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RESEARCH ARTICLE

Progressing toward agroecology in vineyards through systemic innovation

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Abstract

Viticulture is facing major challenges, and agroecology is recognized as an innovative approach to enhance food system sustainability. However, knowledge is lacking about how winegrowers design innovations to support agroecology, which limits the ability of farmers and advisers to effectively steer and assess progress toward agroecology. This study aims to develop a tool to assess the agroecology level of vineyards, and to investigate the link between progress in the agroecological transition and the systemic and farm-scale reasoning of innovations. To this end, we interviewed 24 winegrowers, developed a table to characterize the agroecology level of the farms and identified the farmers' agronomic rationales. Agroecology levels varied widely among the surveyed farms. The agroecology elements of synergy, efficiency, and a circular and solidarity-based economy explained most of the differences between farms at the extreme ends of the score ranges. We used semi-quantitative and qualitative indicators to highlight systemic reasoning in highly agroecological farms. The winegrowers from the most agroecological farms changed their practices more frequently, mainly by implementing practices that rely on system reorganization and redesign and by addressing a wider variety of results when changing their practices. The analysis of these farms revealed several success factors, including the adjustment of other practices after a change, careful observation of the agroecosystem, and a paradigm shift involving long-term reflection on practice effects. Moreover, successful farms are smaller, and have often reduced land areas to gain increased flexibility in production factors. They seek autonomy regarding inputs and promote synergies with respect to the farm's different business activities. This work provides valuable support to winegrowers and advisers by offering them a simple tool to track the progress of vineyards when transitioning to a more agroecological system. This study also identifies key traits of agroecological farms that can inspire and be adopted on other farms.

Keywords Farm · Sustainability · Practice change · Transition · System design · Pesticide use · Crop–livestock system · Agroforestry

1 Introduction

Viticulture stakeholders, like those in other cropping systems, adopted a productivist model in the mid-twentieth century to achieve higher yields through the intensive use of external inputs such as pesticides, synthetic fertilizers and water. This approach has led to significant environmental and human health issues, including soil degradation (Karimi et al. 2020), biodiversity loss (Paiola et al. 2020), water pollution (Herrero-Hernández et al. 2020), and scarcity (Costa et al. 2016), as well as increased greenhouse gas emissions (Rugani et al. 2013), all of which contribute to climate change. Addressing these challenges requires a profound transformation of viticultural systems (Duru et al. 2015a). Agroecology is increasingly recognized as an innovative approach to enhance food system sustainability (HLPE 2019; Barrios et al. 2020). Definitions of "agroecology" vary and have evolved since the concept first appeared in literature in the 1930s with Basil Bensin (Wezel et al. 2009).

At the heart of agroecology is the idea that a crop is an ecosystem where ecological processes occur, such as nutrient cycling and predator–prey interactions (Altieri 1995), and that these functions should be enhanced (Gliessman

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2006) (Fig. 1). While agroecology initially focused on environmental aspects, its scope has expanded to involve human, social, economic and political dimensions (Rosset and Altieri 1997; Gliessman 2006; Barrios et al. 2020), extending from the plot scale to the entire food system. Different tools exist to characterize the level of engagement in the agroecological transition (Darmaun et al. 2023). The Food and Agriculture Organization (FAO) proposed a Tool for Agroecology Performance Evaluation (TAPE) as a first step toward characterizing agroecology at the farm level (Mottet et al. 2020), and the OASIS tool (Original Agroecological Survey and Indicator System) was developed to assess agroecological transition (Peeters et al. 2021; Škorjanc et al. 2021). The TAPE framework mainly focuses on the farm and household levels, although smaller (e.g., plot, herd) and larger (e.g., landscape, territory or community) scales are also considered but require further refinement to be fully suited to a European context for comparing farms.

When adopting an agroecology approach, the principles are meant to be applied in a systemic way on farms (Rosset and Altieri 1997). Some practices can foster the agroecological transition (Wezel et al. 2009), but their effects also depend on the context and on their integration into the broader farming system. These practices are more effective when implemented coherently with others taking into account the specific local ecological conditions that influence the practices and their impacts (Meynard 2017). However, some authors focus on identifying and promoting individual practices as tools for change. For example, Wezel et al. (2014) provide a comprehensive list of such practices, discussing their potential, advantages, and limitations. In the French winegrowing sector, a guide to agroecological viticulture was created to assist winegrowers in transitioning to agroecology through the rapid implementation of standard practices (IFV 2017). Similar to Guyomard et al. (2017), this guide suggests that stacking agronomic practices on farms could drive the agroecological transition, although this view does not fully account for the need for a systemic approach as emphasized by other authors.

Farm transition to agroecology, as conceptualized by Prost et al. (2023), is described as a pathway starting from an unsatisfactory initial situation, moving through an uncertain and unpredictable transitional phase characterized by changes, and ultimately reaching a point where agroecological principles are more widely implemented. During this transition, farmers design and implement innovations that put the theoretical agroecological principles into practice. Changes in on-farm practices have been highlighted as generally occurring over a long period of time (Chantre and Cardona 2014; Merot and Wery 2017; Fouillet et al. 2023) and involve a step-by-step design process with iterative feedback loops (Meynard et al. 2023). Both internal factors (e.g., farm-specific characteristics, labor) and external factors (e.g., market dynamics, policy incentives) influence this pathway and the underlying strategies (Fanchone et al. 2020; Dupré et al. 2020). Agroecological transitions have been shown to involve profound transformations at the farm scale (Chantre and Cardona 2014), and changes occurring during an agroecological transition are frequently categorized as redesign levels (Hill and MacRae 1996) that lead to disruptive systems (Meynard and Jeuffroy 2021). Shedding light on successful pathways provides valuable insights for future initiatives supporting agroecology. Some farms, acting as

Fig. 1 Examples of vineyard innovations that contribute to agroecological principles : crop diversification in the inter-rows (left) and grazing by sheep and goats (right). Photo credit : J. Castell, E. Robelot

"lighthouses" (Nicholls and Altieri 2018) have successfully developed highly innovative systems, and demonstrate strong links between the practices implemented, the farmer's desired target and the broader system (Verret et al. 2020; Salembier et al. 2021). Analyzing such on-farm innovations can produce actionable knowledge that may inspire other farmers.

In viticulture, Fouillet et al. (2023) highlighted substantial reductions in pesticide use in several vineyards, but other farms are struggling to curb their use. The agroecological transition in viticulture remains relatively rare due to several constraints. First are technical and biophysical challenges, where pathogens such as downy mildew can wipe out an entire crop yield (Fermaud et al. 2016). Additionally, economic barriers limit winegrowers' ability to invest in new practices due to transition costs, uncertainties regarding profitability, and sometimes limited access to financial support. Organizational challenges also play a role. Merot and Wery (2017) showed that transitioning to organic farming increases system complexity. This, in turn, leads to the implementation of different strategies and changes at the farm scale, including land use, equipment, and economic adjustments (Merot et al. 2020). Finally, regulatory constraints, particularly the strict production requirements set by the French National Institute of Origin and Quality (INAO), which oversees protected designations of origin such as AOC (appellation d'origine contrôlée), make adopting certain practices more difficult. These factors highlight the need for greater integration of changes at the farm scale into studies on agroecological transition (Prost et al. 2023).

Many studies have focused on specific aspects of farm system transition, such as reducing synthetic inputs or diversifying crops, without addressing the agroecological transition as a whole. We assumed that the ability to overcome barriers to the agroecological transition may be closely linked to the production and circulation of knowledge as well as the reasoning behind innovations implemented over the long term, particularly when these are designed within the broader systemic framework of the farm. Our work aimed to analyze, for the first time, the reasoning behind the changes in practices of winegrowers who are engaged to varying degrees in an agroecological transition, highlighting how these rationales vary according to their progress along the transition pathway. In this paper, we addressed the following research question: Is the level of advancement in the agroecological transition of a vineyard farm linked to a reasoning specifically involving (i) systemic changes and (ii) consideration of the farm scale? This study proposes a framework for characterizing agroecology at the vineyard level and a method for analyzing the systemic reasoning behind changes in practices, both of which can help support farmers' agroecological transitions.

2 Materials and methods

2.1 Selection of farms

A total of 24 vineyard farms were selected from the main French winegrowing regions (Occitanie, Bordeaux/Nouvelle-Aquitaine, Provence/Rhône Valley, and Loire Valley) to cover a diverse range of pedoclimatic and economic contexts and ensure a balance among the different types of farms in each region. Additional criteria were also included when choosing the farms: (i) winegrowing is one of the farm's two main sources of agricultural income; (ii) the vineyard size is at least 4 hectares, which is considered a threshold for economic viability in the regions studied; (iii) farms with different levels of innovations, from farms with "low" levels of innovation having implemented a priori none or very few agroecological practices, to farms with "high" levels of innovation having implemented numerous innovations (Table 1). The production system (conventional or organic) was not a selection criterion, although we sought to include a minimum number of farms of both types.

2.2 Semi-structured interviews

We conducted semi-structured interviews, beginning with a general question about the farm and the main changes in practices that had taken place since the start of the farmer's career to provide an overview of these changes. The practice changes that were considered concerned various categories: weed management, soil fertility, pests and diseases, biodiversity management, and pruning and thinning techniques. The different components of the farmers' agronomic rationales were collected (Quinio et al. 2022). This means that, for each practice change, we identified the determinants behind the change (the farmer's motivations and the characteristics of the situation), the expected results of the change, the implementation details (areas of the farm, modalities, parameters, adaptation to the available resources, etc.), and the farmers' satisfaction criteria. We paid particular attention to the consequences after a practice was implemented, meaning that we sought to identify the links with other practices (induced changes or adaptations) or the implications for the whole production system. Finally, questions were asked about the major themes that were not covered during the interview to ensure that no significant changes had been overlooked.

2.3 Characterization of the level of agroecology

A table was created (Table 2) to characterize the level of agroecology in vineyard farms. It was inspired by the framework developed by the FAO (Mottet et al. 2020) in the first

Table 1 Innovations implemented in the 24 farms surveyed. The innovations considered are those mentioned in the literature as contributing to agroecology (Wezel et al. 2014; IFV 2017). The regions studied are abbreviated with letters: O for Occitanie in southwestern France; B for Bordeaux/Nouvelle-Aquitaine in western France; P for Provence/Rhône Valley in southeastern France; L for Loire in central-western France. The farming systems have been abbreviated as: C for conventional agriculture, Or for certified organic agriculture. * indicates innovations that were abandoned (voluntarily or not)

FARM ID	OCCIT_7	NVAQ_4	OCCIT_9	PACA_6	PACA_5	OCCIT_4	OCCIT_10	LOIRE_1	NVAQ_3	PACA_2	LOIRE_9	OCCIT_1	PACA_4	PACA_7	LOIRE_10	OCCIT_2	LOIRE_6	OCCIT_8	OCCIT_6	NVAQ_2	LOIRE 7	NVAQ_1	LOIRE_8	PACA_1
Region	O	B	O	P	P	O	O	L	B	P	L	O	P	P	L	O	L	O	O	B	L	B	L	P
Vineyard area (ha)	20	70	10	40	29	51	50	27	27	45	15.5	11.5	14	6.5	4	10	13	6.5	50	81	15.7	30	8	4.5
Farming system	C	Or	C	C	Or	C	C	C	Or	Or	Or	Or	Or	Or	Or	Or	Or	Or	C	Or	Or	Or	Or	Or
Hedgerows										X		X	X	X	X			X	X	X	X	X	X	X
Agroforestry and associated crops									X*					X		X*		X	X			X	X	X
Grazing (sheep)										X		X	X		X		X				X		X	X*
Grazing (poultry)															X*	X					X*			
Horse-drawn tillage																	X			X	X	X*	X	X*
Spreading manure, mulch or straw		X			X		X				X		X	X	X	X*	X	X	X	X	X	X		X
No use of synthetic products									X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Spraying of herbal teas, essential oils or biodynamic preparations							X	X	X		X	X			X	X*	X			X	X	X	X	X
Mating disruption			X			X		X*											X			X		
Release of parasitoids						X														X				

Table 1 (continued)

FARM ID	OCCIT_7	NVAQ_4	OCCIT_9	PACA_6	PACA_5	OCCIT_4	OCCIT_10	LOIRE_1	NVAQ_3	PACA_2	LOIRE_9	OCCIT_1
Reduced tillage intensity								X	X		X	
Sowing of cover crops				X			X	X		X	X	X
Resistant grape varieties					X		X					
Total innovative practices	**0**	**1**	**1**	**1**	**2**	**2**	**4**	**4**	**4**	**4**	**5**	**5**

FARM ID	PACA_4	PACA_7	LOIRE_10	OCCIT_2	LOIRE_6	OCCIT_8	OCCIT_6	NVAQ_2	LOIRE_7	NVAQ_1	LOIRE_8	PACA_1
Reduced tillage intensity		X				X			X		X	X
Sowing of cover crops	X*			X*	X	X*	X	X		X	X	
Resistant grape varieties							X					
Total innovative practices	**5**	**5**	**6**	**6**	**6**	**6**	**7**	**7**	**8**	**8**	**8**	**8**

step of the TAPE tool. Seven elements were selected from the ten proposed by the FAO, focusing on those directly relevant to the winegrowing production context at the farm scale. A total of 20 key indicators were identified, drawing from the indicators proposed by the FAO and supplemented by the IDEA4 assessment method (Zahm et al. 2023). Simple modalities were proposed for each indicator, with references aligned with those suggested by IDEA4 when possible.

This table includes indicators with different characteristics (Table 2): (i) indicators specific to vineyard activity (e.g., genetic diversity, integration of livestock), particularly those related to environmental principles, and others related to farm scale and other crops (e.g., production diversity, water savings); (ii) indicators with thresholds (e.g., genetic diversity, product market through direct sales) that align with those in other methods (especially the IDEA4 method) or indicators with qualitative modalities; (iii) indicators that rely on the researchers' qualitative analysis based on the farmer's statements, with raw data refined afterward (e.g., yield achievement, economic viability, agricultural system–landscape connectivity).

The different modalities were converted into scores ranging from 0 to 3 for each indicator. The scores for each indicator were normalized with a weight of 1, ensuring that all indicators contributed equally to the following calculations. Normalized scores were then summed within each element (e.g., diversity) and aggregated by theme: environmental (12 indicators, maximum score of 12), social (5 indicators), and economic (2 indicators).

2.4 Analysis of the systemic nature of practice changes

2.4.1 Representation of practice changes in diagrams

For each farm, interview data were visually represented in a diagram linking various types of information (Fig. 2). The boxes and connections depicted in the diagram represent only those established by the winegrower during the survey. These diagrams illustrate the reasoning behind practice changes on the farm, using some components of the concept of agronomic rationale (Salembier et al. 2021; Quinio et al. 2022). The diagrams consist of the following elements:

– Practice changes, defined as the introduction or modification of any practice aimed at achieving a new outcome. A comprehensive list of these changes can be found in the supplementary data. Each practice change is categorized according to the efficiency, substitution and redesign (ESR) framework (Hill and MacRae 1996) re-adapted by Merot et al. (2020), who used it at the finer scale of cropping practices by dividing the rede-

Table 2 Table of principles and indicators to characterize the level of agroecological transition of vineyard systems. The table is structured around seven main principles and divided into 20 indicators. Indicators are classified as follows: (V) for viticulture-specific aspects and (F) for farm-wide considerations

Principles	Indicators	Score: 0	Score: 1	Score: 2	References
Diversity	Diversity of crop/livestock production (F)	Viticulture only	Viticulture and one other crop/livestock production	Viticulture and two or more other crop/livestock production	(Kremen and Miles 2012; Lin 2011; Liebman and Schulte 2015)
	Genetic diversity of grapevine (V)	≤ 3 varieties	[4–7] varieties	≥ 8 varieties	(Masset and Weisskopf 2024)
	Diversity of products sold (F)	Wine	Wine and one other product	Wine and two or more products	(Lin 2011)
Synergies	Mobilization of the agricultural system–landscape connectivity (F)	Low	Medium	High	(Chaplin-Kramer et al. 2011; Paredes et al. 2021)
	Integration of livestock (V)	No grazing	Grazing by animals or horse-drawn tillage (<50% area)	Grazing by animals or horse-drawn tillage (>50% area)	(Ryschawy et al. 2021; Brewer et al. 2023)
	Management of soil–plant system (V)	Herbicides used on rows or inter-rows	Tillage of all inter-rows OR every other inter-row at least part of the year	All inter-rows permanently grassed	(Winter et al. 2018; Paiola et al. 2020; Karimi et al. 2020)
	Integration of trees or associated crops (V)	No trees	Trees or associated crops (<10% of the vineyard area)	Trees or associated crops (>10% of the vineyard area)	(Beillouin et al. 2021)
Efficiency	Management of soil fertility (V)	Synthetic fertilizers	Organo-mineral fertilizers	Organic amendments	(Diacono and Montemurro 2010)
	Management of pests and diseases (V)	Prevalence of synthetic products	High use of copper and biocontrol only	Low use of copper and biocontrol only	(Baldi et al. 2021; Karimi et al. 2021; Pham et al. 2022)
	Management of water (V)	Irrigation (>10% of area)	Irrigation (<10% of area)	No irrigation	(Ingrao et al. 2023; Hannah et al 2013)
Recycling	Recycling of biomass and nutrients (V)	No	Green manure/compost produced on the farm OR cover crop	Green manure/compost produced on the farm AND cover crop	(Abad et al. 2021; Brito et al 2025; Seitz et al 2024)
	Specific system to save water (F)	No	System in place but no significant savings	System in place and significant savings	N/A
	Production or use of renewable energy (F)	No	Yes, produced or consumed	N/A	N/A
Knowledge sharing	Farmers' interest in agroecology (F)	Low	Medium	High	(Soini Coe and Coe 2023)
	Farmers' participation in networks (F)	No	Participation in a few networks (meetings)	Participation (trials, training) in several networks	(Navarrete et al. 2015)
Circular and solidarity economy	Products marketed through direct sales (F)	Direct sales: < 5% of wine	Direct sales : [5–50%] of wine	Direct sales: > 50% of wine	(Alonso Ugaglia et al. 2020)
	Valorization of local resources (F)	No	Supply of inputs from local businesses	Recovery of by-products from the local community	(Angeon et al. 2006)
	Relationship with consumers (F)	No links with the consumers	On-farm sales	On-farm sales and wine tourism	(Gilg and Battershill 2000)

Table 2 (continued)

Principles	Indicators	Score: 0	Score: 1	Score: 2	References
Resilience	Yield achievement (V)	Target yields mostly not achieved	Target yield mostly achieved	N/A	N/A
	Economic viability (F)	Farm financially unsustainable	Farm temporarily financially unsustainable	The farm is viable	N/A

sign level into two: reorganization (Ro), which corresponds to a change in a cropping practice that leads to rethinking one or two other cropping practices, and redesign (Re), which corresponds to a change in a cropping practice leading to a change in a large part of the technical crop management.

- Expected results of the change: These outcomes specify the anticipated or targeted effects using action verbs (e.g., destroy, provide, limit) and direct targets (e.g., insects, vines, soil) to prevent confusion with indirect effects. Two categories of expected outcomes were identified: primary outcomes (e.g., enhancing soil fertility, reducing pesticide use) and secondary outcomes (e.g., creating unfavorable conditions for disease establishment, reducing the use of harmful products). A comprehensive list of the expected results can be found in the supplementary data.
- Perceived positive or negative impacts of the change, which may vary in nature (biophysical, economic, organizational).
- Implementation choice: Additional actions may occasionally be necessary depending on the winegrower's constraints and chosen implementation methods. For instance, one winegrower may choose to purchase and spray herbal teas, while another may choose to harvest, prepare and spray their own. In the latter case, harvesting and preparing the herbal teas are necessary steps in the spraying process.
- Adaptations of the practice following the change or stopping of a practice.
- Adaptations of other farming practices following the change.

2.4.2 Indicators to assess farmer's systemic reasoning

Depending on the fundamental system characteristics (Walliser 1977; Le Gal et al. 2010; Darnhofer et al. 2012) and the structure of our diagrams, we defined several semi-quantitative indicators to assess the farmer's level of systemic thinking (Fig. 2). The following indicators assess the number and diversity of the components, as well as the interconnectedness between these components:

(i) Total number of expected results motivating the implementation of each practice and diversity of these expected results
(ii) Total number of new practices adopted by the farmer since establishing their farm and ESR classification (Hill and MacRae 1996)
(iii) Average number of practice changes per expected result (P):

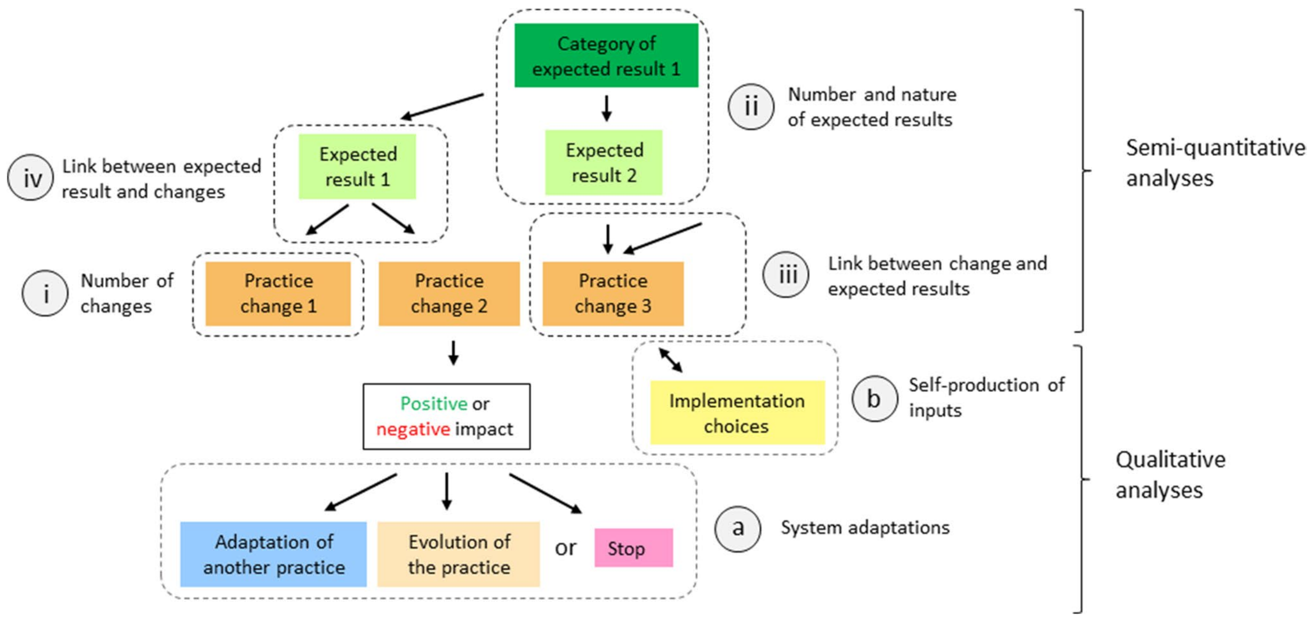

Fig. 2 Flowchart of the indicators used to assess the systemic approach. Indicators (i) to (iv) are semi-quantitative indicators that evaluate the systemic reasoning behind changes in practices. Indicator (a) is a qualitative indicator to assess systemic reasoning, while indicator (b) is a qualitative indicator used to assess reasoning at the farm scale

$\underline{P} = \frac{\sum_{i=1}^{n} Pi}{n}$ where P_i represents the number of practices associated with one expected result i and n is the total number of expected results.

(iv) Average number of expected results per practice change (R):

$\underline{R} = \frac{\sum_{j=1}^{m} Ri}{m}$ where E_i represents the number of expected results associated with one practice change j and m the total number of practice changes.

Spearman's correlation coefficients were calculated between these different indicators and the global agroecology scores of each farm.

Moreover, by comparing practice changes across farms in a qualitative way, we identified some of the factors determining their success. The comparison of farms was carried out based on the following themes: the adaptation of practices following changes (Fig. 2), the nature of satisfaction criteria after the introduction of a practice, the time frame considered during changes, and the agroecosystem observation.

2.5 Consideration of farm scale in designing innovation

A farm is a unit dedicated to the exploitation of various resources for production, management, and decision-making within agricultural activities (Le Gal et al. 2010). It is characterized by the area of land allocated to the activity (vineyard and other productions), financial capital, labor, workers, equipment, knowledge and skills. We identified the similar characteristics in the farm-scale strategies implemented in farms with a high level of agroecology through a qualitative cross-analysis of interviews. The themes considered are changes in vineyard size, the on-farm production of inputs (Fig. 2), and the complementarity between the farm's various activities.

3 Results and discussion

3.1 Surveyed farms showed a large range of agroecology levels

The global agroecology scores (Fig. 3) varied widely for the 24 farms surveyed, ranging from 4.5/20 for farms with a low agroecological level (low-AE farms) to 15.5/20 for highly agroecological farms (high-AE farms). The global scores are well distributed between these extremes, indicating varying levels of progress in agroecological transition within the farm sample. The median is 10.5/20. Each selected winegrowing region encompasses both low- and high-scoring farms.

An analysis of scores for each agroecological element shows that some principles have more influence on the global scores than others. Most high-AE farms tend to have higher scores in specific environmental elements, particularly efficiency and synergy. Regarding the efficiency

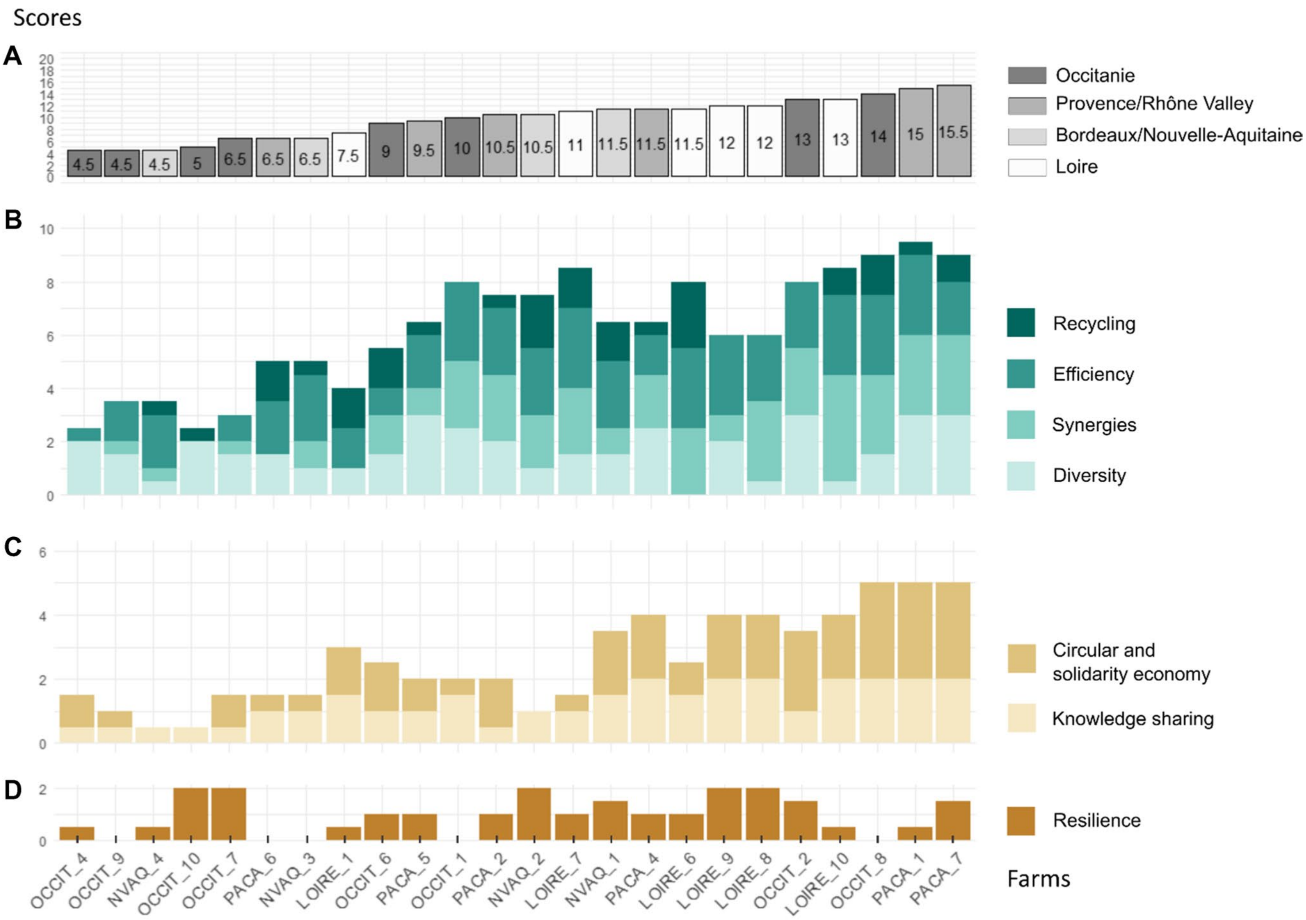

Fig. 3 Agroecology scores of the 24 farms surveyed, ranked from lowest (left) to highest (right) overall scores. **A** Global scores, **B** scores for agroecosystem elements, **C** scores for social elements, and **D** scores for the economic element.

element, high-AE farms more often use natural plant protection products such as copper and sulfur (pest and disease management indicator), often at lower doses than the regional averages, whereas low-AE farms show a greater reliance on synthetic products. High-AE farms also favor organic amendments, including manure or compost, over synthetic fertilizers (soil fertility management indicator). The presence of irrigation systems (water management indicator) does not appear to be a distinguishing factor among various agroecology levels across farms. Concerning the synergy element, the high-AE farms generally maintain more extensive and consistent ground cover throughout the growing season, in contrast to low-AE farms, which tend to use herbicides or rely on mechanical weeding (soil–plant indicator). Additionally, more high-AE farms use animals within the vineyards, whether for grazing or animal traction (integration of livestock indicator), and they also implement species mixtures, such as agroforestry or intercropping (integration of trees or associated crops indicator). These farms often adopt practices that promote landscape connectivity, including planting hedgerows or managing semi-natural habitats (agricultural system–landscape connectivity indicator).

The recycling element does not appear to significantly influence overall scores. High-AE farms tend to have rainwater harvesting systems (water recovery indicator), but no correlation can be observed for solar panels (renewable energy indicator). In terms of organic recycling, high-AE farms tend to produce their own amendments, whereas low-AE farms often sow cover crops, which enhance their scores in the recycling element. The diversity element does not vary significantly across agroecology levels. The diversity of grape varieties (grape varieties indicator) and the diversity of crop/livestock production (diversity of production indicator) are not linked with the agroecology level. Low-AE farms tend to diversify at the farm level by including crops such as cereals or olive trees, while high-AE farms exhibit diversification within the vineyard plots themselves. Product diversification (product diversity indicator) is associated with crop/livestock production, although high-AE farms provide additional products, such as grape juice in addition to wine.

High-AE farms score higher in the social elements of co-creation and knowledge sharing, as well as in the circular and solidarity-based economy. In terms of knowledge sharing, farmers with higher scores exhibit a greater interest in agroecological elements and demonstrate more active participation in farmers' networks, such as economic and environmental interest groups (GIEEs). Regarding the circular and solidarity-based economy, these farms maintain closer connections with consumers through activities such as farm visits and on-farm sales, while prioritizing the use of local resources, such as manure sourced from neighboring farms.

Finally, regarding the element of *economic resilience*, which is characterized by activity viability and yield achievement, no trend can be identified between the low-AE and high-AE farms.

3.2 High-scoring AE farms perform more systemic practice changes

The number of practice changes varies among the surveyed farms (Table 3), with a minimum of four changes (NVAQ_4 and PACA_2; rank (rk) 13 and 22, respectively) and a maximum of 16 (PACA_1; rk = 2). High-AE farms changed more of their practices over time ($r^2 = 0.72$). The survey period ranged from 4 years (OCCIT_8; rk = 3) to 47 years (LOIRE_7; rk = 47), but we did not note any correlation between the survey period and the number of changes ($r^2 = 0.02$), and the average number of changes per year followed the same pattern as the total number of changes. There is a range of different practice changes. There are more efficiency (E) and substitution (S) changes in low-AE farms than in high-AE farms. In contrast, the changes in high-AE farms are predominantly reorganization (Ro) and redesign (Re) changes, although some efficiency and substitution changes also occur. The average number of expected results associated with each practice change varies from 3 (OCCIT_9; rk = 24) to 17 (PACA_1; rk=2). High-AE farms have more expected results associated with practice changes ($r^2 = 0.80$). These expected results are grouped into several major categories (Fig. 4): limiting fungicides and insecticides, improving soil properties, maintaining good water status of the vines (and in some cases, reducing herbicide application), increasing biodiversity, optimizing farm resources, objectives related to other farm activities

Table 3 Indicators of systemic reasoning for the farms surveyed. The farms are listed in order of their agroecological score (from the lowest on the left to the highest on the right) and ranked based on these scores. For farms with the same overall agroecological score, the highest rank is given to the farm with the highest environmental dimension score. The practice changes are classified into four types: efficiency, substitution, reorganization and redesign. For each indicator, the color gradient ranges from the lowest value (in red) to the highest value (in green). Spearman's correlations (r^2) were calculated between each indicator and the overall agroecological score

Indicators / Farm ID	OCCIT_4	OCCIT_9	NVAQ_4	OCCIT_1	OCCIT_7	PACA_6	NVAQ_3	LOIRE_1	OCCIT_6	PACA_5	OCCIT_1	PACA_2	NVAQ_2	LOIRE_7	NVAQ_1	PACA_4	LOIRE_6	LOIRE_9	LOIRE_8	OCCIT_2	LOIRE_1	OCCIT_8	PACA_1	PACA_7	r^2
Agroecology score	**4.5**	**4.5**	**4.5**	**5.0**	**6.5**	**6.5**	**6.5**	**7.5**	**9.0**	**9.5**	**10.0**	**10.5**	**10.5**	**11.0**	**11.5**	**11.5**	**11.5**	**12.0**	**12.0**	**13.0**	**13.0**	**14.0**	**15.0**	**15.5**	
Agroecology rank	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	
Number of years covered by the survey	42	19	8	11	24	21	13	9	5	27	20	22	19	47	23	7	11	21	17	18	6	4	13	20	
Vine area (ha)	51	10	70	50	20	40	27	27	50	29	11.5	45	80	15.7	30	14	13	15.5	8	10	4	6	4.5	6.5	**-0.7**
Number of practice changes	5	5	4	5	5	5	5	9	7	6	7	4	7	11	15	10	9	11	14	9	6	7	16	9	**0.72**
% efficiency changes	0	20	0	17	20	20	20	0	0	20	0	25	0	0	13	10	11	0	0	0	0	14	0	11	
% substitution changes	80	60	25	17	40	40	60	89	29	40	14	0	29	45	27	0	11	45	29	67	20	0	25	22	
% reorganization changes	0	0	25	50	20	20	0	0	43	20	57	50	43	27	33	60	44	45	36	0	40	43	38	44	
% redesign changes	20	20	50	17	20	20	20	11	29	20	29	25	29	27	27	30	33	9	36	33	40	43	38	22	
Number of expected results	4	3	5	6	4	7	8	6	4	6	9	5	14	12	17	7	9	13	13	9	14	10	18	14	**0.80**
Average number of expected results per practice change	1.0	1.0	1.5	1.3	1.2	1.4	1.6	1.1	1.1	1.4	1.4	1.2	2.0	1.5	1.4	1.4	1.6	1.4	1.7	1. 4	2.3	1.7	1.7	2,6	**0.65**
Average number of changes per expected result	1.5	1.7	1.2	1.3	1.2	1.1	1. 1	1. 5	1.8	1.3	1.1	1.0	1.1	1.2	1.4	1.6	1.4	1.2	1.7	1.2	1.1	1.3	1.7	1.6	**0.08**

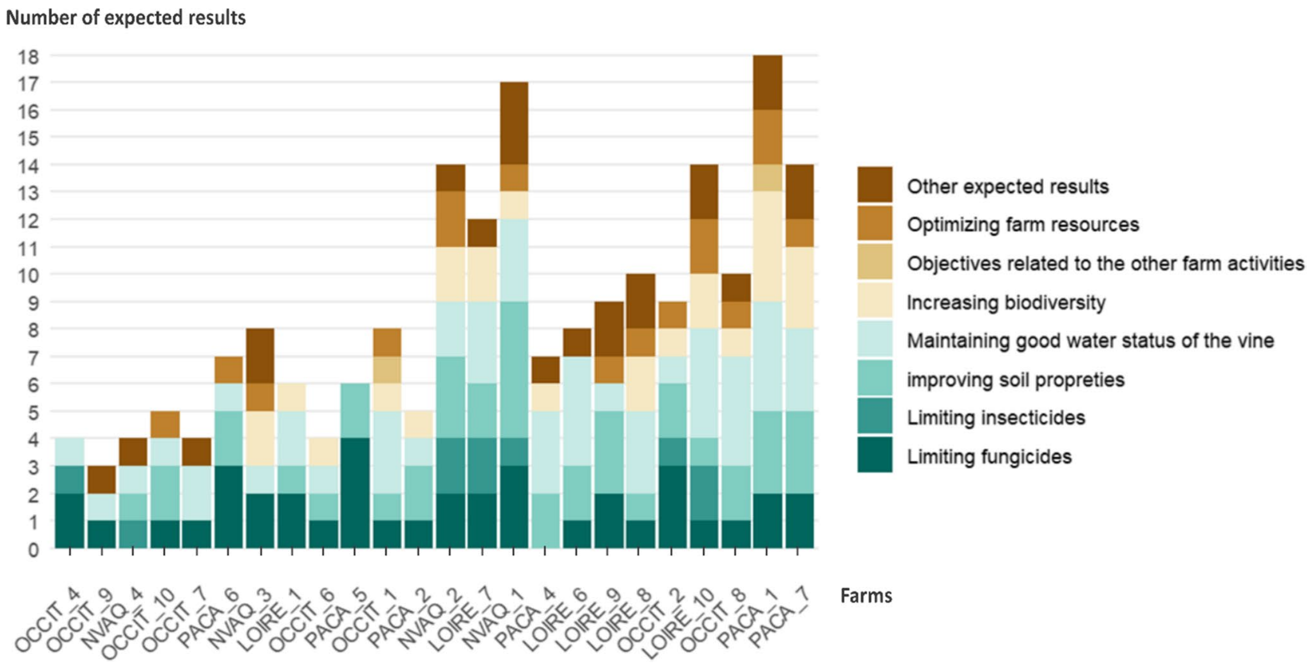

Fig. 4 Number of expected results grouped into different major categories. Farms are ordered according to their overall agroecology score, from the lowest on the left to the highest on the right

and other objectives that do not fit into these categories. Low-AE farms tend to have fewer categories of expected results. They focus mainly on limiting chemical inputs (fungicides and insecticides) and managing water resources for the vines. These objectives are common across many farms, regardless of their agroecology level. In contrast, enhancing soil properties and increasing biodiversity emerge as central themes in high-AE farms. Moreover, for the high-AE farms, the number of expected results per category appears to be higher. The average number of practice changes per expected result (Table 3) ranges from 1 (PACA_2; rk = 13) to 1.80 (OCCIT_6; rk = 16), and there is no significant correlation with the agroecological scores (coeff r = 0.08). The average number of expected results per practice change varies from 1 (OCCIT_4; rk = 24 and OCCIT_9; rk = 23) to 2.6 (PACA_7; rk = 1), and tends to be higher in high-AE farms ($r^2 = 0.65$).

3.3 Some criteria identified when changing practices on high-scoring AE farms

Farmers with high-AE farms tend to adjust other practices following a change, either to facilitate the implementation of a new practice or to achieve the expected results. For example, PACA_7 stopped trimming the tops of their vines in the summer to reduce the incidence of black rot. To make this possible, they decided to discontinue the copper treatment usually applied in July, as it would have been impractical without trimming—the tractor would not have been able to pass. However, stopping the trimming led to increased humidity, so they implemented early shoot thinning and removed lateral shoots earlier in the season. NVAQ_2 began braiding the vines and had to adapt the sprayers to treat the upper canopy by adding small elastic bands to pull down the branches. This also required additional manual trimming after harvest to cut the connections and lower the shoots enough so they could be pulled and shredded. Some of these adjustments are also observed in certain low-AE farms. For instance, OCCIT_10 adapted its black rot management practices after reducing fungicide use on resistant grape varieties by removing pruning wood from the plot or shredding it between the rows, removing affected grape clusters for the following season, and temporarily increasing the number of treatments. There are examples where these kinds of adjustments were necessary for the successful implementation of the practice but were not made, leading to failure and abandonment, even though the practice had the potential to meet the initial objectives. This was the case, for example, with NVAQ_1, which tested sowing cover crops under vine rows. The farmer observed that the grass grew too tall because the cover crop was sown on mounds of soil created by existing soil management practices, increasing the risk of frost. The farmer noted that adjustments, such as modifying soil management or elevating the vines, were necessary, but since no specific changes were made, the practice was ultimately abandoned.

Additionally, a different set of satisfaction criteria is observed among the high-AE farms. Several examples show that farmers in high-AE farms have a better tolerance for elements that might be considered undesirable by most winegrowers. For example, PACA_7 observed more quackgrass (Elymus repens) under the vines, but this was not a problem for them and they see some advantages: “Quackgrass is the big enemy of winegrowers. But for me, it’s not a problem—far from it. In fact, quackgrass grows under the drip irrigation pipes and takes its share of the water as it flows. But since it has trailing roots, I actually see it as helping water penetrate the soil more quickly.” OCCIT_8 observed wild boars in the vineyard and, although they do eat some of the grapes, they also consume snails and scratch the soil, thereby enhancing organic matter decomposition. The farmer also said “I consider disease as a symptom. This year, I still had powdery mildew despite some treatments. That means the vine is still physiologically struggling. It also means the soil hasn’t fully recovered yet. I connect diseases to the condition of the plant, the soil and the climate.” PACA_4 plans to use grubbed-up vines in their plots for intra-plot diversification as a way to turn unsatisfactory results into opportunities. No such original criteria was indicated by low-AE farmers.

A paradigm shift from short-term to long-term vision was also observed across farms. High-AE farms implement practices whose effects may take time to be measurable, and those farmers accept not seeing immediate results while continuing the new practice. For example, OCCIT_2 stated that it will take seven years to improve soil quality after permanent grass cover had been implemented. LOIRE_10 noticed that the vine’s response to herbal tea application was better six years after the first spraying. PACA_1 anticipated a yield reduction over seven years when they began growing cover crops and performing restorative pruning to promote vine longevity. PACA_7 has uprooted rows of vines to plant trees, with the goal of creating an agroforestry system, and plans to sow cereals after the vines are removed: “We plant with transformation in mind.” Yield objectives, as well as actual yields, are generally lower for these farms compared to low-AE farms.

Finally, several farmers of high-AE farms mentioned spending significant time observing the behavior or status of the vines (e.g., PACA_7, PACA_1, OCCIT_8). They also track bioindicator plants to assess the impact of their practices and the evolution of biodiversity in their plots, as in the case of PACA_7: “The bioindicator plants in my vineyard are still something I keep an eye on. I don’t count them. […] I spend a lot of time in my vineyard, I can still see what’s happening. It also gives an indication of the work that needs to be done (or not), whether the vineyard is healthy or if I need to be cautious.” These observations allow farmers to remain responsive to changes. OCCIT_8 said about the implementation of cover crops: “It’s an empirical approach. It works or it doesn’t. Does the vine do better? Are there insects? The year I sowed sainfoin, there were bees everywhere; it’s a very nectar-rich plant. As a result, there were bee-eaters everywhere, eating the bees. So we see that biodiversity evolves based on what we do.” PACA_1 conducts extensive observations of the bioclimatic behavior of plots to assess the impact of practice changes, particularly agroforestry practices.

3.4 Changes in practices more closely related to the farm scale in high-AE farms

3.4.1 Farm-scale adjustments and management of vineyard areas

Changes in the size of vineyard areas across farms vary according to their agroecology level (Table 4). In low-AE farms, vineyard areas were generally stable or expanding acreage. For most farms, this expansion resulted from a new partner joining the farm (e.g., OCCIT_10 and PACA_6). Farms with intermediate agroecology scores had relatively stable or declining vineyard acreage. In the high-AE farms, these dynamics varied more, with a primary trend of decreasing acreage in recent years. The reduction in vineyard areas can be attributed to several factors. Some vineyard owners opted to sell plots that are too far from the main farm (e.g., LOIRE_6, OCCIT_2) or difficult to manage, particularly those planted on slopes or complex soils (e.g., OCCIT_1, PACA_2), to simplify their work organization. Constraints related to labor management, such as workforce shortages, also partly explained this decrease (e.g., PACA_4, LOIRE_8). PACA_4 said about 6 ha: “I stopped farming these vines because they are bush vines. Machine harvesting is not possible, and I don’t have the money for manual harvesting. Plus there are too many missing vines, gravity-fed irrigation. It’s too much work.” Reducing vineyard areas may be a strategic lever to lower production costs (e.g., OCCIT_1) or to enable the implementation of more time-consuming practices with positive effects on the remaining plots, such as PACA_1 who has increased the time they spend in the vineyard by 10%, mainly due to restorative pruning. In some high-AE farms, the reduction in vineyard areas was associated with a diversification of farm activities, freeing up time for other tasks (e.g., PACA_1, OCCIT_2, PACA_7). Meanwhile, some high-AE farms expanded their vineyard areas (e.g., LOIRE_10 and OCCIT_8), but these farms are recent and their acreage is small (4 ha and 6 ha, respectively), so this increase reflected an establishment phase.

3.4.2 Self-production of inputs and do-it-yourself equipment

High-AE farms tend to self-produce some inputs more frequently compared to low-AE farms. The surveyed

Table 4 Different points highlighting the farm-level reflection of the various farms surveyed. The farms are ordered according to their agroecological score, from the lowest on the left to the highest on the right. The - symbol indicates that the respondent did not mention the variable. *nc* indicates farms that are not concerned, as they produce only wine or grapes. The vineyard dynamic symbols are as follows: = stable; ↗: expanding; ↘: declining.

Variables/FarmID	OCCIT_4	OCCIT_9	NVAQ_4	OCCIT_10	OCCIT_7	PACA_6	NVAQ_3	LOIRE_1	OCCIT_6	PACA_5	OCCIT_1	PACA_2	NVAQ_2	LOIRE_7	NVAQ_1	PACA_4	LOIRE_6	LOIRE_9	LOIRE_8	OCCIT_2	LOIRE_10	OCCIT_8	PACA_1	PACA_7
Dynamic of vineyard areas over time	=	=	=	↗	=	↗	=	=	=	=	↘	↘	=	=	=	↘	↘	↗	↘	↘	↗	↗	↘	↘
Mention of an adaptation of at least one agricultural tool	-	-	-	-	-	-	-	-	-	-	-	-	**Yes**	-	-	-	-	**Yes**	-	**Yes**	-	**Yes**	-	-
Self-production of inputs (manure, shredding, herbal teas or seeds)	-	-	-	**Yes**	-	-	**Yes**	-	**Yes**	-	-	-	**Yes**	**Yes**	-	-	**Yes**	**Yes**	**Yes**	-	**Yes**	**Yes**	**Yes**	**Yes**
Link between different farm activities for agronomic purposes or commercialization	*nc*	-	*nc*	-	-	-	*nc*	*nc*	*nc*	-	**Yes**	**Yes**	**Yes**	**Yes**	*nc*	*nc*	*nc*	-	**Yes**	**Yes**	-	**Yes**	**Yes**	**Yes**

farms self-produce several types of inputs. Some farms took advantage of their large crop or grassland activities to grow cover crop seeds, which were then sown in the vine inter-rows (e.g., OCCIT_10, OCCIT_9 and OCCIT_6): "It's pretty profitable since we've got available land. We plow and sow using the vineyard equipment, and we harvest with the equipment of an employee who has a small business. Since we have enough land, we do crop rotations. Our yields may not be great, but they're enough" (OCCIT_6). Certain high-AE farms harvested local plant species to make herbal teas (low-risk natural preparations) used to treat the vines (e.g., PACA_1, LOIRE_7, LOIRE_8 and LOIRE_10), sometimes incorporating a wide variety of species. In addition to harvesting, some farms began cultivating such species (e.g., NVAQ_3 and NVAQ_20). NVAQ_20 invested in building an herbal tea processing facility to streamline input preparation. Harvesting plants was time-consuming, as noted by LOIRE_10, and required careful monitoring of production processes (e.g., LOIRE_8). While some winegrowers mentioned that these practices help reduce costs because buying these products is expensive, NVAQ_20, which sprays herbal teas on 80 ha, mentioned that their economic profitability was limited but the preparations are more effective for vine treatment than purchased products. Manure production was another form of self-produced inputs (e.g., NVAQ_20, LOIRE_7 and PACA_7). These farms acquired cattle to maintain grasslands, produced manure, and, in the case of LOIRE_7, help conserve an endangered breed. PACA_7 used manure from its poultry activity, which gets enriched with straw from the cereals grown on the farm, and they are working on an experimental project to recycle the giblets and increase the amount of manure. Other farms made use of crop residues or waste. LOIRE_6 used hay produced on the farm to mulch the vine rows and retain soil moisture, and OCCIT_8 collected shredded material, composting it for several years before spreading it in the vineyards.

DIY equipment was a strategy adopted by three high-AE farms to improve work quality and reduce costs. For example, NVAQ_2 is designing new tools to perform with horses what is currently done with tractors, such as tools for establishing cover crops and creating mulch. LOIRE_9 adapted a seeder to sow wheat in the vine inter-rows. OCCIT_2 designed an independent-element roller crimper to manage cover crops on uneven ground, as well as a mobile waterproof chicken coop to protect the chickens from predators at night and a DIY harvester designed for rows when the farm previously grew wheat in inter-rows. OCCIT_8 modified a manure spreader to fit its row width, explaining that "agricultural tools are expensive, so it's better to repurpose and adapt."

3.4.3 Agronomic and commercial complementarities between crop productions

Some low-AE farms are also involved in other activities beyond winegrowing, including field crops, olive trees, truffle oaks, and medicinal and aromatic plants. However, no significant connections between these farming activities were identified in the interviews, other than the consideration of crop complementarity in terms of timing to avoid overlapping labor peaks. Higher complementarity between activities is observed on high-AE farms. While some farms already had livestock before grazing their vineyards (e.g., OCCIT_1), others bought animals specifically to benefit the vines through grazing (e.g., LOIRE_7, LOIRE_8, OCCIT_2) without the intention of selling animal products. Grapevines can also support other crops. For example, PACA_1 uses a pergola trellising system to shade vegetables, while PACA_7 has implemented a project to set up poultry runs under pergola vines to avoid bird attacks. Having a variety of crops and other farm products, including fresh vegetables, fruits, meat, and eggs, enables these farms to sell their products directly on the farm or during events, increasing their attractiveness to consumers (e.g., PACA_2, OCCIT_2, PACA_1, and PACA_7). Some high-AE farms emphasized the importance of maximizing the value of cultivated areas (e.g., OCCIT_2, OCCIT_1, PACA_4, and PACA_1). To simplify operations, the new production activity can be managed by another farmer as part of a territorial strategy (e.g., OCCIT_2 and PACA_1). With regard to diversifying their farm with vegetable production, PACA_1 said, "I work the farm alone, so I wanted to have multiple active contributors and help people who want to settle down here (but who may not have the opportunity due to land constraints), with the desire of layering different crops."

3.5 Discussion

In this paper, we studied the reasoning underlying the changes in practices on vineyard farms during their agroecological transition. For the first time, we created a table to assess the level of agroecological transition of vineyard farms. Based on their agroecology level, we showed that high-AE farms adopt a more systemic and farm-scale approach to innovation than low-AE farms. This analysis provides new insights into the characterization of farms and their transition dynamics to foster agroecological principles. These findings complement other approaches proposed to evaluate transitions in viticulture, such as studying transition scenarios at the cropping-system scale (Aouadi et al. 2021) or through quantitative assessments of production systems (Gil et al. 2022).

3.5.1 Methodological progress in agroecology characterization and systemic analysis in farms

This study provides a new tool for characterizing agroecology at the farm level by developing a table specifically tailored to viticulture. Additionally, based on the farmers' agronomic rationales, we propose, for the first time, quantitative indicators to analyze the systemic reasoning underlying farming practice change at the farm scale. The combination of these two methodologies represents an original approach to studying the agroecological transition on vineyard farms.

Numerous policies and initiatives promote the agroecological transition in agriculture, in both France and Europe (MAAF 2012; European Commission 2020). A crucial first step involves clearly defining agroecology and assessing where farms stand in this transition, and research to achieve this aim is needed (Prost et al. 2023). The characterization method we developed provides objective information on the level of agroecological integration within farms by establishing clear and straightforward criteria based on actions implemented on farms, addressing the needs identified by Dumont et al. (2021).

We developed a new framework specifically tailored to characterize agroecology on vineyard farms, as none of the existing frameworks were completely suitable for several reasons. First, existing tools for assessing agroecology are primarily designed at the territory, food system, or policy level, as highlighted by Geck et al. (2023) in their synthesis of agroecological assessment methods. Second, existing farm-level characterization methods are broad and designed for general applicability across diverse global contexts, which makes them unsuitable for the specific needs of viticulture. These tools include the FAO's Tool for Agroecological Performance Evaluation (TAPE) (Mottet et al. 2020), the Farm Level Agroecology Criteria Tool (F-ACT) (Biovision 2021), the Guide for the Evaluation of Agroecology (GTAE) (Levard et al. 2019), and OASIS tool (Peeters et al. 2021), all of which are based on the FAO's 10 Elements of Agroecology (Barrios et al. 2020) and the HLPE's 13 principles of agroecology (HLPE 2019). Some principles in these tools are not necessarily applicable to viticulture, such as "culture and traditions" (except for some specific sites with a significant cultural heritage that were not included in our sample) and "responsible governance" principles, and the modalities of the various indicators lack the precision necessary to address our research question. This has also been noted by Namirembe et al. (2022), who emphasized that existing indicators and scales lack universal relevance, and stated that TAPE cannot be used as an off-the-shelf tool. Given these limitations and to better suit viticulture, we adapted the FAO framework, a globally validated structure, by relying on the IDEA4 assessment method (Zahm et al. 2023). Based on this method, we established specific indicators and modalities for our table. While the IDEA4 method primarily evaluates farm impacts using quantitative data (which was not our objective), it provides well-defined criteria and scoring systems tailored to different farming systems, including viticulture. By adapting these tools, we were able to identify key indicators for our table and incorporate relevant quantitative modalities, based on farmers' descriptions of practices.

Our table of agroecology at the farm level considers agronomic, economic, and social dimensions, while other studies on agroecological transition have primarily focused on agronomic aspects. Some research has described the diversity of implemented practices (Ameur et al. 2020; Akakpo et al. 2021), while others have examined specific aspects of agroecology, such as input use (Dupré et al. 2017). Our results, which highlight the contribution of social elements to the overall agroecology score in the surveyed farms, confirm the interest of studying agroecology holistically, as emphasized by Wezel et al. (2020). However, socioeconomic dimensions were not central to our approach. Consequently, these dimensions were represented by fewer indicators compared to the environmental and agronomic dimensions (five, two, and thirteen indicators, respectively).

Furthermore, one of the elements of our table, economic resilience, was challenging to assess: studies have shown that subjective farm resilience depends on numerous factors (Perrin et al. 2020), that it can also be evaluated objectively using various indicators (Dardonville et al. 2022), and that it can also depend on several external factors beyond farm activities (Key 2020) that we did not study in this work. Given these challenges, we selected simple indicators for assessing economic resilience from both an objective and a subjective point of view: yield stability and farmers' perceptions of their farm's viability. These indicators approach economic resilience in a holistic way, are easily measurable through farmer interviews, and allow for comparative analysis between farms. Economic resilience also depends on environmental resilience (Tittonell 2020) and therefore overlaps with agroecological principles, such as diversity, synergy, and recycling.

Certain regional factors influence progress with regard to specific agroecological elements. These differences include the number of authorized grape varieties within protected designations (FranceAgriMer 2019), dominant marketing channels through cooperatives or merchants (Alonso Ugaglia et al. 2019), and climate conditions that influence weed management practices and disease control (AGRESTE 2019; Fouillet et al. 2022). All of these can influence agroecology scores in our table. However, we did not observe significant regional differences in agroecological scores. This is likely due to the selection criteria of our farm sample, which was not designed to be regionally representative. Notably, we found examples that diverged from dominant regional models: low pesticide use was observed in Bordeaux (e.g., NVAQ_3), cover cropping was practiced in areas where it is less common (e.g., PACA_1), direct sales outlets existed in cooperative-dominated regions (e.g., PACA_7), and grape varieties were cultivated in areas with stricter protected designation rules (e.g., LOIRE_9). This demonstrates that agroecological transitions are possible in every region and supports the idea that indicator modalities should not be tailored to specific regional contexts, which means our table has the potential for use in a range of viticulture contexts.

Agronomic rationale refers to the systemic connections that farmers establish between specific practices, the conditions under which they act, and the expected outcomes (Quinio et al. 2022). While this concept has primarily been used to analyze individual practices or sets of practices (Salembier et al. 2016; Verret et al. 2020), we extended it to the farm level. Whereas action logic has typically been described qualitatively through narratives (Quinio et al. 2022), we developed quantitative indicators to capture the systemic reasoning behind practice changes. These indicators allowed us to conduct a comparative analysis of the surveyed farms, and to establish correlations between the level of systemic reasoning and the overall agroecology score within each farm. As they are not specific to viticulture, indicators designed to analyze systemic reasoning could be applied in other studies.

3.5.2 Key conditions enabling farms to advance in their agroecological transition

In our work, we showed that synergy within the farm is a key element for farms to advance in their agroecological transition. High-AE farms scored high on the synergy indicator, showing that they integrate more animals, associated crops and landscape elements with viticulture production, which is consistent with findings from previous studies using the FAO framework (Lucantoni et al. 2023; Savels et al. 2024). The diversity element does not correlate with the level of agroecology. This can be explained by the fact that diversity indicators focus on productive diversity at the farm scale, similar to the FAO's diversity element, which is designed to capture farmers' actions. It does not account for wild biodiversity on the farm, essential for ecosystem functioning, and does not contradict the established role of biodiversity in agroecology (Nicholls and Altieri, 2018; Wezel et al. 2020). This reinforces that, within our methodological scope, what matters most is how diversification is introduced to foster synergies within the farm. Our findings, therefore, suggest that the level of agroecology in farms is not solely determined by the addition of "agroecological practices" (Nicholls et al. 2016). Instead, practices must be reasoned in a systemic way. Some farms that implement numerous innovative practices (e.g., NVAQ_20, NVAQ_1, LOIRE_7) have a medium agroecological score (approximately 10/20), while others, such as PACA_7 and OCCIT_8, with fewer innovations, achieve higher scores (14/20 and 15/20). We showed that in high-AE farms, each main category of expected results is pursued through multiple expected sub-results, with each expected result achieved through a greater number of practices, demonstrating a high level of synergy. For instance, pesticide reduction is approached from multiple angles, with farms implementing practices that simultaneously aim to improve spray quality, utilize low-toxicity products, enhance the vine's natural defenses, and create unfavorable conditions for disease establishment. Finally, we identified synergies between different production areas. These synergies are either agronomic or commercial, as the diversification of production enables farms to communicate more effectively and to sell on-site or in local commercialization networks, for example, complementing the findings of Björklund et al. (2009), which showed that farmers who interacted with consumers were encouraged to diversify their production.

Adaptability is another key characteristic of high-AE farms. Tittonell (2020) mentioned that a transition towards agroecology increases adaptability. We observed a significant number of practice changes in agroecological farms, reflecting their ability to adapt to new challenges and issues. These modified or newly implemented practices involve redesign, necessitating adjustments across the entire system at the plot level and of production factors at the farm level. At plot scale, this adaptability is reflected in continuous adjustments after an initial testing phase, which aligns with the findings of Catalogna et al. (2022). On a broader scale, we observed that agroecological farms adjust their vineyard production areas to adapt production factors, mainly to achieve greater flexibility in labor and financial resources, and sometimes to implement labor-intensive, environmentally friendly practices. A similar trend was observed on some farms during their conversion to organic farming (Merot et al. 2020). Moreover, high-AE farms tend to be smaller than low-AE ones ($r^2 = -0.7$ between AE score and vineyard size), a result that corroborates the findings of Pépin et al. (2021) on vegetable farms. One possible explanation is that having fewer employees allows for greater flexibility, as most of the work relies on the farm manager as mentioned by several farms. These findings all showed a release in production resources during the agroecological transition leading to the emergence of a new system, a more agroecological one, as described in the theory of reorganization associated with the adaptive cycle (Holling and Gunderson, 2002).

Local and direct marketing are also important factors in supporting agroecological transitions. We observed that lower plot-level yields, frequently observed in the high-AE farms of our sample, combined with reduced cultivated areas are sometimes offset by higher selling prices. This is the case for PACA_1, where, after reducing yields and vineyard area, the focus shifted to improving wine quality and raising selling prices, while also increasing consumer awareness about agroecology through expanded on-farm activities, a process that also takes time. At the same time, the winegrower is making changes in their marketing strategy: the share of wine sold for export is being reduced to reorient sales toward restaurants in France and directly to consumers. By limiting the number of intermediaries in the sales process and establishing a direct link with consumers, winegrowers can maximize their revenue from wine sales, as shown by Mora (2006). As our data show, there is a correlation between the overall level of agroecology and the use of short supply chains for commercialization, which promotes local sales and strengthens consumer relationships. In France, 60% of organic wines are sold locally, compared to approximately 24% of conventionally produced wines (AGRESTE 2020). None of the farms identified as high-AE are part of a wine cooperative system. Indeed, the profitability of farms that sell their products through cooperatives is generally based on maximizing yields within the constraints of protected designation regulations, without control over selling prices. Farms like PACA_5 and PACA_6 have faced difficulties because the cooperative they belong to had reduced the volumes accepted due to the wine crisis, significantly impacting their revenues, and PACA_6 forgoes certain practices such as organic amendments to cut costs. In contrast, we showed that some high-AE farms reduce their vineyard areas and yields to produce “better” on less land. In some cases, yield losses are anticipated during the transition to practices known to temporarily lower yields, such as shifting from soil tillage to ground cover, until yields stabilize and increase again (Merot and Smits 2020). Our analysis did not reveal a difference in perceived viability between high and low agroecological farmers, contrary to Mouratiadou et al. (2024), who showed that agroecological levers are more often associated with positive economic outcomes.

3.5.3 Resources (knowledge, tools) to support farmers in their agroecological transition

Our findings emphasize the importance of understanding the systemic reasoning behind changes to better support transitions. Unlike conventional approaches that address each problem as a technical substitution (Rosset and Altieri 1997), practices based on ecological processes generate effects that are partly unknown and highly context-dependent (Meynard 2017). Therefore, agroecology requires diversifying knowledge sources more than technical ones (Doré et al. 2011) and raises questions about how knowledge is acquired and shared. More specifically, this uncertainty in action (Duru et al. 2015b) creates tension between valuing localized knowledge and the demand for more generalizable insights (Girard and Magda 2020). Understanding the dynamics at play in transitioning farms is essential for effectively supporting agroecological changes (Prost et al. 2023). While a systemic approach is widely promoted, it remains challenging to operationalize it, leaving farmers (and their advisers) without a clear methodological framework for integrating it into their practices. Understanding the farmers’ action logics behind agroecological-oriented changes allowed us to identify key traits of systemic application on farms that can be inspire others.

In this work, we developed a tool and produced knowledge that can be used by advisers to support winegrowers as they move forward in their agroecological transition. A vineyard’s agroecological transition can be viewed as a step-by-step design process (Meynard et al. 2023), often supported by advisers or network facilitators who play a key role in transitions (Moojen et al. 2024). The step-by-step design involves successive cycles, each consisting of four steps: diagnosis, exploration, implementation and assessment. In the diagnosis phase, the table we developed can serve as a simple and effective tool to assess the farm’s position within the agroecological transition and monitor the progress. It also helps when considering innovations that can simultaneously contribute to multiple agroecological elements. Our results indicate that it is crucial for farmers to clearly articulate their objectives for practice changes before the exploration step. Advisers can assist in this task by helping clarify systemic connections between the innovation and the other farming practices to ensure coherence in the farming system, and anticipate the need to modify other practices. We demonstrated that agronomic innovations are strongly interconnected to organizational, commercial and social innovations in the context of agroecological transitions, particularly in highly agroecological farms. This highlights the need for advisers to encourage farmers to consider the broader benefits of agroecological practices beyond agronomic advantages and to enhance coupled innovations (Meynard et al. 2017). In line with González-Chang et al. (2020), advisers can also support farmers in navigating the necessary conceptual steps to understand and adopt agroecological practices, by helping them anticipate how they plan to evaluate their practices, specifically, which criteria they will use to determine success and how they intend to assess it.

Our results show that high-AE farms are closely connected to their local peers, as reflected in the results of our agroecological characterization of strong participation of farmers in networks, and implementation of some innovation at this scale (e.g., grazing with a shepherd, sharing manure with another farm). As demonstrated by Lucantoni et al. (2023) and Mouratiadou et al. (2024), these networks foster collaboration and facilitate frequent exchanges of knowledge and materials. Farmer exchange groups and collective dynamics play a crucial role in learning and developing innovative systems (Kroma 2006). Collective organizations enable farmers to share their on-farm design experiences and provide resources to support farmer-led innovation in equipment development. One example of this, as shown by Salembier et al. (2020), is the Atelier Paysan R&D organization, which helps farmers develop farm equipment tailored to their needs while remaining adaptable to other contexts. Groups of farmers who voluntarily come together to work on a specific theme and test innovative practices are able to accelerate action-oriented knowledge creation (Navarrete et al. 2018). Finally, the benefits of emerging forms of cooperation in agriculture, such as collective interest cooperative associations (known as sociétés coopératives d'intérêt collectif in France) that bring together diverse stakeholders through economically and socially beneficial projects, are starting to be studied (INRAE 2022). Territorial embeddedness also involves leveraging local resources. Some innovations are easier to implement at the territorial level, including service exchanges between complementary farms (Martin et al. 2016), such as grazing livestock in vineyards (Ryschawy et al. 2021).

4 Conclusion

This study aimed to develop a practical tool to characterize agroecological levels at the farm scale and to examine how systemic and farm-scale reasoning supports progress in agroecological transition. It highlights and characterizes the diversity of agroecological transition levels among vineyard farms and emphasizes the key factors that distinguish the most advanced farms from others. Our results suggest that highly agroecological farms prioritize systemic changes, fostering synergies, adaptability, and circular and solidarity-based economies. These farms adopt an iterative approach to innovation, combining careful observation, continuous adaptation of the system, and long-term strategic reflection. They prioritize autonomy and flexibility; system reorganization appears to be crucial for achieving a deeper integration of agroecological elements.

Beyond offering a characterization tool for assessing agroecological progress, this work provides valuable insights into the reasoning behind changes in practices, which could help winegrowers and advisers in their transition efforts. The systemic approach required for the agroecological transition challenges traditional advisory methods, highlighting the need for future research to analyze and propose ways to widely disseminate these practices and reasoning principles.

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Data availability The datasets analyzed during the present study are available from the respective authors on reasonable request.

Declarations

Ethics approval The authors declare that they have complied with ethical standards.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The authors affirm that human research participants provided informed consent for publication of the images in Fig. 1.

Conflict of interest The authors declare no competing interests.

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