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RESEARCH ARTICLE

Analysis of factors that influence adoption of agroecological practices in viticulture

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Abstract

Public policy reforms and consumer requirements for the environment have raised awareness among winegrowers of the need to review their farming practices. This renewal of production aims for high economic, environmental, and social performance, as well as product quality. Therefore, it often assumes changes in farming practices due to adoption of agroecological practices (AEP). However, adopting these changes depends not only on demonstrating positive economic and environmental impacts of AEP but also positive social impacts. This study investigated winegrowers' perceptions of AEP and analyzed the most important drivers of adoption of AEP. It was based on quantitative economic and sociological data from a survey of winegrowers in the Loire Valley (France). An original scoring method was used to identify adopters and non-adopters of AEP. Then, a logit econometric model was used to explore statistically significant relations between the adoption of AEP and internal and external farm variables. Results confirmed that winegrowers' perceptions converged with the results of the econometric analysis. AEP were adopted mainly by winegrowers sensitive to human health. Adoption also depended on the context and type of AEP: wine tourism activities on the farm, environmental training, and sales revenue were positively correlated with the adoption of AEP. However, the absence of partners, vineyard area and winemaking on the farm were negatively correlated with adoption. Thus, public and private agricultural actors should consider these influential factors to increase adoption of AEP by farmers.

Keywords Agroecological practices · Adoption factors · Viticulture · Scoring · Logit model · Winegrower · Farm

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Introduction

The agricultural context is undergoing profound economic, political, and environmental changes that challenge farmers more than ever to manage increasing complexity, adapt ecological and social production conditions, and reorganize their agricultural activities (Expósito & Velasco, 2020; Nogueira, 2019). In this context of multiple public policy incentives and of a competitive market, the renewal of production challenges towards quadruple performance (i.e., economic, environmental protection, social performance, and product quality) often assumes changes in farming practices, particularly in viticulture (Belis-Bergouignan & Cazals, 2006; Forbes et al., 2013).

These changes lead farmers to adopt technological innovations in their practices, and more generally to position themselves in relation to society's expectations about the use of production practices with lower environmental impacts (Ghali et al., 2014; Jourjon et al., 2017; Kelley et al., 2017). Farmers must thus adopt alternative approaches that respect the environment to reduce impacts of agricultural activities on natural resources, meet consumer demand, and promote sustainable development of agriculture (Annunziata et al., 2018). Therefore, it is important to understand what winegrowers think about the adoption of agroecological practices (AEP) to be able to help extension services accompany them during these changes. Research on this issue may give key information to extension agents and public-policy makers to address drivers for the adoption of AEP.

Despite the existence of certain technological changes and a variety of agroecological policy instruments, adoption rates of AEP remain low in France, as in the rest of Europe (Kuhfuss & Subervie, 2018; Lozano-Vita et al., 2018; Ridier et al., 2013). This lack of adoption of AEP may partly explain why viticulture continues to use an excessive amount of chemical products in France: although the wine sector covers less than 4% of French agricultural area, it uses 20% of all pesticides sold (by mass of active ingredient), and has one of the highest treatment frequency index (Del'homme and Ugaglia, 2011).

Besides the specific issue of practices that decrease pesticide use, the issue of adopting AEP remains important and topical. Specifically, analysis of the adoption of AEP refers to two major issues. The first refers to the complexity in determining whether a viticulture practice is "environmentally friendly" (Rouault, 2019), because its environmental impacts vary among farms and even fields, and depend on multiple farm characteristics, soil and climatic conditions, grape varieties, and even on how the winegrower performs the practice (Kuhfuss & Subervie, 2018). Therefore, AEP should be considered according to their environmental impacts. Identifying adopters or non-adopters of well-defined practices and precise specifications associated with a label is not difficult for the researcher, but it is more complicated to identify adopters of AEP because some farmers can practice a variety of "green" practices without producing under a quality label. Since one key issue in this study was how to define whether a winegrower was an adopter of AEP or not, we used life cycle assessment (LCA) (Renaud-Gentié et al., 2014; Rouault et al., 2016) to identify viticulture practices that are estimated to have particularly high environmental impacts. This method, which considers all phases of production of a product — here, grapes — can consider a wide variety of impacts, such as water pollution, emission of greenhouse gases, and the use of natural resources (Penavayre et al., 2016; Renaud-Gentié et al., 2014).

The second issue is related to the drivers and barriers that influence farmers' perceptions and adoption of AEP. The economic literature has long been interested in the issue of the adoption of AEP (see for example, Bechini et al., 2020; Kuhfuss & Subervie, 2018; Läpple & Rensburg, 2011). Indeed, AEP are implemented not only for their environmental and economic advantages but also for other socio-economic agricultural and political reasons (Garini et al., 2017; Knowler & Bradshaw, 2007; Ward et al., 2018; Willock et al., 1999).

Although adoption statistical models can contain many explanatory variables, proxies used for these variables are diverse and lead to divergent results (Knowler & Bradshaw, 2007), which makes it difficult to design decision-making plans for large-scale adoption of AEP. Indeed, Ward et al. (2018) showed that the adoption of a package of farming practices or technologies is a complex decision influenced by multiple factors. Zulfiqar and Thapa (2017) showed that intensity of adoption is varying among farmers and this variation validated that the adoption of innovation should be seen as a combination of several components. Thus, we worked to identify the main factors that influenced adoption by statistically exploring significant relations between adoption of AEP and several internal and external farm variables.

We first reviewed the literature of innovation adoption to identify the main factors that influence adoption of AEP. We then developed an original approach based on qualitative and quantitative surveys to collect data, a scoring method to identify adopters and non-adopters of AEP, and a binary logistic (i.e., logit) model to identify mechanisms for and barriers to adoption of these practices.

Literature review of factors that influence adoption of agroecological practices

The adoption of innovations holds an important place in the economic literature and in the specific fields of agricultural economics (Sunding & Zilberman, 2001) and environmental economics (Jaffe et al., 2004). Adopting innovations is often considered a long-term investment and depends first on comparing costs and benefits that this investment generates. Griliches (1957) empirically highlighted the importance of economic factors that influenced the adoption of new practices by studying the spread of hybrid maize in Iowa (USA). In 1962, the sociologist Rogers developed an innovation-diffusion model that divides the process of adopting an innovation into four phases: knowledge, position, adoption or rejection, and confirmation of the decision. The decision to adopt AEP agrees with the literature, which describes the adoption process as following a logistic trend (Abadi Ghadim & Pannell, 1999; Griliches, 1957; Rogers, 1962).

However, despite public policies to encourage and facilitate adoption of many practices to protect the environment, implementation of these practices has been slow, particularly in viticulture (Kuhfuss & Subervie, 2018; Lozano-Vita et al., 2018). Nonetheless, Porter and van der Linde (1995) emphasize that environmental innovation can lead to a double positive impact (i.e., environment and competitiveness).

Thus, studying the adoption of agroecological technologies and AEP is a difficult subject given the many unobservable drivers. The literature review of adoption revealed no universal classification of the drivers for adopting innovations in agriculture. Summarizing the studies about adoption of AEP, Table 1 demonstrates that adoption may depend on a wide variety of drivers, including farmer and farm household characteristics, attitude and beliefs, the innovation characteristics, farm structure and financial and management characteristics, and the socio-economic environment.

Some studies classify these factors as either economic (e.g., income, production, taxes, subsidies, costs-benefits of AEP) or non-economic (e.g., personal motivations and preferences, labor, awareness and sensitivity about the environment, social norms) (Lozano-Vita et al., 2018), while others distinguish objective (e.g., observable, such as technical traits, economic attributes, age, location) or subjective factors (unobservable, such as individual attitudes and preferences) (Blazy, et al., 2011; Di Bianco et al., 2019; Mignouna et al., 2011; Roussy et al., 2017); Nonetheless, empirical adoption studies rarely include such "subjective" drivers of adoption because they are difficult to construct from surveys or due to difficulty in making model predictions based on unobserved drivers (Blazy et al., 2011).

However, drivers of innovation adoption in general, and of AEP adoption in particular, depend on the local context (Knowler & Bradshaw, 2007; Ormrod, 1990). Many empirical studies on AEP adoption were performed in developing and emerging countries, and focused specifically on smallholder farms. Most studies in developing countries consider AEP to be related to water and soil conservation, best management practices (BMPs), integrated pest management (IPM), improved crop seeds, and irrigation technologies. AEP is used when a combination of practices is studied, even though practices are usually considered separately (Oyetunde-Usman et al., 2021; Pham et al., 2021; Ward et al., 2018). Recently, Benitez-Altuna et al. (2021) combined practices for vegetable production in Chile using the scoring method developed by Rigby et al. (2001). For developed countries, AEP refer mostly to soil and water conservation (SWC) practices, especially in the USA, and to organic farming in Europe (Roussy et al., 2017; Serebrennikov et al., 2020).

Factors that influence adoption of agroecological practices in developing countries

Farmer age is usually negatively associated with AEP adoption (see Asfaw and Neka (2017), Bekele and Drake, (2003) and Tiwari et al., (2008) for conservation agriculture (CA) practices; Mauceri et al., (2005) for IPM technologies), which indicates that young farmers are less sensitive to risks and adopt agroecological innovations more easily (Mauceri et al., 2005). However, it had a positive and significant effect on adoption of no-tillage CA practices (Ntshangase et al., 2018; Okoye, 1998) and on technological innovations such as resistant maize technologies (Alexander & Van

Table 1 Summary of factors identified in the literature and their influence on adoption of agroecological practices

	Adoption factor	References	Main result
Farmer and farm household characteristics	Farmer age	Alexander and Van Mellor, (2005)*; Mignouna et al., (2011)*; Okoye, (1998)*	+
		Asfaw and Neka, (2017)*; Bekele and Drake, (2003)*; Mauceri et al., (2005)*; Tiwari et al., (2008)*; Ntshangase et al., (2018)*	-
		Kuehne et al., (2017)**; Mekuriaw et al., (2018)*; Mzoughi, (2011)**; Roussy et al., (2017)**	NS
	Level of education	Asfaw and Neka, (2017)*; Henning and Cardona, (2000)**; Gillespie et al., (2004)**; Gebru et al., (2019)*; Gillespie et al., (2004)**; Kim et al., (2005)**; Mariano et al., (2012)*; Mzoughi, (2011)**; Ntshangase et al., (2018)*; Paudel et al., (2008)**;Ward et al., (2018)*	+
		Alexander and Van Mellor, (2005)*; Läpple and Van Rensburg, (2011)**; Mekuriaw et al., (2018)*; Serebrennikov et al., (2020)**	NS
	Family size	Amsalu and de Graaff, (2007)*; Gebru et al., (2019)*; Ndiritu et al., (2014)*	+
		Mariano et al., (2012)*	-
		Asfaw and Neka, (2017)*	NS
	Off-farm labor	Gedikoglu et al., (2011)**	+
		Asfaw and Neka, (2017)*; Kim et al., (2005)**; Peterson et al., (2015)**	-
		Amsalu and de Graaff, (2007)*	NS
	Gender	Asfaw and Neka, (2017)*; Bayard et al., (2006)*; Gebru et al., (2019)*; Mzoughi, (2011)**; Zelezny et al., (2000)*;	+
		Peterson et al., 2015**	-
		Bonabana-Wabbi, (2002)*; Mariano et al., (2012)*; Mekuriaw et al., (2018)*; Morris and Doss, (1999)*; Ward et al., (2018)*;	NS
	Farm size	Ghazalian et al., (2009)**; Mariano et al., (2012)*; Pham et al., (2021)*; Ward et al., (2018)*	+
		Läpple and Van Rensburg, (2011)**; Pham et al., (2021)*	-
		Asfaw and Neka, (2017)*; Pham et al., (2021)*; Serebrennikov et al., (2020)**	NS
	Distance from home to farm	Asfaw & Neka, 2017*	-
	Land ownership	Abdulai et al., (2011)*; Zeng et al., (2018)*	+
		Gebru et al., (2019)*	-
		Mekuriaw et al., (2018)*	NS

Table 1 (continued)

	Adoption factor	References	Main result
Farmer attitudes and beliefs	Environmental awareness	Mzoughi, (2011)[**]; Serebrennikov et al., (2020)[**]	+
		Serebrennikov et al., (2020)[**]	NS
	Farmers' knowledge about human health	Garini et al., (2017)[***]	+
Characteristics of agroecological practices	Cost of the practice	Pereira et al., (2017)[***]	-
	Ability to try out the practice	Chatzimichael et al., (2014)[**]; Di Bianco et al., (2019)[**]; Kuhfuss et al., (2014)[**]; Pannell et al., (2006)[**]	+
	Ease of implementation	Pannell et al., (2000)[*]	+
	Intrinsic characteristics	Kuhfuss and Subervie, (2018)[***]	-
		Asfaw and Neka, (2017)[*]	+
Farm economic characteristics	Availability of inputs and materials	Garini et al., (2017)[***]	+
		Bélis-Bergouignan and Saint-Ges, (2004)[***]	NS
	Economic features	Cavanagh et al., (2017)[*]; Kim et al., (2005)[**]; Mzoughi, (2011)[**]; Rodriguez-Entrena and Arriaza, (2013)[**]; Rolfe and Harvey, (2017)[**];	+
		Buckley et al., (2012)[**]	-
Exogenous factors	Socio-professional relationships	Cullen et al., (2008)[***]; Forbes et al., (2013)[***]; Hunecke et al., (2017)[***]; Kuhfuss and Subervie, (2018)[***]; Lanza Castillo et al., (2021)[***]; Jourjon et al., (2016)[***]	+
	Neighborhood	Beharry-Borg et al., (2013)[*]	+
		Konrad et al., (2019)[**]	NS
	Information	Asfaw and Neka, (2017)[*]; Galliera and Rutström, (2021)[***]; Hunecke et al., (2017)[*]	+
		Bélis-Bergouignan and Saint-Ges, (2004)[***]	NS
	Consumer demand	Bélis-Bergouignan and Saint-Ges, (2004)[***]	+
	Territorial dynamics	Bélis-Bergouignan et al., (2008)[***]; Kuhfuss et al., (2014)[***]; Kallas et al., (2010)[***]	+
	Financial incentive payments	Garini et al., (2017)[***]; Pannell et al., (2006)[**]; Varela-Candamio et al., (2018)[**]	+

[*]Research realized in *developing countries; ** developed countries; ***viticulture, *NS* not significant.

Mellor, 2005; Mignouna et al., 2011). Education level also has positive effect on AEP adoption in most studies performed in developing countries, but it also has a non-significant effect in one study (Alexander & Van Mellor, 2005).

Some results indicate that gender influences the decision to adopt environmentally friendly practices, suggesting that female have higher environmental ethics and are therefore more likely to adopt conservation practices (Zelezny et al., 2000). Other studies suggest that conservation and land management is a job for a "male" (Bayard et al., (2006) for CA; Gebru et al., (2019) for introduced agroforestry practices). Bonabana-Wabbi, (2002) found no significant difference between male and female farmers in adopting IPM in Uganda**.** The same lack of difference was found for adopting improved maize technologies in Ghana (Morris & Doss, 1999) and improved rice technologies in the Philippines (Mariano et al., 2012). Ward et al., (2018) found a non-significant effect of gender of the head of household on CA adoption, but the number of females in the household was significantly positive.

Other studies found insignificant correlations between the aforementioned factors and AEP adoption. Mekuriaw et al., (2018), who investigated factors that influence CA adoption, found that age, education, and gender of the head of household had no significant influence on adoption of SWC practices. Availability of labor is considered as a factor that may influence adoption (Abadi Ghadim & Pannell, 1999). The presence of additional working family members or family/household size is widely included as a proxy of labor supply in empirical studies, especially in developing countries. They were found to be significantly positive, significantly negative or non-significant.

Land ownership is considered in the literature to drive adoption decisions, especially for long-term investment innovations such as CA practices (Abdulai et al., 2011; Zeng et al., 2018). However, they were found to have a non-significant influence on adoption or maintenance of SWC practices (Mekuriaw et al., 2018) or a significantly negative influence on adoption of agroforestry practices (Gebru et al., 2019).

Pham et al., (2021) showed that the influence of farm size depends on the practice considered: it was negative for crop rotation and intercropping, non-significant for SWC practices and the use of organic fertilizers, and positive for leaving the land fallow. Ward et al., (2018) found that farmers with larger farms were more likely to adopt no-tillage and intercrop practices in Malawi, perhaps because they have more labor and are better able to support labor-intensive practices, such as no-tillage. They also have more land and are better able to risk yield losses for their main crop due to resource competition between the main crop and an intercrop. Mariano et al., (2012) found a positive but non-significant effect of farm size on the adoption of integrated crop management practices. In addition, access to credit (Mariano et al., 2012) or economic barriers such as total income (Cavanagh et al., 2017) can positively or negatively influence adoption of AEP.

The influence of many factors external to farms remains uncertain in the adoption literature, but information has been identified as a main factor, and it becomes particularly important as the complexity of new practices or technologies increases (Hunecke et al., 2017). Farmers need to be informed about new practices before adopting them. For example, Asfaw and Neka, (2017) found that access to extension services and training were significantly positively correlated with adoption of SWC practices.

Factors that influence adoption of agroecological practices in developed countries

In developed countries, farmer characteristics such as education and gender have significant effects on the adoption of some of BMPs, though the effects are smaller than those in developing countries. A review of factors that influence AEP by Roussy et al., (2017) shows that although the age of the head of household has usually non-significant effect (see also Kuehne et al., (2017)), the education level remains important and increases adoption even in developed countries, where the education level is relatively high and homogeneous. For example, Mzoughi, (2011) found that farmer's age did not influence the willingness to adopt integrated farming or organic farming, and that education level had a positive 10% significant effect on adoption of organic farming. In contrast, Läpple and Van Rensburg (2011) found no significant effect of higher education level on adoption of organic farming. More recently, education level had no influence on adopting manure treatment or CA practices (Serebrennikov et al., 2020). Mzoughi (2011) also found that adoption of integrated farming was higher for female farmers. In the same European context, Peterson et al., (2015) also found that farmer gender significantly influenced adoption rates of BMPs, but that women were less likely to adopt several practices, particularly practices that required planting (e.g., cover crops, filter strips, grassed waterways).

In the literature, farm size both positively (Ghazalian et al., 2009) and negatively (Läpple & Van Rensburg, 2011) influences adoption. A systemic review of factors that influenced adoption of sustainable farming practices in Europe reported that farm size has a small mean effect on adoption, and that the direction of effect reflects existing divergence in the literature about the effect of farm size on adoption of innovations (Serebrennikov et al., 2020). Other socio-economic factors have been found to influence decisions to adopt AEP, such as off-farm employment or income from an off-farm source (e.g., nutrient-management practices/injection manure into the soil, see Gedikoglu et al., 2011), which are associated mainly with adoption of capital-intensive practices rather than labor-intensive practices (Kim et al., 2005; Peterson et al., 2015).

Economic features such as income and the proportion of income that comes from the activity concerned by the innovation also influence adoption of BMPs (Kim et al., 2005; Mzoughi, 2011). Only Buckley et al., (2012) found that farmers with higher gross margin were less willing to adopt water conservation, while Rodriguez-Entrena and Arriaza, (2013) found that farmers of more profitable farms were more likely to adopt soil conservation. Rolfe and Harvey, (2017) identified economic factors, especially farm financial health, as a key motivation for adopting AEP in sugarcane production. They also showed that it can be simple to adopt an inexpensive practice that can generate long-term profit. Incentive payments (e.g., through economic policy instruments) can positively (Varela-Candamio et al., 2018) or negatively influence adoption of AEP (Cullen et al., 2008). Pannell et al., (2006) state that governments have to promote innovations that are not only good for the environment, but also economically better than the practices they are to replace. If not, the adoption rate could be disappointing and the cost-environmental benefit ratio too small to justify such a change in practices.

Di Bianco et al., (2019) and Kuhfuss et al., (2014) noted that a practice's "triability" (i.e., ability to try a practice out before adopting it) and observability allows farmers to have economic and technical evidence that it functions, and thus positively influences its adoption rate. Farmers can acquire new information and learn by implementing the adoption process itself, or by communicating with other farmers, researchers, and extension agents (Chatzimichael et al., 2014). Pannell et al., (2006) argued that uncertainty surrounding new technology is often high in early adoption stages, which encourages farmers to rely upon their communication networks.

Furthermore, farmer attitudes and beliefs, specifically environmental awareness, have been clearly shown to determine the adoption of organic farming in France (Mzoughi, 2011) and in the European Union (Serebrennikov et al., 2020). However, no consistent evidence was found of their influence on both manure treatments or CA (Serebrennikov et al., 2020). In the EU, Serebrennikov et al., (2020) conclude that environmental attitude and education exert much more influence on farmers' adoption probabilities than age or farm size.

Based on this review, factors that influence adoption of AEP differ somewhat between developing and developed countries, but there is no clear evidence of which factors influence adoption, since they also differ among countries and within countries. This may be due to characteristics of a given innovation and the timing of its adoption in the diffusion process. This is why Padel, (2001) recommends, when comparing results of studies, considering the degree of adoption of an innovation (in her case, organic farming) among countries and when the studies were published. According to Läpple and Van Rensburg, (2011), characteristics of early-, medium-, and late-adopter groups differ significantly: the factors that influence adoption influence adopters differently, particularly farming intensity, age, information gathering, and farmer attitude.

Factors that influence adoption of agroecological practices in viticulture

For viticulture, despite the large amount of literature on factors that influence adoption of AEP, few studies address viticulture practices. Interviewing winegrowers in Trento (Italy), Garini et al., (2017) found that external biophysical and socio-economic drivers, farmers' individual attributes and cultural conditioning influenced the motivation to adopt AEP. In their study, farmers reported that their knowledge of human health, market availability of farming equipment, and aesthetic values strongly influenced their adoption of AEP. Moreover, public-policy incentives motivated farmers to adopt AEP in the viticulture sector.

Kuhfuss and Subervie, (2018) highlighted the role that collective organizations, represented mainly by winery cooperatives, could play in disseminating information that helps winegrowers target certain practices. Education and economic motivations were not the main drivers of adoption. Sharing knowledge and experience within these organizations is an important mechanism for adopting AEP, in particular by increasing access to suitable equipment, accelerating learning, and transmitting information from peers. In fact, membership in a cooperative usually requires complying with a precise set of specifications. When winegrowers do, they are more inclined to adopt AEP, since the advantages (particularly organizational and economic) of belonging to a group provide sufficient motivation (Jourjon et al., 2016).

In addition, Hunecke et al., (2017) and Lanza Castillo et al., (2021) noted the importance of social capital, approximated by formal and informal farmer networks, and social pressure in the adoption of irrigation technology among winegrowers in central Chile.Similarly, Cullen et al., (2008) and Forbes et al., (2013) highlighted that social learning of practices, and the associated technical and economic knowledge, decreases farmers' perception of risk, and promotes changing management practices that favor the environment.

Studying vineyards in Catalonia (Spain), Kallas et al., (2010) found that farmers' objectives influence the decision to convert to organic farming, and that those who are not risk averse are more likely to adopt it. Galliera and Rutström, (2021) highlight perceptions of costs vs. benefits, direct information, know-how, and support for the investments as key factors that promote adoption of BMPs and sustainable pesticide use to improve groundwater quality in hilly vineyards in Italy. In a study of vineyard crop protection in Galicia (Spain), Pereira et al., (2017) explained that the low rate of adoption of agroecological innovations in viticulture was due to their higher prices, higher labor costs, and novelty.

Winegrowers engage in AEP more quickly when they can be assured that their neighbors have already committed to AEP or are engaging in them. Although this field observation has not been confirmed, it shows that territorial dynamism forms part of a collective decision system that reflects a mechanism for adopting AEP across an entire geographic area (Bélis-bergouignan et al., 2008; Kuhfuss et al., 2014). Another factor that increases adoption probability is farm location in a less economically favored area, which may be related to subsidies distributed by the EU's Common Agricultural Policy to preserve these areas (Kallas et al., 2010). Characteristics of AEP themselves influence farmers' decision-making. For example, Kuhfuss and Subervie, (2018) explained that farmers have rejected many agroecological innovations because of their intrinsic characteristics (specific characteristics related to the practice), and that winegrowers adopt the least demanding AEP rather than the most demanding.

This review of the literature confirms the absence of universally significant influences of factors on the adoption of agroecological innovations. Thus, mechanisms for and barriers to adoption depend on the context and the AEP. Consequently, adoption studies, especially in agriculture, should be contextualized to the type of innovation and the territory in which it is implemented.

Methodology

The diversity of studies about the adoption of innovations highlights this topic's importance. Most of these studies used linear regression (ordinary least square) and discrete choice models such as logit and probit to determine which variables were significantly correlated with adoption. They also reflect differences in the quality of analyses (Abadi Ghadim & Pannell, 1999). Some focused more on the analysis methods than on the phenomena analyzed (Knowler & Bradshaw, 2007). Results depend strongly on the context of the region in which adoption is analyzed and on how the analyzed innovation or practice is defined (Di Bianco et al., 2019).

In this article, we study the adoption of AEP by winegrowers in the Loire Valley production area (northwestern France). However, AEP are multiple and complex. Their effects depend on many variables (e.g., farm, soil, climate), and they have no specific characteristics that allows to distinguish "AEP" from "non-AEP". To address these challenges, we developed a method that combined quantitative and qualitative analyses to capture winegrowers' adoption or non-adoption of AEP, and to explain the factors that influenced adoption. Thus, AEP were defined according to their environmental impacts estimated with LCA (Renaud-Gentié et al., 2014; Rouault et al., 2016), followed by two complementary surveys.

Sampling and data collection

A mixed qualitative and quantitative survey was used. The qualitative survey was conducted through semi-structured interviews with 12 winegrowers in the Loire Valley.[1] It was used to identify winegrowers' perceptions of AEP, their reasons for using or not using them, and certain context-related variables not specified in the literature. Results of this survey were used to strengthen and supplement the quantitative analysis, which was performed to collect data from a representative sample of winegrowers in the same study area, using a questionnaire.[2]

The Pays de la Loire is a French administrative region including a large part of the Vallée de la Loire natural region. It is the 7th largest wine region in France in terms of production potential (4% of volume) and has 1195 farms that specialize in viticulture. A sample of 120 winegrowers (10% of all farms) was selected in the Vallée de la Loire natural region (Fig. 7) based on four criteria determined with local experts:

- (i) Specialized winegrowers with farms at least 1 ha in size
- (ii) Surveyed farms proportional to the real distribution of winegrowers: 1/2, 1/4, and 1/4 of farms in the administrative departments of Maine-et-Loire, Loire-Atlantique and Indre-et-Loire, respectively
- (iii) 1/3 of farms selling mainly bulk production to traders and/or a cooperative, 1/3 of farms selling mainly through direct sales (e.g., from the cellar, by delivery), and 1/3 of farms using a combination of the two previous types
- (iv) 2/3 of conventional farms and 1/3 of third-party environmentally certified farms using an organic label or a government-promoted label (level 3 "high environmental value" label) or a business-promoted label (Terra Vitis).

[1] See the Supplementary Information for the interview guide, translated into English.
[2] See the Supplementary Information for the questionnaire's structure and some of its questions.

Out of the 120 winegrowers contacted, 88 ultimately accepted to be interviewed for the face-to-face quantitative survey. According to agricultural advisors, this response rate is due to the sensitive topic of the survey and media pressure on farming practices.

Identification of adopter and non-adopter groups

This step was a methodological challenge due to the complexity in determining which practices were "agroecological". Thus, we first identified practices that cause the most harm to the environment (i.e., "non-AEP"). As long as a winegrower did not adopt non-AEP, the winegrower was considered an adopter of AEP.

Non-AEP were identified in collaboration with colleagues specialized in LCA of viticulture, as a part of the ECO3VIC[3] project (Czyrnek-Delêtre et al., 2018; Perrin et al., 2022; Renaud-Gentié et al., 2019; Rouault et al., 2020; van der Werf et al., 2020). When applied to viticulture, LCA assesses all phases of the farm production cycle and considers multiple impacts due to factors such as use of pesticides and fertilizers, greenhouse gas emissions, consumption of fossil resources, and pollution by fertilizers and pesticide products(Penavayre et al., 2016; Renaud-Gentié et al., 2014).

Based on LCA results for environmental impacts (e.g., terrestrial acidification, abiotic resource depletion of the farm, freshwater ecotoxicity, marine eutrophication) of 600 operations commonly used in viticulture in the Loire Valley (Rouault et al., 2020; Van der Werf et al., 2020), we identified six practices[4] that were most harmful to the environment: synthetic fertilization; chemical weeding; applying more than 4-kg copper/ha/year; applying pesticides that contain the active ingredients folpet, metiram, or cymoxanil; using carcinogenic, mutagenic or reprotoxic (CMR) chemical inputs; and always applying pesticides instead of using non-chemical practices. These practices were considered "non-AEP" due to their environmental impacts.

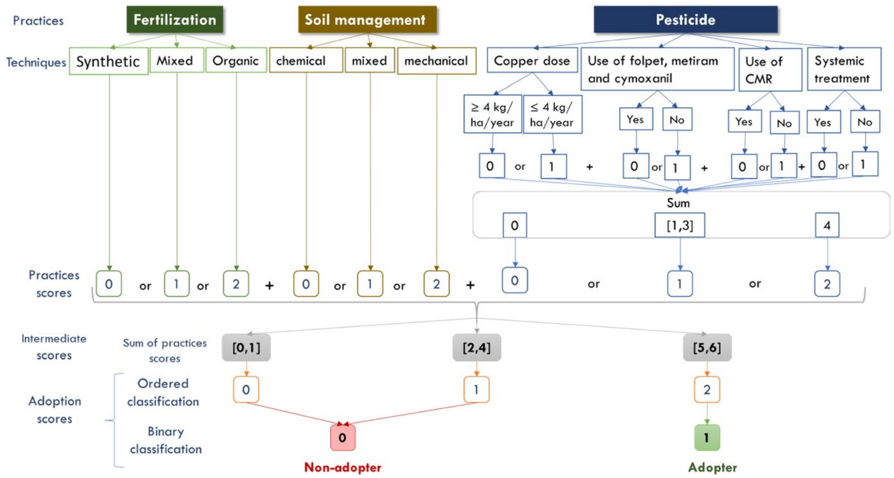
Then, in our surveys, we identified all practices used by winegrowers. Each practice was compared to the reference list of non-AEP and given an "AEP score". For each winegrower, the sum of all practice scores (i.e., "adoption score") determined whether the winegrower was an "adopter" or "non-adopter" of AEP.

Assigning practice and adoption scores

The scoring method (see Fig. 1) was inspired by Guyomard et al., (2017) and Nugues et al., (2019). We divided winegrowers' practices into three categories: fertilization, soil management, and pesticide treatment. In each category, several

[3] The ECO3VIC project, financed by ADEME (French Agency for Ecological Transition), contributed to approaches and methods to support decision-making for changes in viticulture practices to decrease environmental impacts. It was an interdisciplinary project that associated scientific partners from technical disciplines (ESA Grappe, INRAE), economics and sociology (ESA Laress), experimentation and development (Chamber of Agriculture Pays de la Loire), and companies and wine-growing organizations (Cave Robert and Marcel; Terra Vitis).

[4] A practice could be associated with a set of operations (e.g., a list of synthetic fertilization operations).



CMR = carcinogenic, mutagenic, or reprotoxic products

Fig. 1 Method for attributing scores to winegrowers to classify them as adopters or non-adopters of AEP. CMR = carcinogenic, mutagenic, or reprotoxic products

practices are possible, and each practice received a score of 0, 1, or 2 if it had high, moderate, or low environmental impacts, respectively with regard to LCA analyses. For fertilization, the use of synthetic fertilizer was scored 0, use of organic fertilizer was scored 2, and use of both (i.e., "mixed fertilization") was scored 1.

For soil management practices, we mainly focused on weeding practices: the use of chemical weeding was scored 0, use of mechanical weeding was scored 2, and use of both (i.e., "mixed weeding") was scored 1.

For pesticide-treatment practices, scoring was more detailed because of their complexity and the many pesticides used. In line with Guyomard et al., (2017), pesticide-treatment practices were defined and classified according to the type and dose of the product used. We defined four criteria to identify non-AEP for pesticides: applying more than 4 kg of copper/ha/year; applying pesticides that contain folpet, metiram, or cymoxanil; using CMR products; and always applying pesticides. Based on these criteria, each pesticide practice received a binary score (0 if used, 1 if not). If the sum of the scores was 0, 1–3, or 4, the practice score equaled 0, 1, or 2, respectively. Thus, non-AEP received the lowest score.

The sum of the practice scores of all three categories equaled the adoption score, which determined whether a winegrower was an adopter of AEP or not.

If the adoption score was 0 or 1, winegrowers were automatically considered non-adopters of AEP. If the adoption score was 2–4, winegrowers were considered in transition towards more AEP but were ultimately considered non-adopters to simplify the subsequent econometric analysis, given the relatively small sample size. If the adoption score was 5–6, winegrowers were considered adopters of AEP. This hand scoring was evaluated in the next section by a statistical approach to confirm its robustness.

Statistical validation of the scoring method

After determining the groups of adopters and non-adopters of AEP with the scoring method, we assessed these results with a variety of statistical analyses. We first used multiple factor analysis (MFA) (Abdi et al., 2013; Escofier & Pagès, 1994) to assess the scoring system by characterizing the groups of winegrowers as a function of their practices (i.e., fertilization, soil management, and pesticide treatment). MFA is a generalization of principal component analysis (PCA) for quantitative variables that can spatially represent variables, main factors, and individuals when variables are grouped. The aim is to visualize relative distances of two observations between two data tables. In these tables, winegrowers were described using a binary variable for each viticulture practice (i.e., 1 if practiced, 0 if not). We included the adoption score as an illustrative variable to verify the agreement between scoring groups and MFA groups. Next, we used hierarchical cluster analysis (HCA) to verify the decision to consider winegrowers with an adoption score of 2–4 as non-adopters of AEP. HCA forms clusters of individuals that are as similar as possible. The variables used were the same as those used in the MFA. R software version 3.6.0 was used to perform these analyses.

Analytical models

To compare winegrowers' statements collected in the qualitative survey to econometric results, we used PCA to analyze winegrowers' perceptions of barriers to and mechanisms for adopting certain AEP. From this analysis, we selected 11 main variables that described reasons for adopting AEP or not from winegrowers' viewpoints (Table 2).[5] The variables that contributed the most to the first two principal components were included, along with other variables (socio-economic and farm characteristics), in the binary logit regression to identify their influence on the true adoption of AEP (Table 3).

The logit regression model is commonly used in econometric analysis of adoption studies (Asfaw & Neka, 2017; Chen et al., 2009; Chomba, 2004; Liu et al., 2018). It is used to explain discrete variable Y, which can take two values (0 for non-adopter, 1 for adopter) (Greene, 2005). It calculates the probability that Y equals 1 and determines the influence of explanatory variables X $\{x_1,\ldots x_n\}$ on Y. X is a vector of explanatory variables that groups sets of factors; in our study, these groups were socio-economic characteristics, farm characteristics, AEP characteristics, and perception of external context factors.

For the ith winegrower, Z_i is an indirect utility function derived from the decision to adopt an AEP, which is a linear function of the explanatory variables (X):

$$\mathrm{Z_{i1} = X_i \beta_1} \quad \text{(AEP adopted)}$$

[5] See also the Supplementary Information no. 4 for less important factors that were mentioned.

Table 2 The variables used in the principal component analysis to assess drivers of and barriers to adoption of agroecological practices (AEP) from the winegrower's point of view

	Variable	Description of winegrowers' perceptions
Drivers for adopting AEP	Environmental perception	Winegrowers' sensitivity to environmental protection
	Human health perception	Winegrowers' sensitivity to human health
	"Polluter pays" tax	Creating a tax that follows the "polluter pays" principle
	Advice	Advice given by professionals (e.g., Chambers of Agriculture, technical sales representatives, banks)
	Reduced taxes	F inancial support through reduced taxes
	Perception of subsidies	Subsidies from the state and/or the European Common Agricultural Policy
Barriers to adopting AEP	Information	The perception that information is unavailable
	Costs	The cost of purchasing new equipment
	Loss yield risk	The perception that a practice risks decreasing the grape yield
	Addlabor	The perception that a practice will require additional labor
	Labor	The perception that labor is unavailable

Table 3 Definition of variables in the logit regression model to assess adoption of agroecological practices (AEP)

Code	Variable	Description	Type of variable
Dependent variable			
Y	Adoption	Adoption of AEP	Dummy (1 yes, 0 no)
Independent variables			
X_1	Individual farm	The legal status of the farm: individual or shareholder	Dummy (1 yes, 0 no)
X_2	Vineyard surface area	Viticulture farm size (ha)	Continuous
X_3	Winemaking on the farm	Winegrower vinifies the grapes on the farm	Dummy (1 yes, 0 no)
X_4	Wine tourism activities	Presence of wine tourism activities on the farm	Dummy (1 yes, 0 no)
X_5	Sales revenue	Wine production revenue (€)	Continuous
X_6	Distance from homestead	The distance between the farthest plot and the homestead (km)	Continuous
X_7	Label	Winegrower produces under a quality label	Dummy (1 yes, 0 no)
X_8	Age	Age of the winegrower (years)	Continuous
X_9	Off-farm activities	Winegrower has off-farm activities	Dummy (1 yes, 0 no)
X_{10}	Environmental training	Winegrower has taken training on environmental issues and AEP	Dummy (1 yes, 0 no)
X_{11}	Human health perception	Winegrower's sensitivity to human health is a driver of adoption	Score from 1 (disagree) to 5 (agree)
X_{12}	Environmental perception	Winegrower's sensitivity to environmental protection is a driver of adoption	Score from 1 (disagree) 5 (agree)
X_{13}	Yield loss risk	Winegrower's sensitivity to potential loss of yield after adopting AEP is a barrier to adoption	Score from 1 (disagree) to 5 (agree)
X_{14}	Perception of subsidies	Winegrower's perception of subsidies is a driver of adoption	Score from 1 (disagree) to 5 (agree)
X_{15}	Labor unavailability	Winegrower's sensitivity to labor unavailability is a barrier to adoption	Score from 1 (disagree) to 5 (agree)

$$Z_{i0} = X_i\beta_0 \text{ (AEP not adopted)}$$

with $X_i = \{X_{i\ ...,}\ X_{15}\}$where X_i is the vector of explanatory variables of the *i*th winegrower, and β is the vector of parameters to be estimated.

A winegrower's decision to adopt is specified as $Y=f\ (X, \varepsilon)$, where ε is an error term with a logistic distribution.

$$Y_i \begin{cases} = 1 & if \quad Z_{i1} > Z_{i0} \\ = 0 & if \quad Z_{i1} \leq Z_{i0} \end{cases}$$

We are then interested in the frequencies of adoption (Y=1) and non-adoption (Y=0) for different values of X, and we examine whether these frequencies vary significantly according to X. We thus examine the probabilities $P\ (Y = 1 \mid x)$ and $P\ (Y = 0 \mid x)$, whose distribution function is given as:

$$P_i(Y_i = 1) = \frac{e^{zi}}{1+e^{zi}} \text{for } Z_i = X_i\beta \text{ and} - \infty < Zi < +\infty$$

where P_i is the probability of the *i*th winegrower's decision to adopt, and Y_i is the dependent variable representing adoption {1 if an adopter, 0 if a non-adopter}.

The coefficients of the logit regression model, estimated by maximum likelihood methods and the marginal effects, were calculated using R software. Several explanatory variables $\boldsymbol{X_i}$ strongly influenced the adoption or non-adoption of AEP[6] (Table 3). Some were related to farm characteristics: farm size, legal status of the farm (individual farm or company with more than one partner), distance between the farthest plot and the homestead, presence of wine tourism activities, sales revenue, label membership, and winemaking activity on the farm. Variables related to winegrower characteristics were age, off-farm activity, perception of human health, perception of environmental protection, and whether the winegrower had taken environmental training. Specific characteristics of practices were considered through the risk of yield loss (winegrowers' sensitivity to possible loss of yield after adopting AEP). To consider external local and national contexts, variables were chosen that reflected winegrowers' perception of subsidies for adopting AEP and labor unavailability.

Results and discussion

Scoring method results: definition of adopters and non-adopters of agroecological practices

The scoring method classified 57% of the 88 winegrowers surveyed as adopters of viticulture AEP and the other 43% as non-adopters. The relatively large percentage

[6] These explanatory variables were chosen based on the literature review and the qualitative survey used to identify winegrower's perceptions. We first integrated as many variables as possible (34; Table 3 in the Supplementary Information). Then, using backward-stepwise and forward-stepwise selection, we reduced them to 15 variables (Table 3) by eliminating the least significant ones.

of adopters was due mainly to the use of better fertilization practices in the Pays de la Loire as compared to the rest of France. Specifically, 77% of the winegrowers surveyed had adopted organic fertilization. In contrast, adoption of agroecological pesticide treatments was low (< 21% and < 31% by non-adopters and adopters, respectively).

The results of the MFA and the HCA validate the used scoring method. The MFA explained 61.14% of the inertia on the first two PCA axes (Fig. 2). The illustrative variables of adoption scores confirmed the scoring classification, with non-adopters (score 0) correlating well with non-AEP (e.g., "mixed fertilization", "chemical weeding") and adopters (score 1) correlating well with AEP (e.g., "organic fertilization", "mechanical weeding", "non-CMR products", and "products without folpet, metiram, or cymoxanil") (Fig. 2). Thus, MFA was able to distinguish adopters from non-adopters.

In comparison, the HCA identified three clusters of winegrowers (Fig. 6). The first was characterized by AEP and contained all adopters that the scoring method had identified, including all winegrowers who used only organic fertilization and none of the winegrowers who used only chemical weeding. The second and third clusters were characterized by non-AEP. In the second cluster, 85% of winegrowers used mixed fertilization, and none used only organic fertilization. In the third cluster, 100% of winegrowers used chemical weeding, and only 15% used pesticides without folpet, metiram, or cymoxanil. The only difference between these two clusters was the percentage of individuals using non-AEP. Since these practices were considered non-AEP according to LCA, we considered winegrowers in these two clusters as non-adopters. Thus, both the MFA and HCA confirmed the scoring method, and all three methods distinguished non-adopters from adopters (Fig. 3). For all used methods, adopters and non-adopters differed mainly in pesticide-use

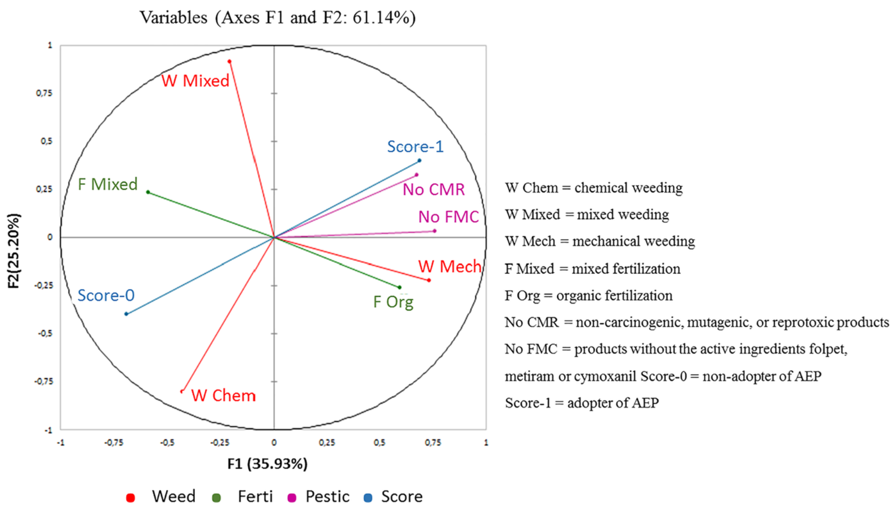


Fig. 2 Correlation circle of multiple factor analysis of AEP related to weeding (Weed), fertilization (Ferti), and pesticide use (Pestic), with scores as illustrative variables

and chemical-weeding practices; for example, 73% of adopters used non-CMR products; 50% used no folpet, metiram, or cymoxanil, and none of them used chemical weeding (Fig. 3). This is consistent with the literature, which shows that these practices are the most risky and demanding in viticulture (Garini et al., 2017; Kuhfuss & Subervie, 2018).

Analysis of winegrowers' perception of barriers to and mechanisms for adopting agroecological practices

PCA results for mechanisms for adopting AEP showed that the winegrowers were particularly sensitive to human health and environmental protection (Fig. 4), especially adopters. Most winegrowers, who did not consider human health, or to a lesser extent, environmental protection, as drivers, were non-adopters. For both adopters and non-adopters, economic measures such as subsidies and increasing taxes (e.g., "polluter pays" tax) or reducing taxes were not considered mechanisms that would encourage adoption of AEP. Other variables such as professional advice and specific training for new practices were not considered important.

Winegrowers' perception of barriers to adopting AEP varied (Fig. 5). Both adopters and non-adopters perceived mainly the potential loss of yield, the additional labor required and the unavailability of labor as major barriers to adopting AEP. Equipment cost, access to bank credit, which was correlated with equipment cost, and information availability were identified less often as barriers.

Analysis of adoption factors of agroecological practices

The results of the logit regression explained the influence of the variables studied on the adoption of AEP (Table 4).

Legal status as an individual farm had a significantly negative effect on adoption. Winegrowers with individual farms were ca. 41% less likely (the highest marginal effects are estimated for individual farms, wine tourism activities, and environmental training) to adopt AEP, maybe due to the lack of funding or labor, or to the perception of the risk of lower yields. Innovative practices usually require more labor, and being associated with partners in a collective-status farm could provide the additional labor needed. Some of these farms may also be considered capital-intensive, and innovation may jeopardize their financial health; here again, partners can provide sufficient financial security to invest in AEP. Partners can also discuss technical procedures of practices and develop expertise. Thus, by encouraging winegrowers to try out new practices and take more risks, the presence of partners may favor adoption of AEP. Di Bianco et al., (2019) found that the presence of a partner influenced early adoption of ecological intensification practices. In the present study, off-farm activity had no significant influence, unlike in the study of Kallas et al., (2010), who reported the presence of off-farm income or an off-farm activity as factors that increased adoption of organic farming in viticulture in Catalonia.

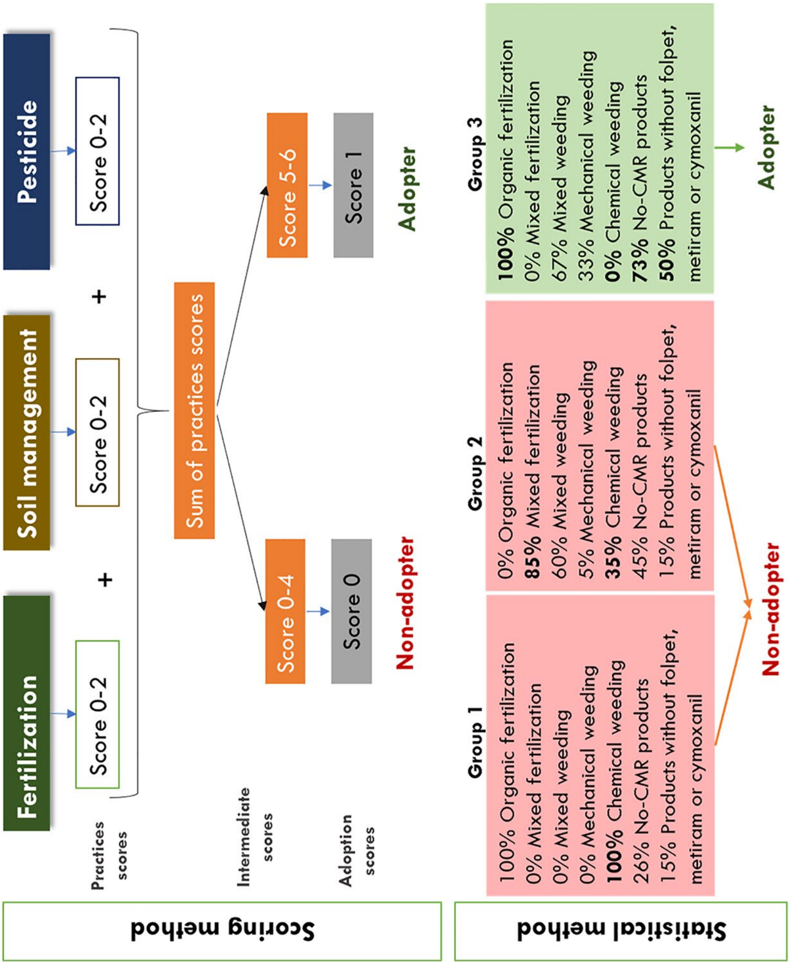


Fig. 3 Comparative summary of the methods used to classify adopters and non-adopters of agroecological practices. CMR = carcinogenic, mutagenic, and reprotoxic

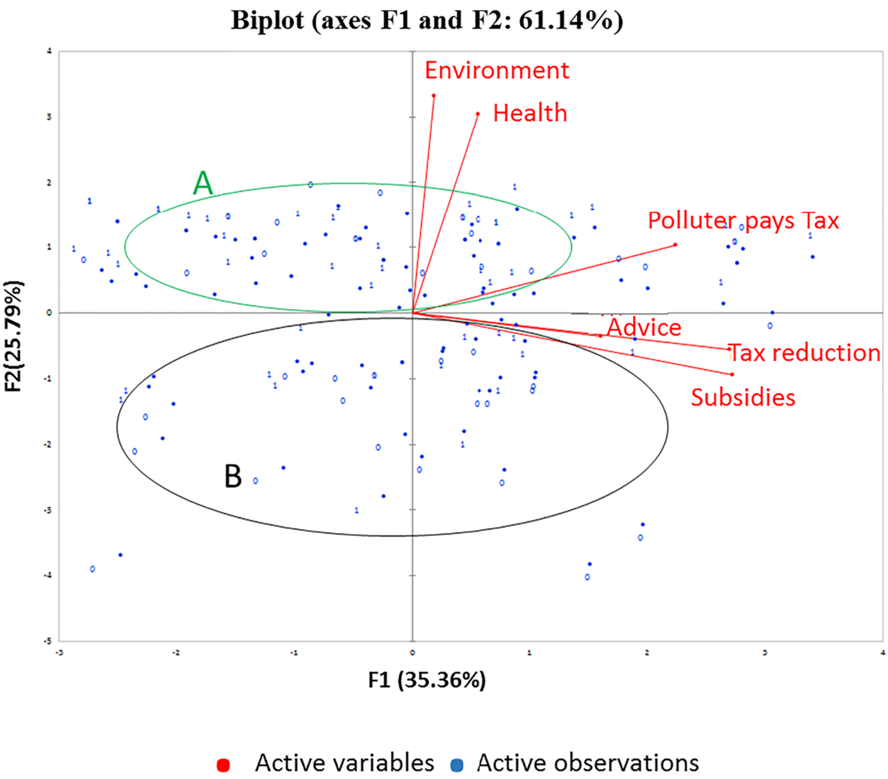


Fig. 4 Position of winegrowers who were adopters (oval **A**) or non-adopters (oval **B**) of AEP in relation to their perception of mechanisms for adopting AEP

Vineyard area had a significantly negative effect on adoption. Thus, the larger the vineyard was, the lower the likelihood of adopting AEP. This result can be explained by the need for additional labor and equipment investment. For example, some equipment (e.g., a confined sprayer) can cover only ca. 20 ha; thus, large farms would need to buy more than one to be able to spray on time. For manual harvesting, larger farms will require more labor. This result contrasts with those of Amsalu and de Graaff, (2007), Asfaw and Neka, (2017), Konrad et al., (2019), and Ward et al., (2018), who reported a positive effect of farm size or main crop area on the likelihood of adopting AEP in Ethiopia, five Baltic sea countries, and South Africa, respectively. They demonstrated that having a large farm encourages farmers to adopt AEP, especially SWC practices, to obtain a positive return on investment. However, Chomba, (2004) observed that farm size did not explain whether or not smallholders in Zambia adopted SWC practices.

Although winegrowers' perceptions of potential yield loss and unavailability of labor were non-significant as a barrier to adopting AEP, their direction of influence was the same as vineyard area, which indicates the importance of labor pressure and

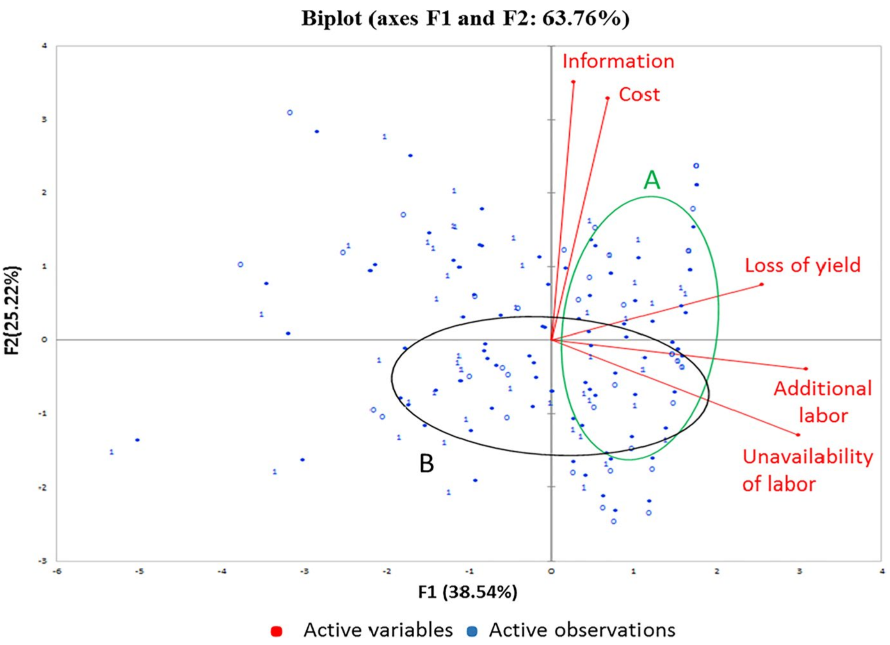


Fig. 5 Position of adopter (oval **A**) and non-adopter (oval **B**) winegrowers in relation to their perception of barriers to adopting AEP

Table 4 Results of the binary logistic regression

Variable	Variable	Marginal effect	Standard deviation	Error	*Z* value	Pr (>|z|)
Intercept			4.300	3.988	1.078	0.281
X_1	Individual farm	−0.418	−3.077	1.224	−2.514	0.012 **
X_2	Vineyard surface area	−0.015	−0.114	0.055	−2.079	0.037 **
X_3	Winemaking on the farm	−0.004	−0.029	0.012	−2.352	0.018 **
X_4	Wine tourism activities	0.366	2.696	0.996	2.708	0.006 ***
X_5	Sales revenue	0.001	0.006	0.003	1.811	0.070 *
X_6	Distance from homestead	−0.001	−0.011	0.126	−0.085	0.932
X_7	Winegrower age	−0.008	−0.056	0.035	−1.592	0.111
X_8	Quality label	0.057	0.416	0.647	0.643	0.520
X_9	Off-farm activities	−0.057	−0.420	0.920	−0.456	0.648
X_{10}	Environmental training	0.245	1.802	0.800	2.253	0.024 **
X_{11}	Human health perception	0.123	0.902	0.463	1.947	0.051 *
X_{12}	Environmental perception	−0.023	−0.169	0.461	−0.366	0.714
X_{13}	Loss of yield risk	−0.036	−0.266	0.317	−0.837	0.402
X_{14}	Financial support	−0.039	−0.286	0.261	−1.096	0.273
X_{15}	Labor unavailability	−0.042	−0.309	0.346	−0.893	0.371

*, **, ***Significant at $p < 0.10$, < 0.05, and < 0.01, respectively.

risk aversion on larger vineyards. Winemaking on the farm had a significantly negative effect on adoption; thus, winegrowers who had their grapes vinified by cooperatives or wine merchants were more likely to adopt AEP, likely because winemaking requires additional labor, and winegrowers prefer to allocate labor to winemaking rather than to implementing AEP. Lozano-Vita et al., (2018) state that the amount of work necessary plays a key role in whether winegrowers decide to change their practices.

The presence of wine tourism activities (e.g., catering, tastings, accommodation) on the farm had a significantly positive effect on winegrowers' decision to adopt AEP (i.e., ca. 37% more likely). Direct contact between winegrowers and consumers seems to motivate winegrowers to adopt AEP to produce residue-free products, in contrast with the use of labels (not significant). Adopting AEP in viticulture adds value to its products, which allows farmers to address consumers' expectations in a new way: they can benefit from their lower environmental impacts and produce higher-quality wine that is free of pesticide residues. Bélis-Bergouignan and Saint-Ges, (2009) and Jourjon et al., (2017) reported similar results, observing that consumer demand positively influenced adoption of agroecological innovations in viticulture. Sales revenue also had a significantly positive effect on adoption. Higher revenue and better financial health of the farm encourages winegrowers to invest and risk changing their practices towards those with lower environmental impacts, because the financial risk is lower. However, this positive effect aggregates yields and selling prices of final products, which may confound interpretation of their relative influence.

Analysis of perceptions showed that AEP are adopted mainly by winegrowers who care about human health and think that these concerns should prompt farmers to change to more sustainable practices. Perceptions of these mechanisms were significantly positive variables in the econometric analysis. Sensitivity to effects of viticulture practices on human health (e.g., of his own health, other farmers, neighbors, or consumers) increased winegrowers' probability of adopting AEP by ca. 12%. Thus, raising winegrowers' awareness of harmful effects of viticulture practices on human health favors the adoption of AEP, in particular, those related to pesticide treatments, such as reducing the amount of copper applied or avoiding CMR products. The perception of environmental protection was not statistically significant. This result could be explained by the fact that both adopters and non-adopters thought that environmental protection is important and can be a driver for adopting AEP. This result may highlight a gap between statements, beliefs, and practices. In addition, although environmental awareness can now be considered common, large economic barriers remain that limit AEP adoption, as shown by the positive influence of sales revenue.

The professional entourage appears to be an important vector for raising awareness, which can be done by environmental training that encourages adopting viticulture practices with lower environmental impacts. Environmental training had a significantly positive effect, increasing the probability of adopting AEP by ca. 25%, which explains why farmers who have taken environmental training opt for

AEP. Winegrowers with such training benefit from the support of extension agents and their advisory organizations, which helps them implement AEP that require specific skills. Knowledge of advantages and disadvantages of AEP in viticulture could increase the probability of adoption. This result is similar to that of Cullen et al., (2008), who observed that farmers who received better training were willing to implement new AEP. In contrast, Bélis-Bergouignan and Saint-Ges, (2004) observed that training was not correlated with adoption of AEP in viticulture. Although winegrowers did not mention environmental training as a mechanism for adopting AEP, it can indirectly influence choices about which practices to implement, and confirms the observation of slight differences between the mechanisms and barriers mentioned and the reality of the adoption of AEP that appeared in the econometric analysis.

Conclusion

Supporting changes in practices requires being able to assess environmental performances of a variety of technical solutions and to identify economic, sociological, and organizational barriers to and mechanisms for adopting them. This study focused on understanding winegrowers' perceptions of agroecological innovations (from vine establishment to harvest) while considering the territorial, economic, and sociological contexts in which they live. It was based on a mixed methodological choice that was strengthened by subsequent statistical analyses. The three methods used identified a relatively high percentage of AEP adopters.

Despite some differences, results of econometric analyses converged with those of analysis of winegrowers' perceptions of barriers to and mechanisms for adoption of AEP. They confirmed that adoption factors depend generally on the context and type of agroecological innovations, and that AEP were adopted mainly by winegrowers who were sensitive to human health. Factors such as wine tourism activities on the farm, environmental training, and high sales revenue were positively correlated with adoption of AEP. Indeed, winegrowers are trying to promote consideration of the environment, which is an element of commercial differentiation that consumers value. Other factors such as the absence of on-farm partners, farm size, and winemaking on the farm had a significantly negative effect on adoption. Winegrowers mentioned these factors according to their own perceptions, identifying the loss of yield, need for additional labor, and unavailability of labor as major barriers to adopting AEP. This identification of barriers to and mechanisms for adopting AEP will serve as a tool for understanding and supporting winegrowers in their agroecological innovation processes. Therefore, this study can aid professionals in the wine sector and public decision-makers.

Appendix

Fig. 6
Fig. 7

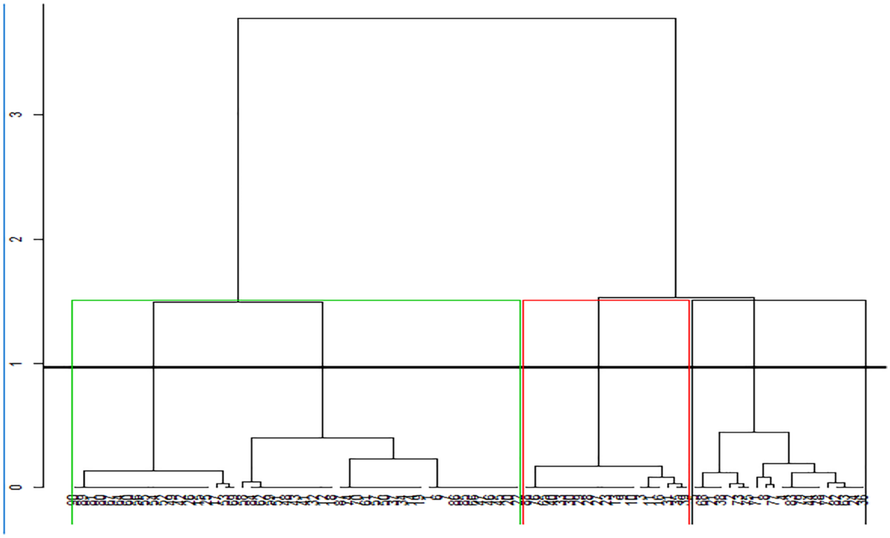


Fig. 6 Hierarchical cluster analysis of 88 winegrowers in the Loire Valley, with one cluster of adopters of AEP (green) and two clusters of non-adopters (red and black) based on their practices

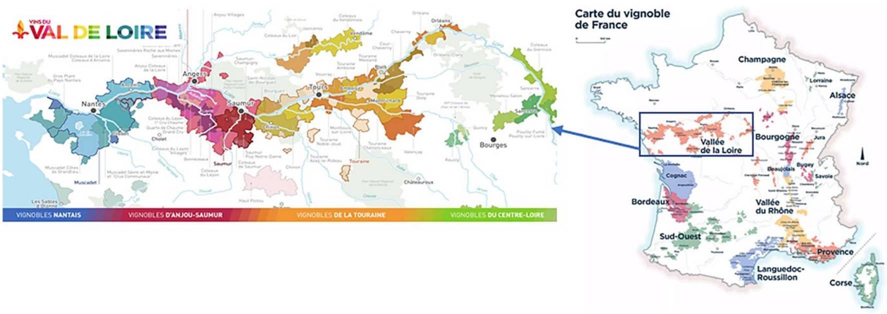


Fig. 7 Map of Vallée de Loire natural region (adapted from vinsdeLoire.fr and vin-champagne.ouest-france.fr)

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Author contribution M. Ghali performed the research question, bibliography, analyzed, and interpreted the models result. He was a major contributor in writing the manuscript. M. Ben Jaballah performed and carried out the quantitative surveys and has a major contribution in models' construction. N. Ben Arfa supervised and contributed to performing models, to analyzing results and writing manuscript. A. Sigwalt performed, carried out, and analyzed results from the qualitative surveys. All authors read and approved the final manuscript.

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Data availability Not applicable.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate No personal data are treated in the study.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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