energy
4	Emergent properties	Efficiency	Use of external inputs
			Management of soil fertility
			Management of pests and diseases
			Emerging efficiency from good practices
		Resilience	Existence of social mechanisms to reduce vulnerability
			Environmental resilience and capacity to adapt to climate change
			Emerging resilience from diversity
			Emerging resilience from self-sufficiency and empowerment
5	Social dimensions	Culture & food tradition	Appropriate diet and nutrition awareness
			Food self-sufficiency
			Local and traditional food heritage
			Management of seeds and breeds
6		Co-creation and sharing of knowledge	Access to agroecological knowledge and interest of producers in agroecology
			Social mechanisms for the horizontal creation and transfer of knowledge and good practices
			Participation of producers in networks and grassroots organizations
			Co-creation and sharing of knowledge
7		Human and social values	Women's empowerment in decision making and access to resources
8			Labour (productive conditions, social inequalities)
			Motivation in agricultural work and continuity of family farming
			Animal welfare
9	Enabling environment	Circular & solidarity economy	Products and services marketed locally (or with fair trade)
			Networks of producers, relationship with consumers, and presence of intermediaries
			Local sourcing and circularity
10		Responsible governance	Producers' empowerment
			Producers' organizations and associations
			Inclusive decision-making processes

Adapted from Mottet et al. (2020).

underdeveloped and inconsistent across countries. Future research should therefore adapt benchmarks to local agroecological realities, particularly where cross-country comparisons are less applicable.

Although TAPE provide a robust framework for assessing agroecological transitions, it does not fully account for management practices such as manure use intensity and mechanization that

directly affect soil health. This limited deeper associations, e.g., between soil compaction and mechanization or nitrogen content and manure application. We recommend complementing TAPE with modules on farm management practices (e.g., manure use, mechanization, grazing rates) to better link agroecological transitions with soil outcomes and generate more actionable insights for policy and practice.

3 Results

3.1 Status of agroecological transitions in the study sites

Step 1 of TAPE, the Characterization of Agroecological Transition (CAET), measures to which degree the 10 elements of agroecology are incorporated into farming systems. The findings show that based on FAO standardized thresholds for categorizing systems, the shift toward agroecological farming is still in the early stages, with an average CAET score (52%) and few households reaching advanced transition levels (CAET > 70%). The generally low score is reflected across all elements of agroecology with human and social values showing the highest mean CAET score of 58% (Figure 1).

Although the distribution of CAET scores across most elements appears relatively homogenous, elements of culture and food traditions, and human and social values, resilience, and synergy show a stronger concentration of scores around the median value (Figure 1). In contrast, diversity, and co-creation and sharing of knowledge displays a somewhat bimodal pattern, suggesting the presence of two distinct groups of farmers with markedly different levels of farm diversification. Meanwhile, elements associated with enabling environments for transitions such as circular and solidarity economy and responsible governance exhibit broader score distributions, reflecting greater variability in how these elements are integrated across study sites. Similarly, the CAET scores varied across countries, with Ethiopia recording the highest CAET scores in 9 out of 10 agroecology elements (Figure 2). In contrast, Madagascar—where agroecological farm practice interventions started 3 years later—recorded the lowest scores in 6 elements, except for diversity, synergy, resilience, and human and social values, where it outperformed at least one other country.

All elements of agroecology exhibit a synergistic relationship, as evidenced by the positive correlation among them (Figure 3). Notably, the CAET score had the greatest correlation with co-creation and sharing of knowledge (0.84***) and human and social values (0.81***) but the weakest link with the element of efficiency (0.67**).

Although the correlations between efficiency and specific agroecological practices such as recycling ($r = 0.44^{***}$) and diversification ($r = 0.47^{***}$) appear relatively weak, the broader trend suggests that farms with more advanced levels of agroecological integration tend to achieve high scores across diversity, or recycling, with efficiency simultaneously (Figure 4).

To assess the country-level variation in the integration of agroecological elements, a principal components analysis (PCA) was conducted. The resulting biplot indicates that the first two principal components explain 70.35% of the total variations, with PC1 accounting for 62.28% and PC2 for 8.07% of the variance (Figure 5a). The two optimal clusters reflect distinct farm typologies, with the second cluster representing farms that are more agroecological, characterized by the highest scores on elements that primarily contribute to PC1. The primary contributors to the first principal component are enabling environments for agroecological transition with circular and solidarity economy, responsible governance, and resilience emerging as the most influential elements (Figure 5b). In contrast, PC2 is majorly shaped by recycling, efficiency, and diversity, which broadly represent the extent of agroecological farm practice integration.

The unidirectional orientation of the PCA vector loadings highlights the complementarity among all agroecology elements, also suggesting they tend to be positively correlated. Notably, the overlapping vectors—such as those between synergy and diversity, efficiency and recycling, human and social values and culture and food traditions, as well as circular and solidarity economy,

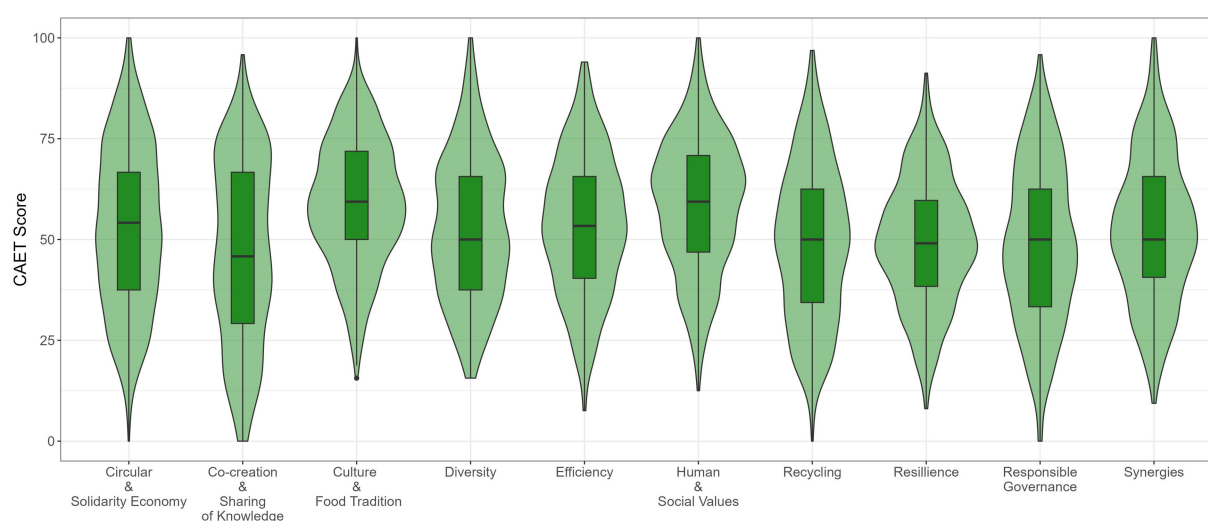


FIGURE 1

Results of TAPE Step 1, the characterization of agroecological transition (CAET) scores across the 10 elements of agroecology. The CAET score, standardized as a percentage, indicates the level of integration of the respective elements of agroecology.

Characterization of Agroecological Transition (CAET)

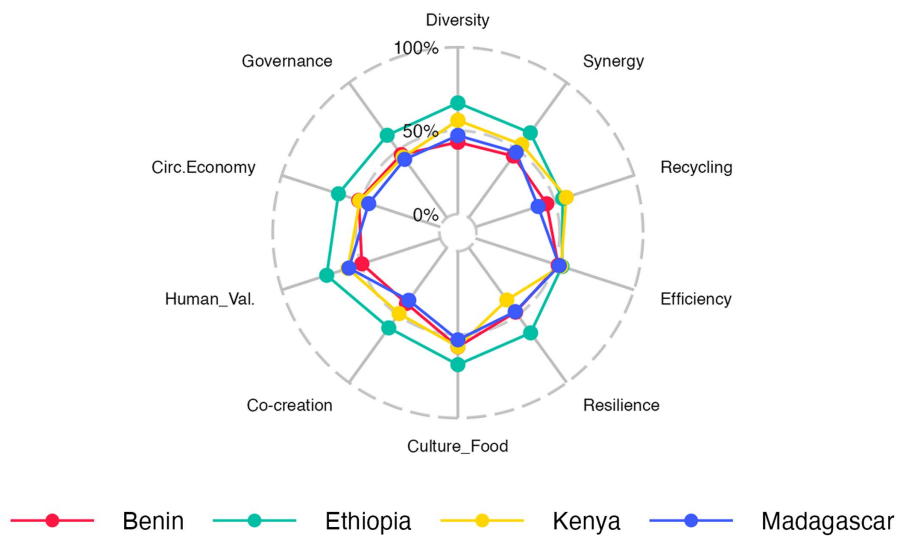


FIGURE 2
A cross-country comparison of the level of integration of each of the 10 elements of agroecology. The CAET score has been standardized into percentages, with higher CAET score indicating higher level of integration of a particular element of agroecology.

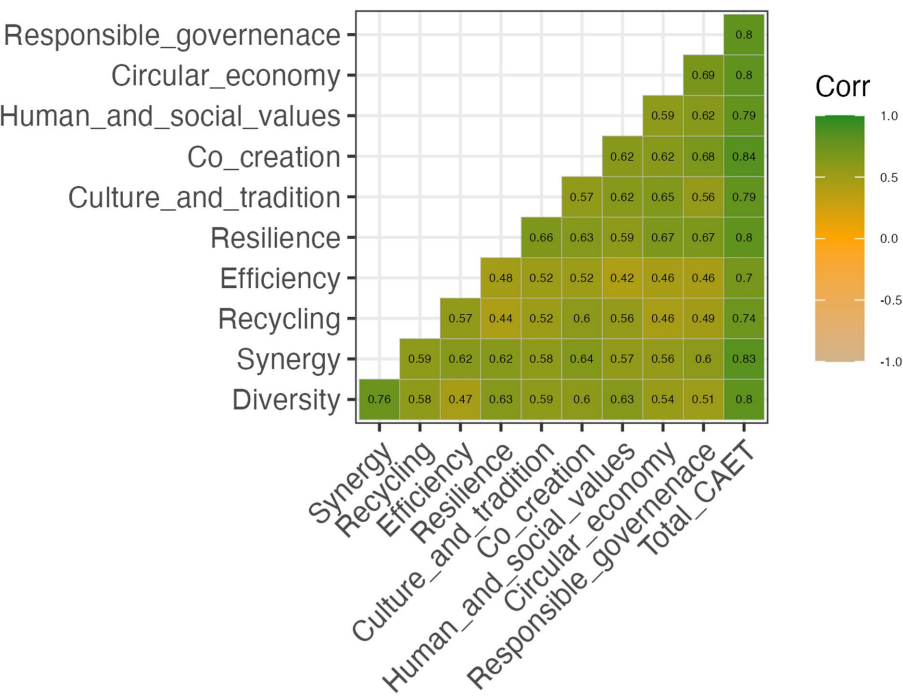


FIGURE 3
Correlation among elements of agroecology in the study site. Values in each box represent the Spearman correlation coefficient, all of which were statistically significant ($p < 0.0001$).

responsible governance, and resilience— imply that these pairs or clusters of elements may be capturing related dimensions of agroecological transition process. Apart from Ethiopia, where datapoints show a slight clustering along PC1, the overall distribution of farms across the countries remains widely dispersed (Figure 5b). This suggests that differences in integration of agroecological elements are shaped more by farm-level adoption patterns than by country of origin.

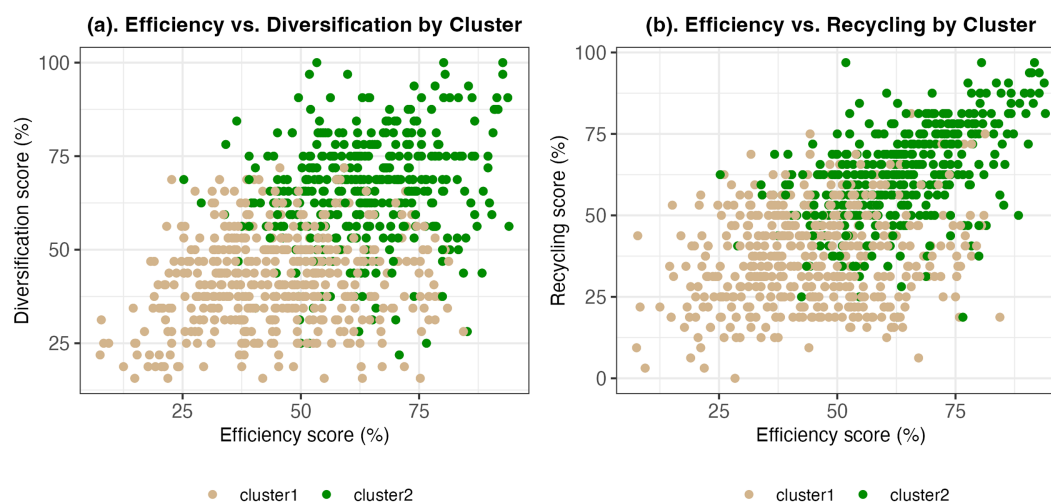


FIGURE 4

Cluster analysis results displayed within scatter plots between efficiency and diversity (left), and between efficiency and recycling (right).

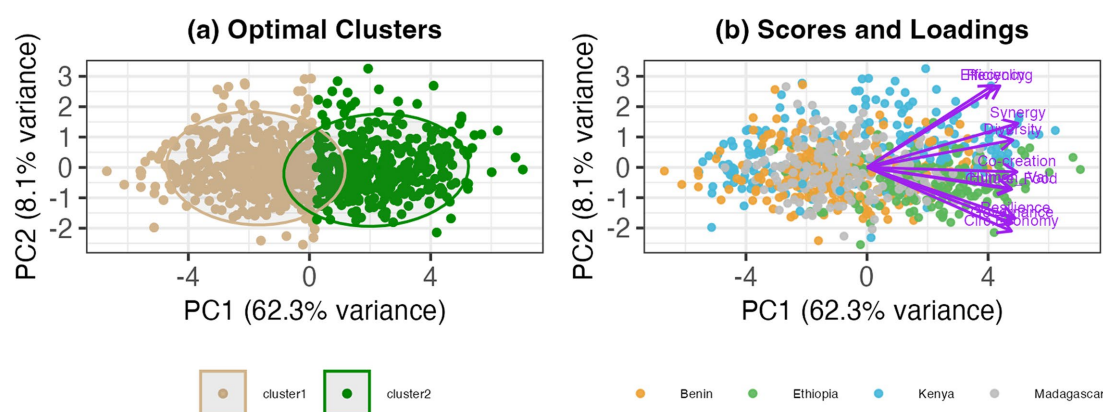


FIGURE 5

Principal Component Analysis (PCA) results showing two optimal clusters identified from the PCA scores. The two principal components (PC1 and PC2) represent the most significant dimensions and are represented in the 2 axes, together accounting for 70.35% of the total variation in agroecological element scores. Each dot represents an individual observation, showing how observations are distributed across the two axes. The clusters, independent of country of origin (a), are illustrated with ellipses drawn around the center of each cluster with clusters 1 and 2 representing farms with higher and lower CAET scores, respectively. Principal Component Analysis (PCA) of agroecological elements across four study countries (b) are represented by vector loadings (purple arrows) that indicate both the direction and strength of each agroecological element's contribution to the PCA dimensions—longer arrows denote greater influence of the corresponding element.

3.2 Performance of agroecology assessed through SDG-aligned indicators

Step 2 of TAPE assesses the overall performance of agroecology across five key sustainability dimensions: Economic, environmental, governance, health and nutrition, and social. For the purposes of this paper, health and nutrition performance are included within the social dimension.

3.2.1 Economic performance of agroecology

TAPE evaluates the economic performance of farms based on farm productivity, value added, and income (Lucantoni et al., 2023; Mottet et al., 2020). On average, the findings reveal a significant positive correlation between the level of

agroecological integration (CAET) and overall productivity (0.41***) (Table 3).

Beyond production factors like diversity (0.6***), synergies (0.42***), and resilience (0.41***), sociocultural aspects—such as human and social values (0.42**) along with culture and food traditions (0.35***)—are also strongly linked with higher productivity. While a strong positive correlation exists between CAET scores and most individual productivity indicators (e.g., value of animals sold, animal products, and crops produced), the correlation weakens when forestry products are included alongside crop production.

A closer examination of the individual indicators contributing to the aggregated income reveals that higher CAET scores are particularly correlated with increased revenues from animal and livestock product sales. The agroecology elements of diversity (0.43***), resilience

TABLE 3 Relationship between economic dimensions and selected elements of agroecology.

Element	Productivity score	Income score	Expenditure on farm inputs	Value added
Diversity	0.578***	0.426***	0.420***	0.454***
Synergies	0.418***	0.341***	0.271***	0.335***
Recycling	0.308***	0.244***	0.202***	0.215***
Efficiency	0.088**	0.13***	−0.06	0.044
Resilience	0.411***	0.426***	0.404***	0.397***
Culture and Food Tradition	0.352***	0.336***	0.293***	0.396***
Co-creation and Sharing of Knowledge	0.274***	0.266***	0.278***	0.277***
Human and Social Values	0.422***	0.404***	0.398***	0.387***
Circular and Solidarity Economy	0.232***	0.275***	0.268***	0.282***
Responsible Governance	0.221***	0.268***	0.308***	0.255***
Total CAET Score	0.41***	0.393***	0.354***	0.37***

Although less pronounced than for productivity, table reveals a significant positive correlation between agroecological integration and aggregated income scores (0.39***). All 10 elements exhibit positive associations with income, with diversity and resilience (0.426***) emerging as the strongest contributors. These gains are largely attributed to higher revenues from crops, forestry, livestock, and animal products, alongside reductions in farm expenditures.

(0.43***), synergy (0.34***), as well as human and social values (0.4**) are especially relevant in driving this positive correlation between CAET scores and net income. Despite the observed increases in productivity and income, advancing agroecological integration was linked to a significant increase (0.35***) in expenditure on farm inputs such as seeds, fertilizers, pesticides, and machinery (Table 4). However, farms that practiced recycling and were efficient in their resource use showed a notable decrease in input expenditure (−0.16**) and thereby enhanced incomes.

3.2.2 Environmental performance of agroecology

TAPE evaluation of environmental indicators focuses on agrobiodiversity and soil health. For soil health assessment, results of TAPE are partially substantiated by the complementary assessment of physiochemical parameters of soil health based on laboratory analysis. The study found a strong positive correlation (0.49***) between CAET scores and the aggregate agrobiodiversity score which combines diversity scores for crops, animals, and natural vegetation and pollinators, number of species and varieties of crops, number of species and breeds of animals, total number of livestock units (Figure 6).

While most agrobiodiversity indicators show a positive correlation with the overall CAET score, the index of natural vegetation and pollinator diversity does not display a significant correlation. Beyond agroecological practices like diversity and synergies, sociocultural dimensions—including human and social values, as well as cultural and food traditions—play an essential role in fostering agrobiodiversity.

To assess the contribution of agroecology to soil health, the TAPE assessment based on 10 biophysical soil health indicators was complemented by soil sampling and laboratory analysis. TAPE results indicate a positive correlation (0.428***) between CAET and overall soil health (Figure 7). Further, production-related agroecological elements—like efficiency, recycling, and synergies—strongly correlate with improved soil health, especially at advanced agroecological transition stages (CAET scores >75).

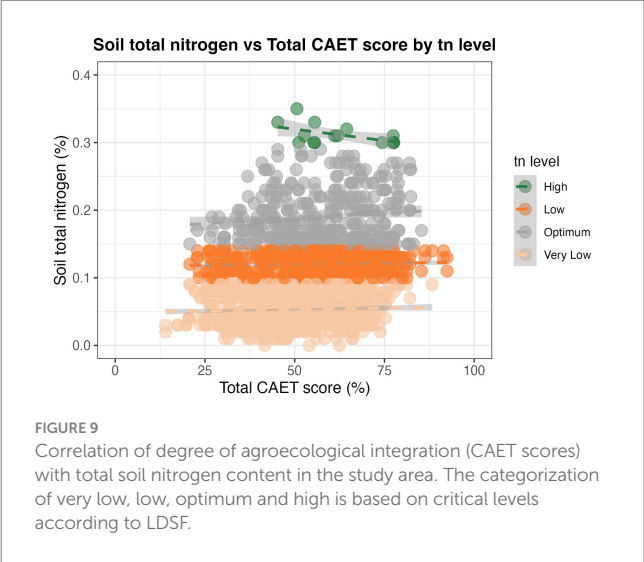
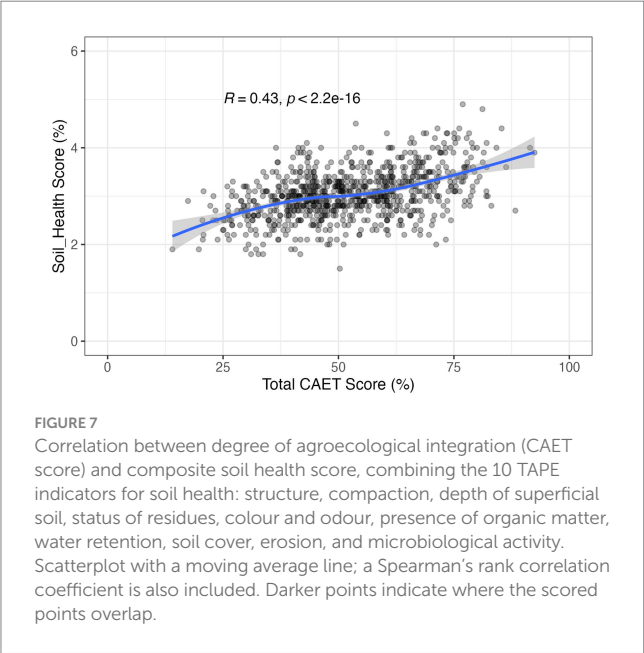
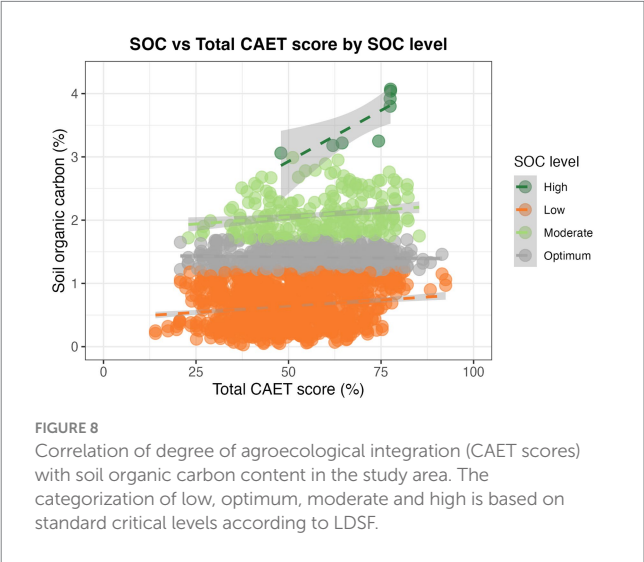
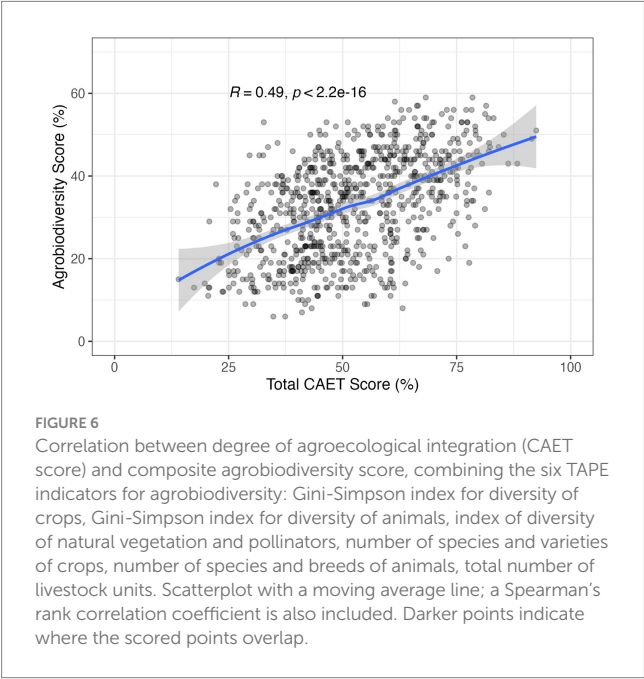
Co-creation and knowledge sharing demonstrate the strongest associations with soil health. Among the TAPE indicators for soil health, factors such as microbiological activity, soil colour and odour, soil cover, and soil erosion exhibit a significantly positive correlation with CAET scores. However, indicators like superficial soil depth, water retention, and residue status show positive correlations only at higher CAET scores (above 60).

Soil compaction and structure show no clear association with CAET scores in the study areas. However, the presence of invertebrates exhibit a modest increases (0.428**) with higher levels of agroecological integration, particularly in systems that emphasize efficiency (0.176***) and synergistic (0.114**) interactions. Interestingly, no significant association was noted between farm diversification and presence of invertebrates. While the broad diversity of soils across the four countries makes generalization difficult, soil sample laboratory analysis partially substantiates the TAPE results suggesting an association between higher agroecological integration and improved soil health characteristics such as soil organic carbon (SOC), pH, and total nitrogen. Although most soils assessed are moderately acidic and low in SOC, the data show a clear correlation between CAET scores above 50 and increased SOC content (Figure 8), highlighting the potential for further SOC enhancement with appropriate management practices. Interestingly, while no consistent correlation between pH and CAET is evident, soil pH shows a slight decline at CAET scores above 50. Further, SOC, a critical indicator of soil health due to its responsiveness to management, varies significantly across the countries studied. In Ethiopia and Kenya, most farms exhibit optimal to moderately high SOC levels, whereas in Benin and Madagascar, the majority of soils are low in organic carbon, both in topsoil (0–20 cm depth) and subsoil (20–50 cm).

Soil samples analysis results reveal low to very low total nitrogen levels, but a strong positive correlation with CAET scores above 50 (Figure 9) indicating that agroecological integration can enhance soil fertility at advanced stages of transition. Positive correlations are also

TABLE 4 ANOVA results for soil organic carbon (SOC) and total nitrogen (TN) by cluster.

Variable	Source	df	Sum squared	Mean squared	F value	Pr (>F)
SOC	Cluster	1	38.1	38.14	107.6	<2e-16
	Residual	1,666	590.6	0.35		
Total nitrogen	Cluster	1	0.408	0.4079	107.8	<2e-16
	Residual	1,666	0.306	0.0038		



observed between CAET scores and soil health metrics such as cation exchange capacity and potassium concentration.

Based on the PCA results, two optimal clusters were identified from the PCA scores. [Figure 5a](#) illustrates these clusters,

independent of country of origin, with ellipses drawn around the center of each cluster. The mean values for soil organic carbon and total nitrogen in cluster one are 1.19 and 0.119%, respectively, while cluster two shows slightly lower means of 0.89% for soil organic carbon and 0.09% for total nitrogen. ANOVA results indicate highly significant differences between the two clusters ($p < 2e-160$) for both SOC and total nitrogen, suggesting that clustering effectively distinguishes the study data into groups with distinct performance characteristics.

Analysis of the clusters provides further insight illustrating that Cluster 1, which is characterized by higher efficiency, recycling, and diversity, also exhibits higher soil organic carbon (SOC) and total nitrogen compared to Cluster 2.

3.2.3 Social performance of agroecology, including health and nutrition

In this study we calculated a diet score as an aggregate of TAPE's food security, dietary diversity, and household food expenditure indices, serving as a proxy for household nutritional status. Our findings show a strong positive correlation (0.22^{***}) between the CAET score and higher diet scores across the four countries (Figure 10), suggesting that households with enhanced agroecological integration tend to have more diverse diets (0.15^{***}), lower food expenses (0.13^{***}), and better food security (0.48^{***}). Beyond agroecological practices (diversity, recycling, synergy, and efficiency), elements of culture and food traditions (0.21^{***}), and the co-creation and sharing of knowledge (0.20^{***}) play a key role in strengthening this positive relationship between agroecological integration and diet scores.

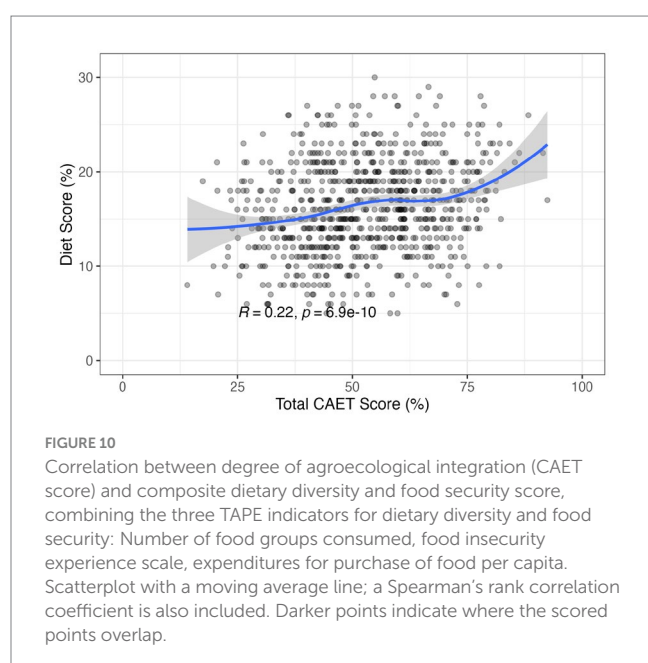
In addition to the above, TAPE assesses the health performance of households through the exposure to pesticide indices. The results indicate that agroecological farmers face significantly lower pesticide exposure risks, attributed to their adoption of ecological and integrated pest management practices (0.35^{***}) and improved spraying mitigation strategies (0.33^{***}). Efficiency (-0.29^{***}) and recycling (-0.18^{***}) are the only agroecological elements significantly associated with reduced chemical pesticide use, while both strongly correlate with increased organic pesticide application (0.36^{***}). However, overall pesticide use, and toxicity show limited correlation with the degree of agroecological integration (CAET scores).

Further, CAET scores are significantly correlated with women's empowerment scores (0.2^{***}) but show no strong linkages with the gender parity index. Despite this, women's legal recognition of land remains considerably lower than men's, even though land tenure security positively correlates with the degree of agroecological

transition. For youth empowerment, CAET scores show no significant correlation with the overall youth score or indices like youth emigration and employment. However, human and social values (0.13^{**}) and synergy (0.1^{*}) are associated with higher youth scores.

4 Discussion

The study findings from the four countries highlight that while agroecology presents a potential in simultaneously achieving multiple societal goals (Bhandari et al., 2024; Faure et al., 2024; Geels, 2011), the transition is progressively slow, necessitating more concerted efforts to unlock its full potential. The nuanced variations across elements offer deeper insights by revealing real differences in adoption and underscoring the heterogeneity in how agroecological elements are integrated across study sites. Social dimensions, such as culture and food traditions and human and social values, are deeply rooted and widely shared within communities (Ziro et al., 2023) which explains their tighter clustering around the median and more uniform integration. In contrast, elements that are more context- or resource-dependent, such as recycling and diversity, display greater variability. Given the central role of social norms in shaping adoption as evidenced by their strong association with overall CAET scores, agroecological interventions should be redesigned to align with cultural contexts and address societal needs to foster their integration by land users. Moreover, co-creation and exchange of knowledge grounded on human and social values are particularly essential in fostering agroecological transitions, emphasizing the need to view agroecology as more than a collection of farming practices (Boutagayout et al., 2023; Faure et al., 2024). In Madagascar, for example, agroecological practices related to the elements of diversity, recycling, and synergies are especially effective in the early stages of transition. However, as agroecological integration advances, adopting a comprehensive food systems approach becomes increasingly valuable in sustaining food systems transitions (Bezner et al., 2023; Kaljonen et al., 2023). The value of this holistic approach is supported by the observed synergies across all agroecological elements, with no significant trade-offs noted. Therefore, beyond implementing agroecological farm practices, enhancing social mechanisms for peer knowledge exchange, raising community awareness, and increasing producer involvement in decision-making and resource governance can further drive agroecological advancement (Altieri and Nicholls, 2020; Ong and Liao, 2020; Utter et al., 2021). While the weak association between efficiency and agroecological farm practices in particular recycling and diversity may be unexpected, the overall trend indicates that farms with more advanced agroecological integration (cluster 2) tend to be more efficient at higher scores of diversity and resilience. This underscores that efficiency gains emerge less from isolated practices and more from their cumulative and synergistic adoption, suggesting an opportunity to accelerate agroecological transitions by optimizing farm diversification and recycling options in ways that strengthen synergies within the agroecosystem (Tiftonell and Giller, 2013). This finding is further supported by the observation that diversification alone does not always translate into improved soil biological activity, particularly where complementary practices such as organic matter management or reduced agrochemical use are absent (McDaniel et al., 2014). Although diversifying farms can boost aboveground biodiversity, the



benefits to soil fauna often remain modest unless supported by soil-oriented management that fosters synergistic interactions among different farm components. Previous studies have highlighted that the benefits of agroecology often emerge through the interaction of practices rather than their singular application, with recycling and diversification contributing to resource-use efficiency, resilience, and ecosystem services (Altieri and Nicholls, 2020; Titttonell and Giller, 2013). Similarly, Wezel et al. (2020) argue that advancing along multiple agroecological elements fosters co-benefits that strengthen farm sustainability. Thus, the clustering of farms with high scores across these dimensions underscores the systemic nature of agroecological transformations, where integration rather than isolated practices drives efficiency gains.

Contrary to the claims that agroecology focuses on ecological sustainability at the expense of economic gains (Falconnier et al., 2023; Fiore et al., 2024), evidence from the four countries align with prior findings (Mouratiadou et al., 2024; van der Ploeg et al., 2019) demonstrating that supporting farmers in adopting agroecological practices may boost overall farm productivity and substantially increase household net incomes. However, this benefit may be constrained by the higher cost of ecological farm inputs in comparison to the conventional alternatives. As Titttonell and Giller (2013) notes, agroecological intensification is often linked with increased input expenses particularly within the resource-limited contexts such in the study sites. Though surprising, given that input reduction is a foundational principle of agroecology (HLPE, 2019), this finding aligns with prior research (Ong and Liao, 2020) which suggest that significant spending on production inputs may be an unavoidable necessity for farmers transitioning from conventional methods to agroecological alternatives. Coupled with the challenges of organic inputs being bulky, labor-intensive to produce and apply, and typically produced on a smaller scale due to resource limitations, supply shortages often lead to higher prices (Amede et al., 2023). According to Sachet et al. (2021), besides investments in social processes – the intensification of agroecological practices necessitates investments in material inputs to facilitate a transition that ultimately translates into long-term sustainability and productivity gains. Nevertheless, these increased expenditures on farm inputs across the study sites are not associated with any detectable income decline among farms with advanced agroecological integration in the study sites. Instead, adopting agroecological farm practices, such as farm diversification and recycling to reduce external input dependency, promoting synergistic interactions within farming system components (Benton and Harwatt, 2022), and empowering farmers including women and youth in natural resource governance, fosters economic resilience and productivity. With respect to farm diversification, integration of livestock, timber and non-timber forest products plays a crucial role in enhancing productivity and thereby income. According to recent studies (Faure et al., 2024; Kumar et al., 2024), agrosilvopastoral practices, which combine crop cultivation, agroforestry, and livestock management, enhance resource efficiency, improve soil health, and support pest control, stabilizing yields and incomes.

The findings make a strong case for agroecology as a key approach not only for achieving biodiversity targets and enhancing economic viability of farming systems but also in supporting the delivery of health, nutritional and food security goals (Ume et al., 2022; van Zutphen et al., 2022). Within the study area, the resulting

improvements in dietary diversity, food security, and reduced food expenditures likely stem from increased agrobiodiversity and an embrace of traditional and cultural food heritage within more advanced agroecological farms. According to Britwum and Demont (2022), harnessing traditional and cultural heritage aids in preserving genetic resources which are essential precursor to food availability and security, and fosters culture-driven preferences that contribute to resilient food microeconomies. Further, an agrobiodiverse system enhances farm resilience leading to diversified diets as well as production and income stability (Cadena-Zamudio et al., 2024; Wang et al., 2024). In pursuit of food security, reducing pesticide use has been shown to mitigate unintended ecological impacts, such as biodiversity loss, pollinator decline, and soil degradation, all key to strengthening a resilient food system (Schneider et al., 2023). This study provides clear evidence that adopting agroecological practices reduces farmers' exposure to pesticides through enhanced use of ecological pest management. This effect was especially noticeable among households that practice recycling and efficiently support natural biological processes by minimizing external input use.

The laboratory analysis of soil samples supports TAPE results, demonstrating a connection between higher levels of agroecological integration and overall improvements in soil health. The observed positive correlation between CAET scores and biophysical soil characteristics (such as microbiological activity, color, odor, soil cover, and erosion) may be attributed to the responsiveness of these indicators to changes in soil management practices such as farm diversification, crop-animal integration, agroforestry, cover cropping, and the addition of organic matter (Bhandari et al., 2024; Cárcelos Rodríguez et al., 2022; Sharma et al., 2024). However, while previous publications suggest that individual farming practices (FAO, 2015; Teixeira et al., 2021) can enhance biophysical soil health characteristics, the benefits to physiochemical properties (e.g., organic carbon and nitrogen content, pH) appear to arise predominantly from the integration of multiple agroecological elements. Long term integration of agroecological elements such as efficiency, recycling, and synergies is likely to improve physiochemical soil health characteristics, particularly at advanced stages of agroecological transition (Ding et al., 2024; Lal, 2016). Importantly, the study highlights that soil health improvements depend not only on sustainable farming practices but also on farmer-centered inquiry and collaborative knowledge co-creation and sharing (Utter et al., 2021). The joint creation and horizontal transfer of diverse knowledge types was found to have the strongest association with enhanced soil health, emphasizing its central role in promoting sustainability outcomes.

Although agroecological integration show clear positive contribution to soil health, the soil sample results reveal that generally, most soils are moderately acidic and low in SOC. This indicates that, unlike biophysical soil attributes, improving physiochemical soil properties is a gradual process necessitating prolonged periods of sustained implementation of sustainable farming practices (Zhou et al., 2021). Our findings are consistent with previous research Ong and Liao (2020) which found that in the early stages of transitioning to agroecology, there is often a temporary decrease in yields due to the time required for soil health to improve and beneficial ecological interactions to become established. Likewise, the initial stages of agroecological transition emphasize the promotion of multidimensional benefits, such as enhancing farm biodiversity, improving efficiency, and building resilient systems through a

collective learning process. This process often prioritizes the attainment of long-term sustainability over short-term productivity gains (Ong and Liao, 2020; Sachet et al., 2021). This focus may lead to a temporary decline in gross output value per hectare until farmers adapt and develop robust resilience, after which a significant increase in productivity and sustainable yields is achieved. The above-mentioned observations highlight the value proposition of soil sampling and laboratory testing as a critical means of validating qualitative soil health assessments. While biophysical indicators are practical and cost-effective to assess (Pires et al., 2005), they may fail to capture gradual or subtle shifts in soil chemistry and nutrient dynamics that only soil sample analyses can reveal. Without periodic validation, there is a risk of overestimating short-term gains or overlooking long-term degradation. Although resource-intensive, soil sampling and laboratory analysis provide reliable, quantitative benchmarks that are essential for tracking agroecological transitions, shaping evidence-based policies, and designing targeted interventions (Tiwarei et al., 2023).

Agroecology is correlated with increased performance on the women's empowerment index, a proxy to women empowerment, agency and inclusion in agriculture (Banerjee et al., 2024), by encouraging active participation in decision-making, which fosters equity and involvement in natural resource governance and management (Singh Bisht et al., 2022). While tenure security is crucial in driving agroecological transitions (Persha et al., 2015), establishing supportive institutional frameworks that prioritize land recognition, particularly for women within the study area, could significantly enhance the scaling of agroecological approaches by supporting sustainable, equitable, and secure food systems. Our analysis indicates that while youth may remain in agricultural roles in the early stages of agroecological integration, agroecological advancements which is often linked to increased labor demands and extended time to realize benefits (Amede et al., 2023), may drive the youths to seek alternative employment opportunities. Coupled with the challenge of insecure tenure rights, limited experience and training, and exclusion from production decisions, youth perceive agroecological farming as a low status, unstable, and underpaying livelihood alternative (Agroecology Coalition, 2024). According to Fiore et al. (2024), this perception and trending disengagement of youths necessitates a delicate balance between realizing short-term economic benefits and the long-term environmental goals as an entry-point to re-engaging the youth in agriculture and fostering agroecological integration.

5 Conclusion

This study provides cross-country evidence on the multidimensional benefits of agroecological integration, highlighting its potential to enhance productivity, income, soil health, agrobiodiversity, and food security, and women's empowerment. By combining TAPE and LDSF, we demonstrate that laboratory-based soil analyses complement qualitative assessments by detecting gradual changes in soil chemistry that are not otherwise possible through qualitative assessments. This underscores the value of integrating both approaches. While improvements in biophysical soil attributes are evident, gains in physicochemical properties such as SOC and nitrogen emerge only with sustained, long-term implementation.

Unlike the narrow focus on isolated practices such as diversification and recycling, agroecological integration benefits most from a systemic and synergistic interaction of multiple dimensions. In particular, the social aspects that are rooted in culture and food traditions, human and social values, and the co-creation and sharing of knowledge emerge as critical drivers shaping farmers' integration of other agroecological elements. For food system transitions to succeed, interventions must therefore be culturally grounded, co-created with producers, and tailored to societal needs.

Despite clear benefits, challenges remain. The higher costs of ecological inputs, labor demands, and insecure tenure can limit adoption, particularly for youth who often perceive agroecological farming as risky and economically unattractive. Addressing these barriers will require supportive policies that make ecological inputs affordable, secure land rights, and invest in labor-saving innovations. Re-engaging youth will also necessitate balancing immediate economic needs with long-term ecological benefits.

Overall, the evidence underscores that agroecology is not just a set of practices but a systemic approach that combines ecological, social, and cultural dimensions. A holistic assessment of food systems is therefore essential for effectively evaluating performance and guiding data-driven decisions on food system transitions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

BA: Conceptualization, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. MG: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. CA: Conceptualization, Investigation, Methodology, Validation, Writing – review & editing. JA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Visualization, Writing – review & editing. AD-D: Conceptualization, Investigation, Methodology, Validation, Writing – review & editing. DA: Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – review & editing. PA: Conceptualization, Investigation, Methodology, Validation, Writing – review & editing. CB: Conceptualization, Formal analysis, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing. RoC: Conceptualization, Data curation, Methodology, Validation, Writing – review & editing. RéC: Conceptualization, Methodology, Resources, Supervision, Validation, Writing – review & editing. FI: Conceptualization, Methodology, Writing – review & editing, Investigation, Resources, Supervision, Validation. VK: Conceptualization, Methodology, Project

administration, Validation, Writing – review & editing, Data curation, Software. DK: Conceptualization, Methodology, Validation, Writing – review & editing, Funding acquisition, Investigation, Project administration, Resources, Supervision. DM: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – review & editing. AS: Conceptualization, Data curation, Methodology, Software, Validation, Writing – review & editing, Formal analysis, Visualization. MO: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – review & editing, Resources. AT: Conceptualization, Methodology, Validation, Writing – review & editing, Data curation, Software, Formal analysis, Visualization. ELW: Conceptualization, Methodology, Validation, Writing – review & editing, Data curation, Software. LW: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing, Investigation, Data curation. EnW: Supervision, Methodology, Project administration, Conceptualization, Writing – review & editing, Investigation, Validation. PZ: Conceptualization, Methodology, Validation, Writing – review & editing. LS: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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