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A social–ecological approach to analyse systemic changes toward agroecological practices in vineyards under geographical indications: A case study of ground cover management in the Anjou-Saumur wine area (France)

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ABSTRACT

Agroecology offers solutions to viticulture challenges, including climate adaptation, reducing phytosanitary product use, and preserving biodiversity and soil quality. In France, where most viticultural production is under geographical indications, strict product specifications regulate practices. Although agricultural policies continue to encourage changes in practices, the question arises as to how to encourage these changes in the context of winegrowing under protected designations of origin. This study contributes to research on viticultural agroecology with a new analytical approach to studying viticultural practices at the farm level by adapting the social–ecological system framework (SES). We conceptualise the viticultural agroecosystem as an agroecological resource system where viticultural practices are considered as interactions between winegrowers and their agroecosystems. Using a mixed-method approach, we analysed data from 34 semi-structured interviews with winegrowers in the Anjou-Saumur region of France. Our findings are twofold. First, by classifying winegrowers based on ground cover management, we reveal diverse transition pathways toward zero-herbicide viticulture, linked to environmental certifications such as Organic Agriculture, High Environmental Value, or Terra Vitis. Second, we highlight that many winegrowers consider several agroecological issues when choosing their practices. This approach provides a nuanced understanding of agro-viticultural practices, incorporating both productive and non-productive zones across small territories. Our results also allow for a better understanding of the agroecological transition by identifying the differences in individual reasoning within a collective associated with protected designations of origin.

KEYWORDS: agroecology, protected designations of origin, viticulture, product specification, socio-ecological systems

INTRODUCTION

Since the beginning of the 21st century, agroecological systems have often been suggested as possible alternatives to the dominant agri-food system (Altieri, 1995). The challenge today is to encourage a transition toward more transformative models (Duru *et al.*, 2015), which implies processes of transformation at the institutional and political level (Anderson *et al.*, 2019), but first and foremost at the producers' level. Given viticulture's extensive pesticide use (Garcia-Ruiz *et al.*, 2023), it is a key sector for addressing one of the most important modern agricultural issues: reducing the use of phytosanitary products (Jacquet *et al.*, 2022; OIV, 2024). The use of phytosanitary products has diminished in French vineyards in the past 10 years (Agreste, 2021), but still requires attention. Although fungicides account for nearly 80 % of phytosanitary products applied in viticulture (Agreste, 2021), insecticide and herbicide use remain a major obstacle for the reduction of pesticides (Gentil-Sergent *et al.*, 2022) as well as for the preservation of biodiversity and soil quality (Mailly *et al.*, 2017). Considering that other global issues, such as climate change, have also started to impact viticultural practices (Neethling *et al.*, 2019), a shift toward more agroecological practices has become paramount in both the academic literature (Aouadi *et al.*, 2021; Macary *et al.*, 2020) and European policy.

In this regard, it appears that ground cover management, *i.e.*, all practices for managing soil plant cover in vine fields—including spontaneous herbs (Fernando *et al.*, 2024), sometimes referred to as weeds—and sown cover crops (Abad *et al.*, 2021a), is a key aspect of viticultural practices for addressing herbicide use as well as other major agroecological stakes. Ground covers in vine fields are known to influence vine vigour, soil structure, and wine quality and therefore influence many aspects of winemaking (Abad *et al.*, 2021a; Cataldo *et al.*, 2020). Ground covers also contribute to the preservation of biodiversity and may impact the spread of cryptogamic diseases (Abad *et al.*, 2021b). Ground cover management practices include herbicide use and several other practices, such as tillage (Dobrei *et al.*, 2015), which also need to be reduced in an agroecological transition (Gentil-Sergent *et al.*, 2022). On the other hand, ground covers may compete with vines for soil resources, and particularly water, leading to a reduction in vegetative development and yield (Delpuech & Metay, 2018). Ground cover management is, therefore, a subject of compromise for winegrowers, between the agroecological issues they face and their need to maintain yields.

Another subject of compromise for winegrowers concerns production under geographical indications (GI). In Europe, 82.4 % of wine production takes place under a GI, whether a protected geographical indication (PGI) or protected designation of origin (PDO) (Šajn, 2023). In France, this figure has risen to 95 % (INAO, 2021), which means that French winegrowing practices are largely controlled by geographical indication regulations (Mazé, 2023). The institutions related to GI in France have already attempted to encourage changes in viticultural practices (Lempereur & Herbin, 2023; Ruggieri *et al.*, 2023). In particular, in response to successive public policies favouring a change in agricultural practices, such as the EGalim law of 2018, the National Institute of Origin and Quality, which is in charge of supervising protected designations of origin and protected geographical indications in France, recommended several ways to change the product specifications to integrate environmental measures (Ruggieri *et al.*, 2023). One such solution is to integrate pre-approved agroecological measures directly into product specifications through a simplified process. However, certain questions remain: How can we encourage these changes in winegrowers' practices? How can we study these changes and their role in the agroecological transition in viticulture under geographical indications?

The existing academic literature has mainly focused on the general sustainability of winegrowing, including economic aspects (Mariani & Vastola, 2015), or on certain agroecological practices, such as cover crops (Abad *et al.*, 2021a; Abad *et al.*, 2021b), soil management (Cataldo *et al.*, 2020; Dobrei *et al.*, 2015), new grape varieties (Montaigne *et al.*, 2016) or viti-pastoralism (Conrad *et al.*, 2022). Some studies have analysed practice changes in the winegrowing sector but mainly focused on the socio-economic factors of change (Perrin *et al.*, 2022; Thiollet-Scholtus *et al.*, 2020). Few studies have taken a more systemic approach to agroecological analysis of viticultural practices (Macary *et al.*, 2020). Studies in agroecology consider how winegrowers approach their practices at the scale of the entire farm (Prost *et al.*, 2023), considering their entire agroecosystem instead of focusing on choices at the plot level. Furthermore, few scientific studies have considered practice changes in the regulatory context of PDO (Fuente *et al.*, 2019), although these wines account for more than half of the European and French wine production (INAO, 2021; Šajn, 2023). This study aimed to fill these gaps by analysing the changes in ground cover management practices at the farm-level and in the context of a regulatory evolution toward zero pesticide use, whether organic or not (Jacquet *et al.*, 2022; Ruggieri *et al.*, 2023).

Our analytical contribution is twofold. First, we developed an original analytical framework to study changes in winegrowers' practices by adapting the social–ecological system (SES) framework of E. Ostrom (Ostrom, 2009). Other studies that have studied farm-level viticultural practices adopted a technical management route approach and the life cycle assessment method, thus studying the environmental impact of all practices (Beauchet *et al.*, 2019; Renaud-Gentié *et al.*, 2014). As these approaches were at the plot scale, they considered all practices linked to grape production, whereas the social–ecological system framework allows us to include both productive and non-productive areas. Second, we used this analytical framework to study the nature of changes in viticultural practices at the level of protected designation of origin winegrowers through the example of ground cover management practices. In vine fields, ground cover is found in inter-rows and headlands and under the rows of vines (Figure 1), making it a valuable area of focus for the study of viticultural practices.

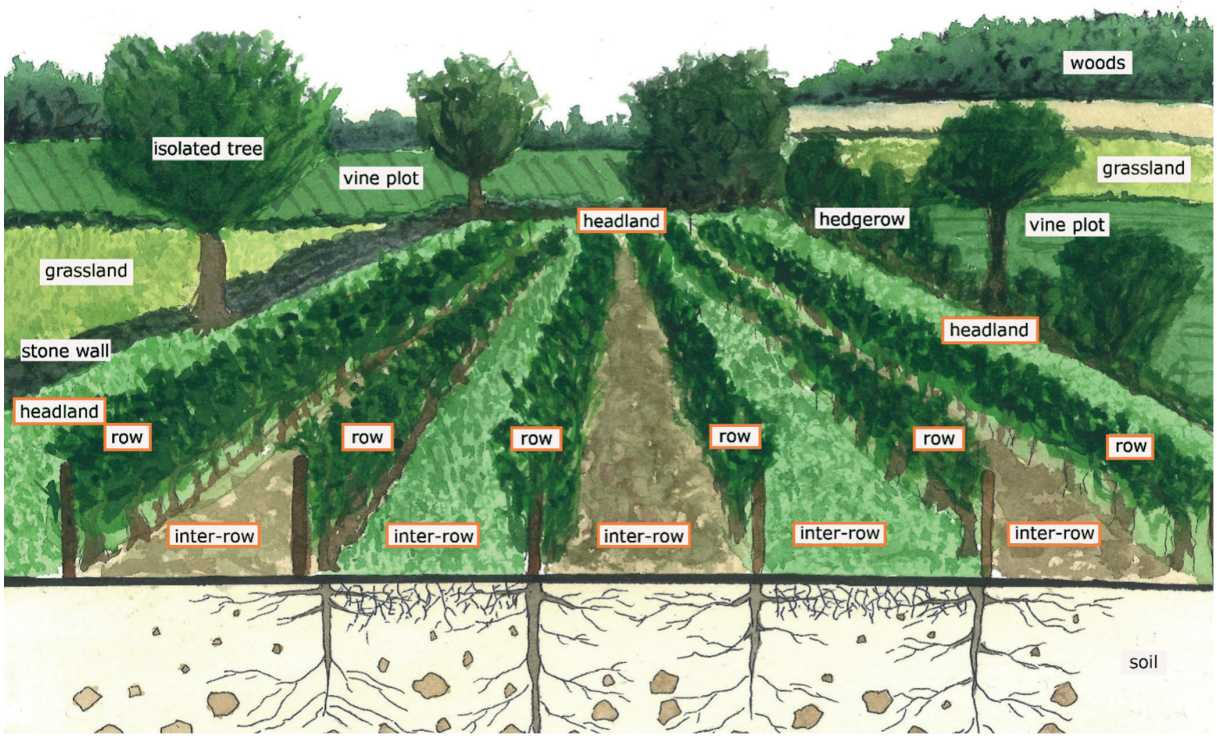

FIGURE 1. Representation of the viticultural agroecosystem, inserted in its landscape, including the different elements composing it when a focus is done on ground cover practices.

In orange are the elements specific to the vine field that can be codified in PDO specifications. Author: F. Ruggieri.

This article is organised as follows. First, we explain the analytical framework used to analyse the practices and changes toward agroecological practices. We then present the context of the area, the study sites that were chosen for the study, and the data collection and analyses. In our results, we show how winegrowers are engaged in different transition pathways toward zero-herbicide viticulture. Then, we analyse the correlation between changes in practices and environmental certifications (*i.e.*, Organic Agriculture, High Environmental Value, or Terra Vitis) and discuss the role of these certifications in changing practices. Finally, we analyse how the winegrowers perceive the agroecological issues they must face and what they consider when choosing their practices.

MATERIALS AND METHODS

1. Analytical framework

The concept of the agroecosystem is often used in agronomy, particularly in agroecology research (Altieri, 1999), as it was designed to integrate the socio-economic factors that can influence the ecological processes of the agroecosystem (Conway, 1987). However, some may argue that the definition of agroecosystems does not sufficiently consider human agency (Preston *et al.*, 2015), when the purpose of the concept of socio-ecological systems is to consider ecological processes and human factors at the same level (Binder *et al.*, 2013). To consider all the elements of a viticultural system, we propose to enhance the concept of the agroecosystem with that of social–ecological systems. Specifically, we propose to use the subsystems of E. Ostrom's social–ecological system framework (Ostrom, 2009) to define the viticultural agroecosystem as a resource system, as described in McGinnis and Ostrom (2014), and viticultural practices as interactions between the resource system and the actors (*i.e.*, the winegrowers). The social–ecological approach has already been used to study systems of practices (Vanwindekens *et al.*, 2012), and the social–ecological system framework, in particular, has already been used in agricultural studies (Duru *et al.*, 2015). Its advantage is that it attributes the same level of importance to the ecological and socio-technical processes involved in grape production (Binder *et al.*, 2013). Therefore, it allows us to analyse the ecological processes allowing the implementation of transformative agroecological practices, but also the role of the perceptions that influence the choice of practices of the people who manage these agroecosystems: the winegrowers.

We propose a definition of a viticultural agroecological resource system at the scale of the "field–margin complex", which includes the field or plot and its boundary landscape, such as hedgerows or perennial non-cropped land strips (Rizzo *et al.*, 2013; Boller *et al.*, 2004). This scale enables

us to focus on viticultural practices that are adapted to local biophysical characteristics (particularly soil and subsoil characteristics) while also considering the non-productive elements of the viticultural landscape. As previously observed among annual crops (Aubry *et al.*, 1998), a group of nearby plots sharing landscape boundaries (or "sets of fields", Aubry *et al.*, 1998) are subject to the same pool of knowledge adapted to the pedoclimatic context in which they are located. Winegrowers often favour this scale when determining their practices (Thenail & Baudry, 2004), so it may therefore help us understand the trade-offs that winegrowers make when doing so (Rizzo *et al.*, 2013). Figure 1 represents the different components of the viticultural field–margin complex, including soil, the rows of vines, inter-rows, and the surrounding ecological infrastructures: headlands, hedgerows, isolated trees and stone walls.

The next step of the conceptual work was to define viticultural practices—the interactions between winegrowers, the actors of the social–ecological system, and their agroecological resource system (Ostrom, 2009; McGinnis & Ostrom, 2014)—considering the challenges facing viticulture. We defined these challenges based on previous studies (Macary *et al.*, 2020) and the work of professional viticultural institutions (INAO & IFV, Lempereur *et al.*, 2017; IFV, 2018; Lempereur & Herbin, 2023), grouping them into four categories:

- Preservation and development of biodiversity
- Preservation of soil quality and structure
- Reduction of phytosanitary product use and preservation of water quality
- Adaptation to climatic variability (the inter-annual changes of climatic events, such as late gel, drought and heavy rains, accentuated by climate change).

Instead of defining the practices *a priori* according to a productive aim, we chose to start from the elements of the agroecological resource system to understand the sets of practices winegrowers could use to address the above viticultural challenges. For example, by acting on ground cover management practices, the winegrower can interact with the inter-rows of vineyard plots to reduce herbicides, manage the vine's access to water resources, improve soil structure, or even develop biodiversity, thus acting on all the agroecological issues mentioned above.

In the context of protected designations of origin, winegrowers' practices are codified in the product specifications ("cahiers des charges") defined by the EU and French regulations (EU regulation n° 1151/2012 of the European Parliament, 2022; article 4). The plot structure in particular is highly regulated, including the spacing between the vines and the rows of vines and even the height of the Vertical Shoot Positioned (VSP) system. The specifications also regulate yields, which impact certain pruning and disbudding practices. An agroecological transformation of viticultural practices under protected designation of origin regulations must therefore consider both the general viticultural issues to be addressed and the codification of practices in the specifications. To simultaneously study these two constraints, we chose to study ground cover management practices in the headlands, inter-rows, and rows of vines. Though these practices are all regulated by the area's product specifications, the regulations leave plenty of opportunities for change. In addition, inter-row ground cover management practices are often mixed with tillage practices, which enables us to consider all the agroecological issues previously defined (Figure 2).

2. Case study

2.1. The Anjou-Saumur wine area

The Anjou-Saumur wine area, part of the larger Loire Valley wine area in France, is situated in the Maine-et-Loire department in the Pays de la Loire administrative region. It encompasses over 2,000 wine estates, 19 protected designations of origin, and one protected geographical indication (Interloire, 2021). The climate in the Anjou-Saumur area is generally temperate, with an oceanic influence in the west and a more continental influence in the east. The soils and subsoil mainly consist of slate shale, sandstone, and carboniferous shale, as well as volcanic rocks, all from the armorican Massif. Vines have been present in the territory for over 2,000 years, and the evolution of the vineyards has shaped today's landscapes. Some protected designations of origin of the Anjou-Saumur region (*e.g.*, "Anjou") have been in place since the first French designation of origin system was created in 1935. Wines produced in the Anjou-Saumur area are of all colours and include dry, sweet, and sparkling wines. The main grape varieties are Cabernet franc for the red wines and Chenin B for the white wines.

The vineyard landscape is an important part of the Anjou's terroir, and its preservation is closely linked to that of biodiversity, in particular through the establishment of hedges and reimplantation of grass in vine fields. Furthermore, a dozen different collectives (either "30,000 groups" or "Groups of Environmental and Economic Interest") have been created in the area since 2015, following national agricultural policies, such as the second Ecophyto Plan in 2016 and the Law for the Future of Agriculture of 2014.

Winegrowers of the area also participate in environmental certification. There are many environmental certifications in France, particularly in viticulture, where four certifications are quite common. Organic Agriculture is a recognised European certification that is quite widespread in agriculture in general and viticulture in particular, representing 22 % of French vineyard areas in 2022 (Interloire, 2023). This certification provides strong added value for practices that eliminate phytosanitary products. In the Anjou-Saumur area, 25 % of the vineyard area and 32 % of wine estates were organic in 2023 (Interloire, 2023). In viticulture, the Organic Agriculture certification is sometimes complemented with Demeter biodynamic certification, although certified organic farming is a prerequisite for this certification. Only 8 % of organic wine estates in the Loire Valley are Demeter certified (Interloire, 2023). The High Environmental Value certification, a French national certification, was created following the

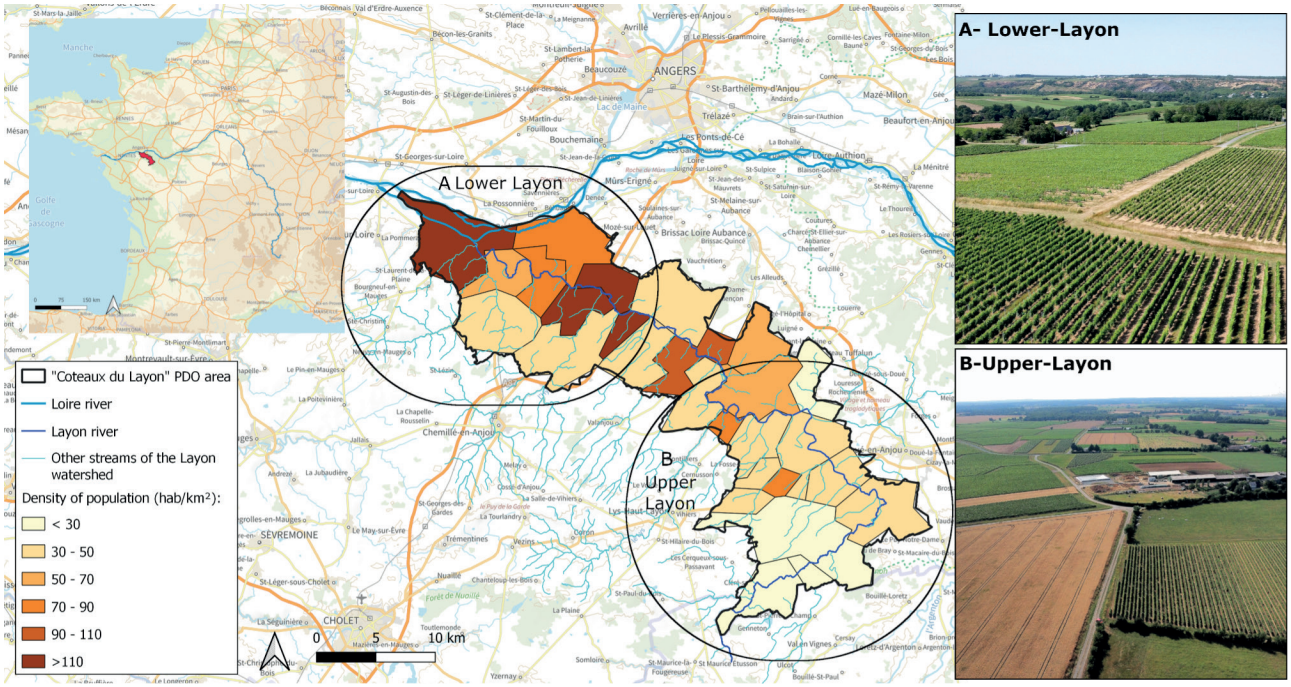

FIGURE 2. Situation map of the study area.

The area is based on the geographical area of the "Coteaux du Layon" protected designation of origin, and pictures of the study sites: (a) the lower Layon and (b) the upper Layon. (Map realisation and photos by F. Ruggieri, source of data: https://www.data.gouv.fr/) PDO, protected designation of origin.

"Grenelle de l'Environnement" in 2008 (law nº 2009-967). This certification has three levels, and only the third level allows farms to use the High Environmental Value label. A great number of viticultural estates have obtained this certification in recent years: in 2022, it was granted to 23 % of French wine estates and approximately 48 % of wine estates in the Anjou-Saumur area (Interloire, 2023). A new version of the High Environmental Value certification (the fourth since 2008) was published after we conducted this study; thus, only the third version applies to the data in this study. Finally, the Terra Vitis certification, created in 1998, is a private certification based on the pillars of sustainable development. As the data for this certification are not public, we do not have detailed information on how many farmers hold this certification in the study area.

Furthermore, in this area, changes in winegrowers' practices are encouraged by an agroecological transition at the institutional level (Ruggieri *et al.*, 2023). Thanks to a nested organisational system, collective agroecological transition strategies are implemented at several geographical scales (Ruggieri *et al.*, 2023). One such strategy that was adopted in 2016 by the Anjou-Saumur wine Federation and encouraged by the National Institute of Origin and Quality was to integrate a new measure in all of the area's product specifications that mandates inter-row plant cover. In the absence of this plant cover, farmers must mechanically control the cover or use biocontrol herbicides. Synthetic herbicides are no longer authorised. In addition to this measure, headland plant cover is also mandatory in all specifications of the area. As the rainfall is higher in the Loire Valley than in the vineyards of the south of France, the winegrowers of this region are accustomed to managing grass in the vine fields, and weed management has been a component of winegrowing practices for a long time.

2.2. Study sites

This study focused on the Layon watershed area. The Layon river is known to be polluted by pesticides (La Jeunesse *et al.*, 2015), which puts additional pressure on winegrowers in the area to reduce pesticide use. To delineate a study area, we used the geographical delimitation of the "Coteaux du Layon" protected designation of origin as a basis (Figure 3), although there are approximately 10 protected designations of origin superimposed on this area.

The Layon area covers a fairly large territory encompassing different types of landscapes and geoclimatic conditions. To capture the diversity of conditions within this appellation area, we selected two study sites: one in lower Layon (downstream; Figure 3a), near the Loire river and the city of Angers, and the other in upper Layon (upstream; Figure 3b), further south, closer to the source of the Layon river.

3. Data collection and analysis

3.1. Sampling and data collection

For sampling, all the wine estates that declared to have produced at least one protected designation of origin wine in 2021 were selected in two municipalities of the lower Layon (n = 51) and three municipalities of the upper Layon (n = 31). The initial sample included 82 wine estates. All winegrowers were contacted, but only those who answered and were available participated in the survey. Thirty-four

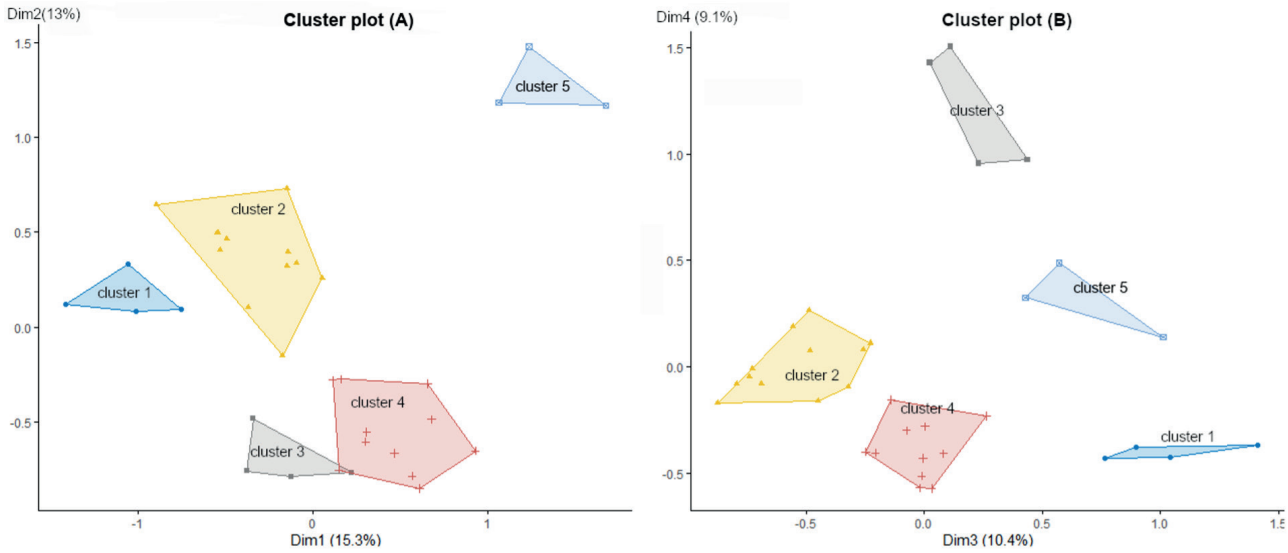

FIGURE 3. Cluster plots of the hierarchical ascendant classification on axes 1 and 2 on the left and axes 3 and 4 on the right.

semi-directed interviews (44 % of the initial sample) were conducted between January and March 2022 (23 in lower Layon and 11 in upper Layon). This sample was not designed to be exhaustive but rather to explore the various modalities of ground cover management practices within the context of changing product specifications. Given this objective, a qualitative analysis was appropriate, and the number of interviews was considered sufficient to reflect the diversity of practices and decision-making motivations, as it encompassed a broad range of winegrower profiles (Table 1).

We obtained free, prior, and informed consent with a written and signed form at the beginning of every semi-directed interview. We interviewed the vineyard manager whenever possible, or another vineyard employee when the manager was not available. The interviews included an initial series of questions designed to characterize, following the SES framework (Ostrom, 2009), the system of actors (socio-economic indicators of the wine estate and the interviewee), a second series of questions to characterize the resource system (cultivated and non-cultivated areas, biophysical characteristics of the plots, environment around the plots, grape varieties, geographical indication wines produced), and a final series of questions to obtain an overview of the vine management practices and techniques.

3.2. Database building and data analysis

To examine changes in cover management practices in response to regulatory shifts aimed at reducing or even eliminating herbicides and other pesticides, we adopted a two-step analytical approach. First, we analysed the cover management practices of the sampled winegrowers to develop a theoretical typology that outlines a potential trajectory of practice changes toward agroecology. Second, we examined how winegrowers perceive their practices, aiming to better understand how these perceptions might influence transition pathways.

3.2.1. Analysis of ground cover management practices and their socio-economic determinants

To analyse winegrowers' ground cover management practices and develop a typology representing theoretical transition pathways, we followed a multi-step process.

Step 1: Defining variables and statistical analysis.

We developed variables to describe the different ground cover management practices within the vine field. These were pre-constructed based on the previously described conceptual framework (see Figure 2), validated using interview data, and aggregated into 12 variables representing ground cover management practices (Table 2).

We conducted a statistical analysis to classify winegrowers according to their cover management practices. First, a multiple correspondence analysis (MCA) was performed to explore relationships between sub-variables and reduce dimensionality, enabling clear data visualisation. Then, a hierarchical clustering analysis was carried out using Ward's minimum variance method (Ward, 1963) on the first five MCA components. This approach grouped winegrowers based on their cover management practices. The analysis utilised the FactoMineR (Lê *et al.*, 2008) and Factoextra (Kassambura & Mundt, 2020) packages in R version 4.3.0 (R Core Team, 2023).

Step 2: Cluster interpretation and typology refinement.

The resulting groups were described and compared to identify the key characteristics defining each cluster. Given the diversity of practices within the sample, the final typology focused on practices that were predominant within each group.

Step 3: Socio-economic analysis.

To complement the typology, we examined the influence of socio-economic factors on cover management practices and their evolution. This involved crossing the clusters with

TABLE 1. Socio-economic description of the wine estates and winegrowers who participated in the survey.

Variable	Sample (*n* = 34)
Median area	31 hectares (min 10 ha, max 452 ha)
Average age of the interviewee	45.6 years
Type of farm	Wine estates, 79 % Combining wine and crop/animal breeding 21 %
Estates certified Organic Agriculture	Totally certified, 35.3 % Partially certified, 6 %
Estates certified High Environmental Value	53 %
Other environmental certifications	Biodynamic (Demeter), 6 % Terra Vitis, 12 %
Mean number of grape varieties	6.4
Majority grape variety on the estate	Chenin, 45 % Cabernet Franc, 31.6 %
Mean number of PDOs	7 protected designations of origin
Main protected designations of origin	Cabernet d'Anjou (rosé), 25.1 % Coteaux du Layon (sweet white), 12.5 % Anjou blanc (dry white), 8.7 % Anjou rouge 8.7 % (red) Crémant de Loire 9.1 % (sparkling)
Sales outlets	Trading companies, 27 % Wine merchants, restaurants, and individuals (France), 52 % Wine cooperative, 6 % Export, 15 %

TABLE 2. Details of the variables and modalities used to describe ground cover management practices.

	Variables	Details and modalities
Cover management of the inter-row	inter_cov	Number of covered inter-rows: *1 out of 2, less than 1 out of 2, or all rows.*
	inter_type_maj	Main type of cover implemented on the plots of the estate: *sown for competition with vines, sown for soil fertility, or spontaneous.*
	inter_manag_cov	Type of plant cover management: *no plant cover, shredding or mowing, light passage, viti-pastoralism, or no details given.*
	inter_pass	Number of passages to manage the inter-row plant cover: *rare or 0, 1–3, 3–5, over 5, or not applicable.*
	inter_sow_pract	Details of sowing practices for those who sow their covers or who mainly have a spontaneous cover but use some sowing practices: *no sowing practices, sowing decided by the plot, sowing tests, or homogeneous sowing on all plots.*
Cover management under the row	row_type_manag	Type of weeding under the row: *glyphosate, glyphosate + pre-emergents, mechanical work.*
	row_pass	Number of passages to weed under the row: *1 to 2, 3 to 5, or 5 to 6.*
Headland cover management	headland_type_cov	Type of cover implemented on headlands: *sown or spontaneous.*
	headland_pass	Number of passages to manage the cover of headlands: *1 to 2, 3 to 5, or 5 to 6.*
Tillage	inter_detail_till	Details of inter-row tillage: *no details, chemical weeding, light tillage, heavy tillage, or no tillage.*
	inter_alter	Frequency of alternating tilled rows: *no alternation, rare or every 10 years, every 3 to 5 years, every 1 to 2 years, not applicable.*
	row_detail_till	Details of under-row tillage: *no tillage, heavy tillage, light tillage, partial tillage, test on some plots, tillage but no details given.*

21 additional variables describing farm-level and interviewee characteristics. Chi-square tests were conducted to determine whether ground cover management practices were influenced by socio-economic factors. This analysis was performed using R's base package in version 4.3.0.

3.2.2. Analysis of the winegrowers' perceptions

To analyse the winegrowers' perception of their practices and how these perceptions affect the transformativity of their individual agroecological transition, we conducted a qualitative analysis of the interviewees' answers about their reasoning and choices in their plant cover management practices. Their responses to the question "what is the objective of this plant cover?" for the inter-row and headlands were coded using thematic analysis according to the previously defined agroecological objectives. The codes were created gradually and grouped into five categories, one for each of the four agroecological goals and one "other reasons" category. The analysis was conducted using NVivo software (version 14.23.2).

RESULTS AND DISCUSSION

Our results are twofold. In the first section, we show how, overall, winegrowers were engaged in several changes in viticultural practices. We also show how they were classified into five clusters, leading to the creation of five types of ground cover management practices, and that these types are correlated with environmental certifications (*i.e.*, Organic Agriculture, High Environmental Value, or private Terra Vitis certification). In the second section, we show that the winegrowers generally have a clear vision of the agroecological issues they must face and that many of them consider several issues when choosing their practices.

1. Classification of winegrowers' diverse practices resulted in five distinct groups

1.1. Statistical analysis

The statistical analysis of winegrowers' cover management practices resulted in the classification of winegrowers into five clusters. The multiple correspondence analysis was first performed on the 12 variables used to describe the ground cover management practices (see Table 2). The first five axes of this analysis explained 54.18 % of the total inertia. The variables that contributed the most to the first two axes were the number of covered inter-rows, the type of cover on the inter-rows, the type of under-row weed management, the number of passages under the row, and the type of cover on the headlands. The variables that contributed the most to the third, fourth, and fifth axes were the type of cover in the inter-rows and headlands, the number of passages in the inter-row, the alternation between covered and uncovered inter-rows, the type of soil work done in the uncovered inter-rows, and the number of tillage passages in the inter-rows.

The hierarchical ascendant classification performed on the first five axes of the multiple correspondence analysis resulted in five clusters, with two large clusters that include two-thirds of the surveyed winegrowers (Figure 3). A full description of the clusters can be found in the supplementary data (S1).

1.2. Cluster interpretation and typology refinement

Although the interviewed winegrowers could be statistically grouped into five clusters according to their farm-level ground cover management practices, a certain heterogeneity remained within each cluster. This variability is due to many winegrowers describing secondary practices, either by testing a new practice on a small area or gradually transitioning to new practices over a significant part of their estate. This was particularly the case for the reduction of under-row herbicide use. Many winegrowers who mainly used herbicides under the rows declared that they had started to either test new mechanical weeding equipment or integrate this new practice in recently planted plots. Likewise, some winegrowers who mainly kept spontaneous plant cover in the inter-rows stated that they had either tested sown cover crops on certain plots when they found it could help the vines or sown covers for entire recently planted plots to boost the vines in their first years.

Therefore, to refine the classification derived from the statistical clusters (Figure 4), we defined practice types focusing on the main practices within each cluster. Each type was then named accordingly, and detailed descriptions are provided in Table 3.

1.3. Analysis of socio-economic determinants of ground cover practices

To analyse ground cover management practices, we conducted Chi-squared tests between the types and the other variables constructed from the interviews (Table 4). Location did not affect the types (p-value of the Chi-squared test between the location and the clusters = 0.35), but yield did show a certain effect (p-value = 0.048). The conventional type had higher yields than the herbicide-free type. Moreover, there was a slight correlation with the number of protected designations of origin per estate (p-value = 0.061): the conventional type had a higher number of protected designations of origin than the herbicide-free cluster.

More importantly, we found that the types were correlated with the environmental certifications of the farms (p-value = 0.005), *i.e.*, Organic Agriculture on the whole farm or part of the farm (N.B.: only two winegrowers were Demeter certified, and we counted them as organic farmers), governmental High Environmental Value certification, and private Terra Vitis certification. The herbicide-free and conventional types—the two larger groups—were mainly composed of organic winegrowers (n = 9; including the two biodynamic farms) and High Environmental Value–certified winegrowers (n = 10), respectively. The sowing type was composed of two High Environmental Value farms, one Terra Vitis and one that had an organic certification on part of the farm. The soil-working type was composed of two organic farms, one Terra Vitis–certified farm, and one farm about to obtain High Environmental Value certification. The tillage-

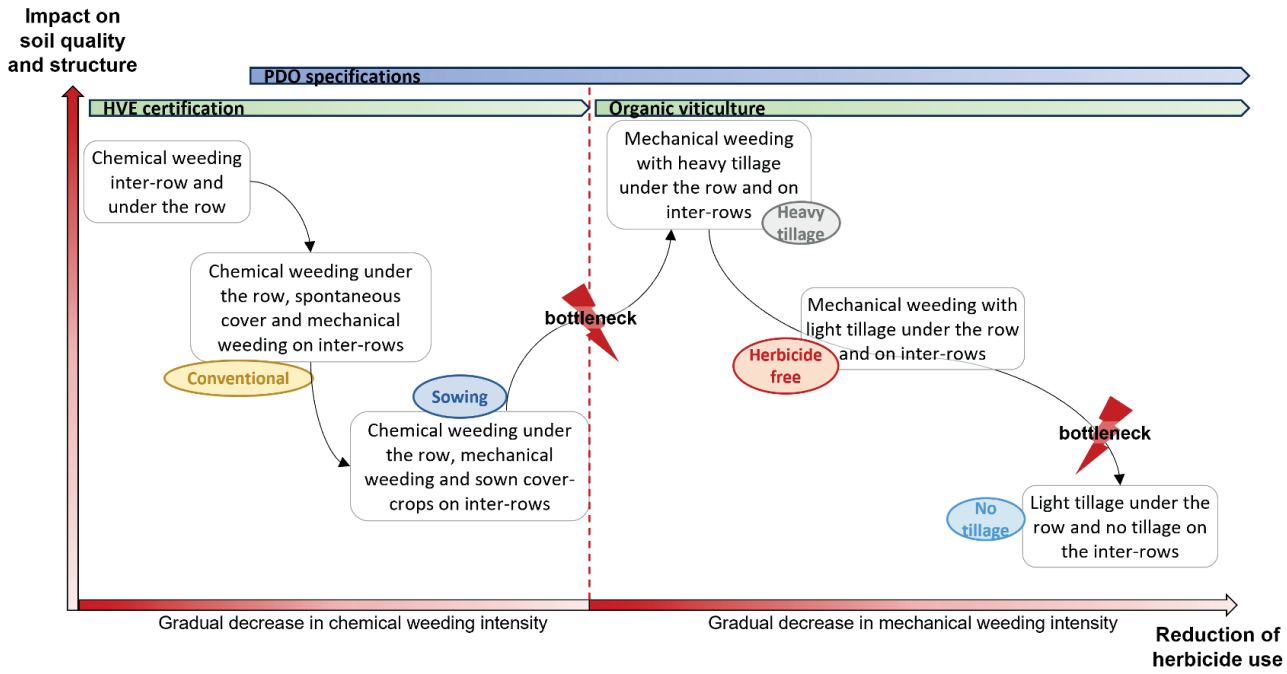

FIGURE 4. Theoretical transition pathway towards a total ban of herbicides while considering the impact of ground cover management practices on soil quality and structure, and the possible certifications that can accompany practice changes.

TABLE 3. Description of types after typology refinement.

Statistical cluster	Type name	Description of main practices
Cluster 1	Sowing type	Winegrowers sow all their plant covers, even in the headlands (they are the only ones to do so). They favour covers with legumes, but also choose species that will not compete with vines too much. Their use of herbicides has decreased since they started their transition towards more sustainable viticultural practices.
Cluster 2	Conventional type	Winegrowers have conventional practices, with spontaneous plant covers or controlled sown covers without legumes, a rare alternation of grassed rows and worked rows. Cover management is done by crushing or mowing in the inter-row, and herbicides under the row.
Cluster 3	Heavy tillage type	Winegrowers are transitioning toward mechanical weeding under the rows; they substituted herbicides with particularly intense practices of tillage and hoeing.
Cluster 4	Herbicide-free type	Winegrowers have stopped herbicide use and practice mechanical weeding on the inter-row and under the row. Their tillage practices are less intensive than cluster 3.
Cluster 5	No-tillage type	Winegrowers chose to strongly reduce or even stop tillage in the inter-row and only practice mowing for ground cover management.

free type was the most heterogeneous, with one organic farm, one High Environmental Value–certified farm, and one farm with no certifications.

Environmental certifications can be an effective strategy in the agroecological transition, especially thanks to the added value on the bottle price. The Organic Agriculture certification, in particular, has effectively changed practices (Merot *et al.*, 2019), especially by reducing chemical pesticide use (Merot *et al.*, 2020). Furthermore, as the Organic Agriculture certification is centred on banning synthetic inputs, it is possible to combine it with the protected designation of origin specifications, which do not regulate such practices. On the other hand, converting to organic farming is often costly because it often involves greater labour, material, and energy needs than conventional viticulture (Merot & Wery, 2017). French public authorities created the High Environmental Value (HVE) certification in 2008 in response to this issue, originally intending for it to initiate a change in practices and create added value to facilitate the conversion to organic farming. This certification got off to a slow start in its first years (Interloire, 2023), and it is still difficult to know whether it significantly changes practices. Our study shows that winegrowers with very different profiles have adopted this certification. Nearly all winegrowers in the conventional cluster held this certification; this may suggest that the High Environmental Value certification has had a minimal effect on their practices, which often included under-row herbicide use. The impact of the new version (V4) of the High Environmental Value certification requires further analysis.

TABLE 4. Results of Chi-squared tests between the cluster type and the other variables constructed at the farm level. The variables are arranged in decreasing order of significance.

Detail	*p*-value of X^2
Type of environmental certifications	0.005
Yield per hectare (on vines)	0.048
Number of produced PDOs	0.061
Number of employees	0.093
Wines without a GI produced on the farm	0.113
Type of transmission (within the family or not)	0.117
Total area of the farm	0.132
Date of arrival of the interviewee on the farm	0.138
Main grapevine variety	0.158
Experience before installation on the farm	0.183
Highest diploma obtained by interviewee	0.195
Electoral mandates (cooperatives, technical institutions…)	0.231
Type of technical advice received	0.247
Electoral mandates of the interviewee within GI institutions	0.262
Location of the farm	0.35
Type of market outlets (cooperatives, large-scale distribution, direct sales on farm)	0.42
Is the winegrower the owner of their land?	0.436
Revenue of the farm in 2019	0.488
Does the winegrower export wine	0.502
Number of vine varieties	0.534
Only a winery or other agricultural production on the farm	0.588
Proportion of vines on the farm	0.618

Although organic farming effectively reduces the use of synthetic pesticides (Merot *et al.*, 2020), certain practices that are not regulated by this certification can still harm the agroecosystem. Cryptogamic diseases are treated using copper and sulfur in organic farming; if used excessively, these compounds can substantially affect soil quality as well as soil water holding capacity (Dagostin *et al.*, 2011; Fuente *et al.*, 2021). Reducing fungicide use is another standing issue for organic viticulture (Jacquet *et al.*, 2022). Additionally, though organic viticulture has proven to increase biodiversity (Beaumelle *et al.*, 2023), some winegrowers (*e.g.*, those in the soil-working cluster) may resort to intensive practices, such as tillage, during the transition to herbicide-free viticulture to maintain yields, which can significantly affect soil quality and structure.

1.4. Transition trajectories towards agroecological ground cover management

Transition trajectories towards agroecology are often gradual processes, where practices evolve step by step as winegrowers adapt to new constraints and learn alternative methods. In our case, if we consider the total ban of herbicides in viticulture as a final goal, we can observe the different stages through which winegrowers might go while transitioning toward this objective. The first step consists of stopping herbicide use on the headlands and inter-rows (now compulsory for protected designation of origin producers in the Anjou-Saumur area) and replacing it with soil work and/or plant cover between the rows (Cataldo *et al.*, 2020) while continuing chemical weeding below the row. This was mainly the case in the conventional type. Some winegrowers, such as those in the sowing type, then opt to sow cover crops between the rows to better

manage competition for water resources, thereby limiting their weeding operations (Garcia *et al.*, 2018). The next stage involves stopping all under-row herbicide use and replacing it with mechanical weeding (Cabrera-Pérez *et al.*, 2022), though this can lead to intensive tillage practices, as seen in the soil-working type. Heavy tillage practices can successfully replace herbicide use and allow an organic certification, but can also harm soil structure and quality (Abad *et al.*, 2021a; Cabrera-Pérez *et al.*, 2022) and the biodiversity of weed communities (Kazakou *et al.*, 2016). Therefore, the end goal must not be replacing chemical weeding with tillage but rather a truly transformative practice of integrating grassland covers into the viticultural agroecosystem, as was the case for at least one winegrower in the no-tillage type. This theoretical transition pathway is represented in Figure 4.

Still, intermediary steps are necessary in this transition process, which can explain the multiplicity of transition pathways (Padel *et al.*, 2020). The difficulty lies in moving from one stage to another during the transition pathway, which requires a period of experimentation (Catalogna *et al.*, 2022) that can result in lock-in effects. In other words, certain stages require trigger effects (Sutherland *et al.*, 2012) that can allow (or not) a choice of practices considering issues related to grass and biodiversity rather than soil, for example. Overcoming these lock-in effects may require winegrowers to change their perspectives and consider their practices differently to make them evolve. Moreover, transition pathways are inherently slow, progressing gradually through successive stages (Meynard *et al.*, 2023). Lock-in effects can further delay this progression by creating barriers between stages. Recognising these barriers and developing strategies to overcome them is crucial to speeding up the transition and securing the long-term adoption of sustainable practices, often spanning several generations (Magrini *et al.*, 2019).

Overall, we found that the winegrowers opted for a trial-and-error strategy before adopting new practices, which allowed them to make gradual changes with little impact on the economic structure of their farms. Trade-offs between maintaining productivity and implementing agroecological principles may hinder the transition toward more agroecological practices (Dumont *et al.*, 2021). Though many studies have considered the factors influencing farmers' changes in practices (Garini *et al.*, 2017; Payen *et al.*, 2023), few have considered the farmers' models of representation (Vanwindekens *et al.*, 2012) and how they can influence their practices and ability to implement changes.

2. Winegrowers' perceptions of their agroecosystem can influence their practices

Table 5 shows the results of our analysis of the winegrowers' answers to the question "what is the objective of this cover?" for the inter-row and headlands. Verbatim examples can be found in the supplementary data (Table S1). The given answers account for the four previously defined agroecological goals of viticulture (*i.e.*, preservation and development of biodiversity, preservation of soil quality and structure, reduction of phytosanitary products and preservation of water quality, and adaptation to climatic variability), but to varying extents. For the inter-row, two reasons predominated: the control of competition (whether positive or negative with regard to the vine) and soil preservation, particularly for bearing tractors that must pass for other practices, such as fungal treatments. For the headlands, the reasons were somewhat better distributed; although the bearing capacity of the soil remained a big issue for all the winegrowers, the headlands played a more important role in preserving biodiversity than the inter-row. It is interesting to note that the winegrowers cited reasons other than agroecological issues as well, namely aesthetics and the need to comply with regulations.

We observed three levels of responses, according to the winegrowers' perception of agroecological issues linked to ground covers. The first level includes purely practical answers, such as improving ground bearing for tractors, aesthetics, cost savings, and the requirement to maintain plant cover according to the specifications. These answers concern just the utilitarian aspect of the cover without meaningfully considering the agroecological issues that ground cover management practices can address. This level had the most responses for both the inter-row and the headland (especially via the response "maintain ground bearing"). The second level includes responses concerning the quality or structure of the soil. This agroecological issue is most impacted by ground cover and is thus often considered when choosing ground cover management practices, especially because a herbicide ban necessarily requires tillage practices for many farms. Finally, the last level of responses included those concerning broader issues, such as the preservation of biodiversity and water resources, improving the quality of the wine, and even monitoring the soil's state using bio-indicative plants.

The winegrowers' perceptions of the agroecosystem differ in two main ways. The first difference lies in how they consider their viticultural practices and the results of those practices. One level of representation remains mainly at the agronomic level, as was the case for the impact of cover practices on the soil (Payen *et al.*, 2023). The winegrowers sometimes disconnected the practice from its agronomic aim and attributed other intentions to it (regulatory or aesthetic intentions, for example), whereas other winegrowers considered the ecosystem services provided by their practice, giving their practices a more agroecological aim (Dumont *et al.*, 2021). The second difference is that winegrowers considered their viticultural agroecosystems with different spatial scales (Toffolini *et al.*, 2015). Although some farmers perceived the resource system as the vineyard plot and limited themselves to the productive zones when choosing their practices, others considered the agroecological resource system as a whole, including the hedges and headlands, allowing for more agroecological choices at the territorial scale.

These differences in perspectives may explain why moving toward transformative practices at the resource system scale can be problematic. First, winegrowers who maintain an agronomic-level perspective of their practices will

TABLE 5. Categories of the winegrowers' motivations for using ground cover.

Element	Types of motivations	Details of motivations	Count
Inter-row	Preservation of soil quality and structure	Maintain ground bearing for passage with tractors	16
		Maintain soil quality and structure	11
		Preserve or encourage soil fertility	10
		Limit soil erosion	5
	Reduction of phytosanitary products and preservation of water quality	Control plant cover and competition with vines	20
		Diminish herbicides	4
	Preservation and development of biodiversity	Conservation of existing biodiversity	5
	Adaptation to climate variability	Preserve water resources	4
	Other reasons	Aesthetics	2
		Obligated by regulations	1
		Lower maintenance costs	1
	Question not properly asked		2
Headland	Preservation of soil quality and structure	Maintain ground bearing	22
		Limit soil erosion	10
	Other reasons	Aesthetics	7
		Lower maintenance costs	5
		Obligated by regulations	4
	Reduction of phytosanitary products and preservation of water quality	Create a buffer zone for chemicals	10
		Use bio-indicative plants	1
	Preservation and development of biodiversity	Enhance biodiversity	9
	Adaptation to climatic variability	Preserve water resources	4
		Carbon sequestration	1
	Question not properly asked		1

struggle to favour ecosystem services over yield when choosing their practices. Second, a more restricted vision of the agroecosystem that does not consider non-productive elements can lead to a bottleneck in changing practices, which only some farmers manage to overcome during their transition pathway. In our theoretical transition pathway earlier, we observed the emergence of significant bottlenecks that hindered the transition from one stage to another. These bottlenecks can arise from a variety of factors, including a lack of skilled labour and investment funds, but they can also come from cognitive barriers and difficulties in shifting perceptions. Indeed, a truly transformative change in ground cover management practices can only occur if ground covers are reimagined, with an acceptance of the potential risk of competition, which should be balanced by the overall ecological functioning of agroecosystems.

For winegrowers, transitioning from the sowing type to the heavy tillage type is often linked to material challenges and, to a lesser extent, a misconception of their ability to eliminate herbicides. However, moving from the heavy tillage to the herbicide-free type and then to the no tillage type is mainly due to a cognitive barrier tied to perceiving ground covers as competitors to the vine. In the heavy tillage type (and, to a lesser extent, the herbicide-free type), herbicides are replaced by intensive tillage to maintain strict control over ground covers, particularly under the vines. This shift requires rethinking ground covers as integral components of the agroecological resource system, where all elements are interconnected, and overall balance can be restored through less intensive practices. Such is the case with the no-tillage type, which involves ceasing tillage between rows and adopting low-intensity mechanical weeding practices under the rows.

We argue that our conceptual framework, defining practices according to agroecological challenges and not only according to a productive aim, can ease this passage through bottlenecks by providing a more global vision of the agroecosystem and practices for both researchers and winegrowers. This conceptual framework, which can be adapted to other types of agriculture, can help to change the general perspectives of agricultural practices to highlight how they can address the issues facing agriculture today. A shift in farmers' perceptions can also act as a trigger, generating more transformative practice changes (Prost *et al.*, 2023). However, this shift must be encouraged by a significant transmission of knowledge, whether through research supporting farmers and technicians (Prost *et al.*, 2023) or through the exchange of knowledge between peers (Anderson *et al.*, 2019).

CONCLUSION

The agroecological transition is the process of transforming our agri-food systems by changing agricultural practices to limit the impact of agriculture on ecosystems while maintaining a sufficient level of agricultural productivity. We chose to study ongoing changes in practices using the example of ground cover management practices in viticultural agroecosystems under protected designations of origin. Reducing pesticide use is an important issue in viticulture, and ground cover management practices can help to drastically reduce reliance on herbicides and promote overall agroecosystem health by reducing the use of fungicides and insecticides. Ground cover management practices are regulated by product specifications in France, particularly in the area of our case study, the Anjou-Saumur wine area. Our new analytical approach, based on the social–ecological systems framework, allowed us to define the viticultural agroecosystem as an agroecological resource system within which winegrowers can interact with the different elements of the system through their viticultural practices to address the issues facing viticulture. From a perspective of participatory research to accompany winegrowers in their changes of practices, this approach can help winegrowers to better integrate these non-productive areas and practices into their work and thus better address the agroecological issues facing viticulture at the landscape level. We showed that, overall, changes in practices are underway at the farm level, even if they do not all have transformative aims. These changes are particularly reflected in the co-certifications of protected designation of origin wine estates with environmental certifications (mainly Organic Agriculture and High Environmental Value certifications). Although all winegrowers were aware of the issues surrounding their viticultural practices and started to change them accordingly, they had different perceptions of what they could and must change. In fact, because of their underlying perceptions of their agroecosystems, they did not all have the same ability to change. Even though the winegrowers' perspectives were not the only reason for their changes in practices, they can nevertheless have a great influence: changing these perspectives could help to accelerate changes in practices. However, doing so will require the transmission of knowledge by giving the winegrowers access to a pool of agroecological knowledge that some cannot necessarily reach on their own.

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