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Winegrowers' decision-making: A pan-European perspective on pesticide use and inter-row management

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ABSTRACT

European viticultural landscapes not only support a significant share of rural livelihoods and cultural traditions, but also conserve biodiversity and sustain various ecosystem services. Winegrowers' practices of inter-row management (including whether to have vegetation in the inter-rows, type of vegetation, duration of vegetation cover, and soil tillage) and pesticide use (including herbicides in the inter-rows, fungicides, insecticides, and pheromone dispensers as an alternative) can affect these services. This study aims to understand winegrowers' decision-making driven by their personal characteristics, attitudes and beliefs towards viticultural practices, physical properties of vineyards, and farm management characteristics in five European winegrowing regions. These include Palatinate in Germany, Leithaberg in Austria, Tarnave in Romania, Bordeaux in France, and Montilla-Moriles in Spain. Based on a questionnaire survey, we constructed decision trees for each behaviour per case study as well as in a generic European model. We found factors that best explain how winegrowers manage their inter-rows and use pesticides. Results showed that not only do behaviours of winegrowers vary drastically across the case studies, but also the factors that explain most behaviours: farmers' attitudes and beliefs and farm management characteristics. This implies the importance of attitudes and beliefs – which are under-researched as compared to other factors – in understanding farmers' behaviour. With the driving factors found to vary per case study, our results also imply the need for locally-adapted policies. Furthermore, our results suggest that the effects of climate change on European viticultural landscapes concern not only shifting production regions and changes in yields, but also changing pressure of pests and diseases. Any long-term behavioural change requires efforts from many stakeholders.

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1. Introduction

Grapevines have been cultivated for thousands of years (Schultz and Jones, 2010) and viticulture has shaped rural landscapes all over Europe (van Helden et al., 2012). These viticultural landscapes provide not only grapes and wines, but also other important ecosystem services such as carbon sequestration and storage, pest control, cultural heritage services, and biodiversity conservation (Paiola et al., 2020; Winkler et al., 2017; Winter et al., 2018). Today, the sustainable provision of such services is threatened not only by climate change (Hannah et al., 2013; Hofmann et al., 2014; Schultz and Jones, 2010) at the global scale but also, and perhaps more importantly, by viticultural practices at the local scale. In particular, winegrowers' pesticide use (Nascimbene et al., 2013; Sanguankeo and León, 2011) and inter-row vegetation management (Winter et al., 2018) are two sets of interacting management practices with large environmental impacts (Hoffmann et al., 2017). Pesticide use here means the use of various plant protection products by winegrowers, including i) herbicides in their inter-rows to remove "weeds" which compete with vines for water and nutrients, ii) fungicides to avoid fungal infestations; and iii) insecticides (or alternatives such as pheromone dispensers) to remove yield-damaging pests. Inter-row vegetation management is about winegrowers' choices in the inter-rows to seed and establish cover crops, or to maintain spontaneous vegetation for certain periods of time, or to have bare soil resulting from intensive tillage or herbicide use.

Viticulture is often pesticide intensive (Orre-Gordon et al., 2013) and has negative environmental impacts. Historical datasets show that vineyards come top for pesticide use among the specialty crops at EU-15 level between 1994 and 2003 (Eurostat, 2007) – more recent data is not available. This high use of pesticides is mainly due to fungicides reducing the risk of severe mildew infections (Delière et al., 2015). Pesticides are associated, amongst others, with contamination of groundwater, degradation of soil fertility and biodiversity loss (Winter et al., 2018), as well as hampering ecosystem services like pest control (Möth et al., 2021; Reiff et al., 2021).

While inter-row management also has negative environmental impacts, data on related practices across the EU is even more scarce. Bare soil with frequent soil tillage is a typical inter-row management practice in European vineyards, especially in rainfall-deficient climates like the Mediterranean (Winter et al., 2018) as, in dry regions, inter-row vegetation tends to compete with grapevines for water (Pardini et al., 2002; Ripoche et al., 2011) and thereby impacts grape quality (Gómez, 2017). In more humid northern European countries, trafficability of vineyards under wet weather conditions is a practical advantage of cover crops (Gary and Fermaud, 2010). Inter-row vegetation also reduces soil erosion (Winter et al., 2018). Furthermore, inter-row vegetation provides habitats for predators of grapevine pests; removing inter-row vegetation results in loss of such habitats and makes vineyards monocultures (Orre-Gordon et al., 2013) which might increase pest outbreaks and insecticide use (Paredes et al., 2021).

Pesticide use and inter-row management have important interactions when it comes to winegrowers' decision-making: Winegrowers who decide on bare inter-rows may implement them either through intensive tillage or herbicide use. Thus, inter-row management has direct implications for herbicide use. Furthermore, inter-row vegetation can indirectly impact insecticide use through increased pest outbreaks if the habitats of predators are lost. At the same time, inter-row vegetation may serve as a disease vector or increase grapevines' susceptibility to disease; such perceptions may limit winegrowers' adoption of inter-row vegetation (Lazcano et al., 2020). Thus, inter-row management and pesticide use are best analysed in tandem. To address their relations, we included questions on how well a behaviour fits to how the vineyard is managed and whether it addresses water competition between inter-row vegetation and vines, for example.

This study aims to answer the following research question: What drives winegrowers' decision-making on inter-row management and pesticide use in Europe? Since European winegrowers show different behaviour in terms of inter-row management and pesticide use (ENDURE, 2007), we comparatively explore winegrowers' decision-making in five European viticultural landscapes. More specifically, we aim, first, to describe the behaviour of winegrowers in terms of type of inter-row management (including the presence, type and duration of vegetation, and frequency of soil tillage), and pesticide use (including herbicides in the inter-rows, fungicides, insecticides, and pheromone dispensers as an alternative), and how these behaviours vary across the case studies. Second, we describe the winegrowers' attitudes towards their vineyard management. Third, we investigate winegrowers' decision-making by testing which drivers influence the behaviour. In doing so, we contribute to the scarce literature on farmers' decision making in which attitudes and beliefs are explicitly considered to explain behaviours across heterogeneous contexts. The remainder of this study is organised as follows: In section 2, we lay out the conceptual background of our study. Section 3 provides the materials and methods, and section 4 the results. In section 5, we discuss our findings. Section 6 concludes.

2. Conceptual background

In the following, we present the conceptual background of our study. We start by describing how winegrowers have considerable freedom in their pesticide and inter-row management under the current policy regime (section 2.1) and the research gaps concerning winegrowers' decision-making (section 2.2). We conclude this section by presenting our framework for understanding winegrowers' decision-making (section 2.3).

2.1. Relevance of policies for winegrowers' behaviour

Pesticide use and inter-row management are influenced by different policy instruments across administrative levels. At the European level, the Good Agricultural Practices (FAO, 2016) are the basis for receiving subsidies. The EU Directive 2009/128/EC on the sustainable use of pesticides (European Commission, 2009), together with several additional regulations[1] set ground rules for pesticide use in the EU and request the adoption of National Action Plans (NAPs) from member states (European Commission, 2020b). Following the NAPs, each government keeps a database with approved pesticides (herbicides, insecticides, and fungicides) for viticulture, application dates, against predefined biotic agents with a defined maximum spraying intensity, and defines areas prohibited from spraying. Another key action requested by the directive is to implement Integrated Pest Management (IPM), supported by instruments from the Common Agricultural Policy (European Commission, 2020b). Vineyards operating under IPM can use fewer pesticides than under conventional viticulture. Furthermore, insecticides are only allowed if pests exceed economic injury thresholds (Paredes et al., 2021). Organic viticulture (European Commission, 2012a) does not allow herbicides, synthetic insecticides or fungicides but plant protection products here might also negatively impact biodiversity and ecosystem services (Möth et al., 2021; Reiff et al., 2021). In organic viticulture, fungicides are mainly limited to copper and sulphur. A recent report shows that most NAPs fail to review their initial plans and to define ambitious targets with regards to pesticide use (European Commission, 2020b).

Inter-row management is comparatively less regulated. The EU soil strategy for 2030 (European Commission, 2021) requires member states to protect and restore soils by adopting sustainable soil management practices. However, this framework is currently not legally binding. Inter-row management is influenced in the context of soil conservation

[1] Regulation (EC) No 1107/2009, Regulation (EC) No 396/2005, Regulation (EU) 2017/625, and Regulation (EC) No 1185/2009.

through rural development programs (European Commission, 2005) and implemented as various Agri-environmental Schemes (AESs) at the national level. For example, Austrian AES ÖPUL 2015 (BMLRT, 2016) provides subsidies for inter-row vegetation cover to increase erosion control. Such AESs are typically voluntary. Alternatively, inter-row vegetation can be required by certain organic labels.

To sum up, pesticide-related policies do not prescribe what exactly has to be done but rather set an upper limit on spraying and control which pesticides may be used, while inter-row related AESs are mostly voluntary or driven by specific organic labels. Thus, winegrowers have considerable freedom in their pesticide and inter-row management. Therefore, improving agricultural policies to reduce pesticide use (Pertot et al., 2017) as well as the negative environmental impacts related to bare soil inter-row management (Winter et al., 2018) is important, but little is known about winegrowers' behaviour and the underlying decision-making process (Schütte and Bergmann, 2019).

2.2. Research gaps concerning winegrowers' decision-making

There is a growing body of literature available on the decision-making of European farmers in general — e.g. reviews by Bartkowski and Bartke (2018) and Dessart et al. (2019) pointing out the importance of heterogeneity of farmers, or on land use decisions globally (Malek et al., 2019). However, transferability of this knowledge to viticulture is difficult for at least two reasons. First, many winegrowers do not maximise their yields but rather limit them to fulfil regional rules, appellation regulations, or individual goals aiming at producing high quality wine (European Commission, 2012b). Second, the price range for wines is comparatively large (Caracciolo et al., 2013), so that winegrowers may be less dependent on agricultural subsidies but more influenced by consumer preferences, marketing strategies and their own perspectives on viticultural best practices (D'Amico et al., 2016; Demossier, 1997; Gade, 2004).

The scientific literature on decision-making in viticulture is limited. Winegrowers are sometimes part of a larger study sample (Demartini et al., 2017; Urquijo and De Stefano, 2016) where decision-making is often not analysed specifically for winegrowers. Studies of decision-making related to viticulture mostly focus on longer term (and often binary) decisions, such as converting to organic farming, participating in an environmental programme, and adopting agroecological practices (Forbes and de Silva, 2012; Garini et al., 2017; Kallas et al., 2010; Marquez-García et al., 2019; Micha et al., 2015; Siepmann and Nicholas, 2018). A few studies focus on winegrowers' land management. Fruitos et al. (2019) analysed how technicians and winegrowers in Mendoza, Argentina, perceive the effects of inter-row management practices on ecosystem services, but did not focus on the actual decision-making related to inter-row management. Marques et al. (2015) investigated barriers hindering winegrowers in central Spain from switching from conventional tillage to cover crops in the inter-rows and found that water constraints, lack of knowledge and little acceptance of yield losses mostly hindered adopting cover crops. However, almost none of the studies took a comparative perspective and analysed decision-making related to viticulture in multiple case studies in parallel. Such studies could be extremely valuable in understanding why pesticide use and inter-row management differ across countries or viticultural regions. For example, a recent study compared the difference of cover crop adoption between French and Spanish vineyards using a qualitative approach (Schütte and Bergmann, 2019), however, not directly linking winegrowers' attitudes with their actual behaviours.

2.3. A framework to understand winegrowers' decision-making

We conducted a literature review to identify potentially relevant drivers explaining winegrowers' behaviour (Fruitos et al., 2019; Garini et al., 2017; Kallas et al., 2010; Marques et al., 2015; Micha et al., 2015; Siepmann and Nicholas, 2018; Urquijo and De Stefano, 2016). To complement the limited body of literature on empirical studies, we also incorporated reviews on explaining farmers' behaviour in general (Bartkowski and Bartke, 2018; Dessart et al., 2019; Malek et al., 2019). We condensed our findings into a conceptual framework on winegrowers' decision-making (Fig. 1) linking drivers identified in the review to behaviours related to inter-row management and pesticide use.

Following Fishbein and Ajzen (1975) we define **behaviour** as "observable acts that are studied in their own right" (Fishbein and Ajzen, 1975, p. 13) – as opposed to using these acts to infer attitudes or other constructs. Behaviours related to inter-row management are: inter-row vegetation management (vegetation vs. bare soil in the inter-row), type of vegetation (seed mixtures vs. spontaneous vegetation), vegetation duration and soil tillage. Behaviours related to pesticide use are: use of herbicides in the inter-row, insecticides, pheromone dispensers and synthetic vs. copper-sulphur based fungicides. Details on how these behaviours were measured in the questionnaire are provided in section 3.2.1.

The term **driver** here refers to any variable used to explain or predict winegrowers' behaviour. We grouped the plethora of variables mentioned in the literature into five categories: winegrowers' personal characteristics such as age, gender and experience in viticulture (Chiffoleau, 2005; Garini et al., 2017; Mara et al., 2020; Marques et al., 2015); vineyard physical properties such as size and slope (Hadarits et al., 2010; Kallas et al., 2010; Neethling et al., 2017; Schütte and Bergmann, 2019); vineyard management properties such as label or grape varieties (Kallas et al., 2010); exceptional circumstances and winegrowers' attitudes and beliefs. A full list of all items per driver category is given in section 3.2.1.

In this study, we incorporated **attitudes and beliefs**. Attitudes are defined as winegrowers' personal evaluations of the behaviours (Ajzen, 1991), while beliefs are salient information about the behaviour (Ajzen

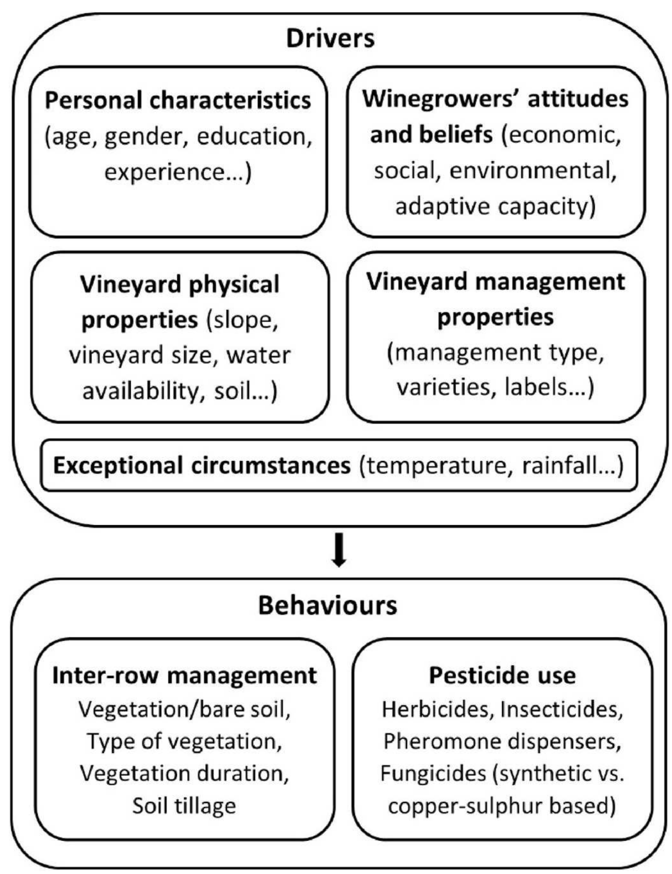

Fig. 1. Conceptual framework on winegrowers' decision making on inter-row management and pesticide use.

1991). Attitudes and beliefs predispose action (Fishbein and Ajzen, 1975) and, therefore, the actual behaviours are not included. Numerous items related to attitudes and underlying beliefs are reported in the literature. We grouped these items into four categories: adaptive capacity, environmental, social, and economic attitudes and beliefs (Fig. 1) to more conveniently present the items and results. We use the term "adaptive capacity" as the ability of winegrowers to respond to changes in biophysical, climate/weather or technological conditions. This is related to the perceived behavioural control component of the Theory of Planned Behaviour (Ajzen, 1991). The environmental attitudes and beliefs group items related to environmental awareness (Garini et al., 2017; Kallas et al., 2010; Menegaki et al., 2007; Meyfroidt, 2013; Schütte and Bergmann, 2019; Siepmann and Nicholas, 2018). The social attitudes and beliefs combine items related to morality and tradition (Alarcon et al., 2020; Cushman, 2015; Gonzalvo et al., 2020; Kallas et al., 2010; Kuhfuss et al., 2016; Lamarque et al., 2014; Micha et al., 2015; Mzoughi, 2011; Senger et al., 2017; Torquati et al., 2015; Xia et al., 2020). The economic attitudes and beliefs combine items on profitability, risk aversion, cost reduction and cross-compliance (Aka et al., 2018; Garini et al., 2017; Guthman, 2016; Hadarits et al., 2010; Kallas et al., 2010; Siepmann and Nicholas, 2018).

We realise that weather conditions may strongly influence especially pesticide use since warm and wet weather, for example, increases fungal infestations (Caffi et al., 2014; Pertot et al., 2017). Thus, we have incorporated **exceptional circumstances** as a fifth driver category. Finally, we use the term **decision-making** to describe how winegrowers link drivers and behaviours.

3. Materials and methods

We selected five case studies to investigate the differences in and drivers of pesticide use and inter-row management by means of a questionnaire survey and various statistical analyses. Section 3.1 presents viticulture-related background of the case studies; section 3.2 describes how we operationalised the key concepts in the questionnaire survey and collected responses; and section 3.3 summarises our statistical analyses.

3.1. Case studies

Five case studies were selected to understand winegrowers' behaviours and attitudes, and to identify drivers of their behaviours. They are from north to south Palatinate in Germany, Leithaberg in Austria, Tarnave in Romania, Bordeaux in France, and Montilla-Moriles in Spain (Fig. 2). They cover important winegrowing regions in Europe (Eurostat, 2017), form a gradient across Europe in terms of climatic conditions and landscape characteristics (Table 1), and differ in their socio-economic and political settings for viticulture. Moreover, winegrowers' inter-row management and pesticide use differ a lot. For example, inter-rows are mostly bare soils in the Spanish case, while in the Austrian case winegrowers commonly seed mixtures in the inter-rows. For all case

Table 1
Selected climate and terrain properties of the case studies. Climate is based on the Köppen–Geiger system (Kottek et al., 2006), in which Cfb is temperate oceanic climate, Dfb is warm-summer humid continental climate, and Csa is hot-summer Mediterranean climate. Data sources: Climate-Data.org (2020), meteoblue (2020), Corine (2018), USGS (2020). Slope is calculated from USGS DEM (SRTM-1-a-s) and Corine land cover 2018 by *the authors.*

Case study	Climate	Annual rainfall (mm)	Mean annual temperature (°C)	Rainy days in the growing season (March-September)	Slope (%) of vineyards: mean and (max)
Palatinate, Germany	Cfb	908	10.7	94	5.2 (56.9)
Leithaberg, Austria	Cfb	636	11.1	65	3.8 (52.3)
Tarnave, Romania	Dfb	759	10.2	57	12.8 (51.8)
Bordeaux, France	Cfb	776	13.8	69	4.3 (50.6)
Montilla-Moriles, Spain	Csa	539	17.2	24	7.4 (53.6)

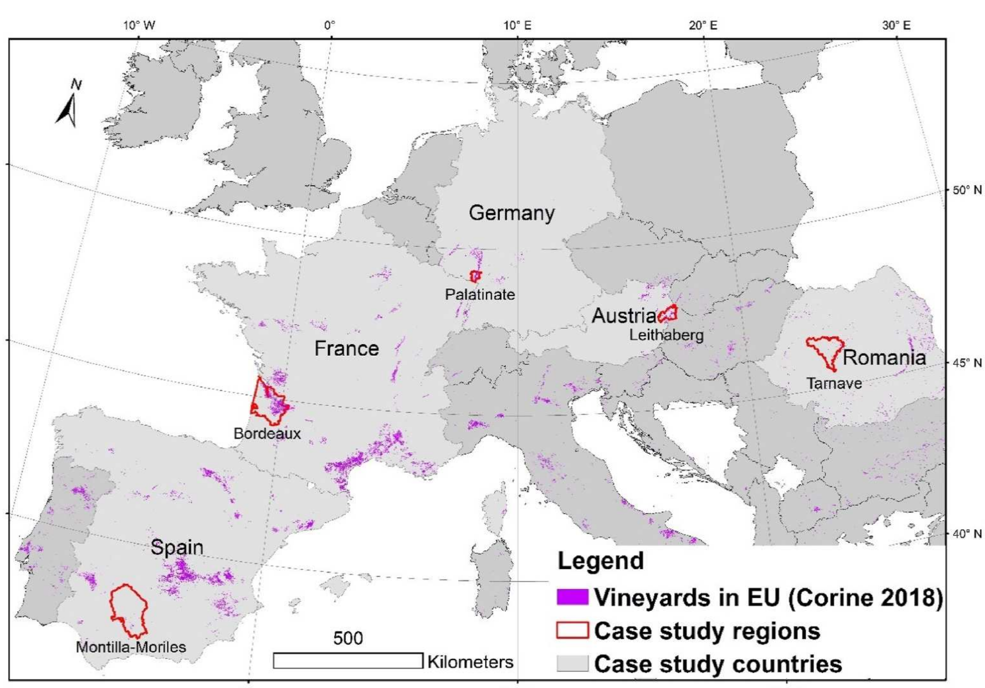

Fig. 2. *Location of the case study regions. The boundaries of each region (NUTS-3 level) are marked with a red line. Purple areas represent viticulture according to Corine land cover 2018. Source:* (Corine, 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Overview of national and regional policy instruments concerning inter-row management and pesticide use in each case study region.

Case study	Inter-row management	Pesticide use
Palatinate, Germany	German fertiliser ordinance requires (de facto) green cover in winter for groundwater protection, i.e., no tillage after 1 August. This is enforced by the extension service of local government.	Non-application of insecticide (by using the alternative of pheromone) is subsidised. Weather station based decision support systems are used by winegrowers for justifying the use of fungicides.
Leithaberg, Austria	Austrian AES ÖPUL 2015 (BMLRT, 2016) provides subsidies for inter-row vegetation cover to increase erosion control: < 25% slope at least green cover in winter, usually whole year; > 25% slope all year green cover. Vegetation cover should be managed not spontaneous — at least one perennial.	Herbicide: non-application is subsidised via ÖPUL 2015. A large supermarket chain only sells wine grown without the use of glyphosate and the label Leithaberg DAC bans the use of glyphosate. Insecticide: non-application is subsidised via ÖPUL 2015. Local phytosanitary authorities provide information on fungal disease and pest outbreak based on weather conditions.
Tarnave, Romania	No specific regulation	Local phytosanitary authorities provide information of fungal diseases and pest outbreak based on weather conditions, as well as recommendations on the doses of insecticides and fungicides.
Bordeaux, France	No specific regulation	Herbicide: Some appellations authorities (ODG: Organismes de Défense et de Gestion) ban herbicide use in the inter-rows. Insecticide: sectors of mandatory insecticide spraying against *Scaphoideus titanus* are defined annually according to local policies (insect vectoring a quarantine disease) based on pest and disease prevalence. Pesticides: Policy to have untreated areas near schools, houses, and water bodies. It is not subsidised but a regulation measure.
Montilla-Moriles, Spain	Economical support when a cover crop is installed.	Insecticide: Some buyers request winegrowers to follow IPM rules. Insecticides can only be used when pests exceed relevant economic injury thresholds. Fungicide: Some buyers request winegrowers to follow IPM rules.

studies, contacts with local winegrowers were already established in previous research projects.

Palatinate (Germany) is one of the most northern winegrowing regions, with oceanic climate and near-Mediterranean microclimates, varied soil types, and famous for the white wine variety Riesling. It is the second largest winegrowing region (about 23.000 ha) in Germany stretching north-south along the Haardt Mountains. Our case study region covers the southern part of the region.

Leithaberg (Austria) is one of the oldest winegrowing regions in the world (Keushguerian and Ghaplanyan, 2015), and has continental climate. It comprises about 3.000 ha and 450 wineries. Soils consist of sandy silt to sandy loam predominantly composed of limestone, acidic schist and gneiss, and both red and white varieties are grown with the principal varieties Weiβburgunder, Chardonnay and Blaufränkisch.

Tarnave (Romania) is located in the middle of Transylvania region, with continental climate and local influence of the Carpathian Mountains against cold currents. The region has brown soils with alternating layers of clay, marl, sandstone, and sand. Tarnave is a traditional viticulture region of Romania, famous for its white and sparkling wines. The main autochthonous varieties are Fetească Albă and Fetească Regală. Since Romania's entry to the EU in 2007 most of the old vineyards in the area have been replaced with new ones through a reconversion program supported by authorities. This region consists of two big (more than a thousand hectares) and many small winegrowers, comprising about 5000 ha and 20 wineries.

Bordeaux (France) is a large production area (127 500 ha) located in southwest of France, with an oceanic climate, and soils of compact sands, silt, or clayey limestone. This area is one of the world's most renowned winemaking regions in the world and vineyards of the area are presently planted with five main red grape varieties: Cabernet Sauvignon, Cabernet Franc, Malbec, Petit Verdot, and Merlot, the latter representing more than 50% of the Bordeaux area. This area is famous for its red varieties and encompasses more than 60 appellations that host a large variety of wines.

Montilla-Moriles (Spain) is located in southern Andalucía, with semi-continental Mediterranean climate and limestone-rich Albariza soils. Denomination of Origin Montilla-Moriles is famous for its specialty white wine variety Pedro Ximénez with higher-than-average alcohol percentages. Winegrowing in this region is facing competition with olive orchards, which is a potentially more profitable form of agriculture and the nearby Denomination of Origin Jerez-Xérès-Sherry.

3.2. Questionnaire survey

3.2.1. Questionnaire design

To comparatively explore winegrowers' decision-making on pesticide use and inter-row management, we conducted a questionnaire survey in the five case study regions.

The conceptual framework described in section 2.3 facilitated the design of the questionnaire (Appendix A). The questionnaire contains questions on behaviours and drivers of behaviour (attitudes and other drivers specified in the framework, section 2.3).

Behaviour: With two sets of viticultural practices, a total of nine behaviours were investigated. For the inter-row management, we asked winegrower about i) their vegetation management (nominal, choices between vegetation in every inter-row, or in every other inter-row, or bare soil), ii) type of vegetation (nominal, choices between different types of seed mixtures vs. spontaneous vegetation), iii) duration of vegetation (nominal, choices between year round vs. temporary), and iv) number of soil tillage operations (continuous) in the inter-rows annually (Fig. 1). For pesticide use, we asked v) the use (binary) and annual frequency of herbicides in the inter-row (continuous), vi) the use (binary) and annual frequency of insecticides (continuous), vii) the use of pheromone dispensers (binary) and number of dispensers per hectare (continuous), viii) annual frequency of synthetic fungicide (continuous), and finally ix) annual frequency of copper-sulphur based fungicide (continuous). The herbicide, insecticide and fungicide spraying frequencies were asked for a normal (average, typical) year as well as for an unusual year in which higher or lower than usual spraying frequencies were used.

Attitude and belief: The attitudes and beliefs included in the questionnaire fall into one of the four groups mentioned in section 2.3: adaptive capacity, environmental, economic and social. We asked winegrowers to rank the level of importance of that attitude or belief for their decision-making concerning inter-row management and pesticide use on a Likert scale from 1 (not important at all) to 5 (very important). No joint attitude scale for the individual groups was created.

Other drivers: Besides attitudes and beliefs, we asked winegrower about: physical properties of the vineyard, management properties and personal characteristics (Table 3). To understand which exceptional circumstances could make winegrowers deviate from their usual herbicide, insecticide, and fungicide sprayings in a normal year, we asked three open-ended questions regarding what characterised such an unusual year for herbicides, insecticides and fungicides, respectively.

The questionnaire was designed in English and then translated into

Table 3
Drivers of behaviour in the survey and their data types. All attitudes were measured as 1–5 Likert-scale ordinal data. The English version of the questionnaire is provided in Appendix A.

Category of driver	Item in the questionnaire	Reference
Personal characteristics	- Age (discrete) - Gender (nominal) - Experience in viticulture (discrete) - Education (ordinal) - Successor (binary)	(Chiffoleau, 2005; Garini et al., 2017; Mara et al., 2020; Marques et al., 2015)
Attitudes and beliefs — adaptive capacity	- Respond to current weather conditions - Have resources (machinery, money, skills) to implement - Follow advice of extension services - Fit with how my vineyard is managed - Have access to vineyards on rainy days - Avoid water/nutrient competition between vine and inter-rows	(Cleary and Hogan, 2016; Neethling et al., 2017; Nicholas and Durham, 2012; Pertot et al., 2017; Talanow et al., 2021; Urquijo and De Stefano, 2016; Winter et al., 2018)
Attitudes and beliefs — environmental	- Have natural enemies against pests - Show environmental commitment - Preserve soil quality - Preserve biodiversity - Consider hedges and trees in the surroundings	(Garini et al., 2017; Kallas et al., 2010; Menegaki et al., 2007; Meyfroidt, 2013; Schütte and Bergmann, 2019; Siepmann and Nicholas, 2018)
Attitudes and beliefs — economic	- Reduce costs in labour, material (seeds), and machinery - Benefit from subsidy - Have competitive advantage - Reduce risk of yield loss - Meet customer requirement - Comply with regulations	(Aka et al., 2018; Garini et al., 2017; Guthman, 2016; Hadarits et al., 2010; Kallas et al., 2010; Siepmann and Nicholas, 2018)
Attitudes and beliefs — social	- Have a nice vineyard - Follow traditions - Respect health of workers, tourists, neighbours, etc. - Do not feel guilty - Follow the behaviour of other winegrowers	(Alarcon et al., 2020; Cushman, 2015; Gonzalvo et al., 2020; Kallas et al., 2010; Kuhfuss et al., 2016; Lamarque et al., 2014; Micha et al., 2015; Mzoughi, 2011; Senger et al., 2017; Torquati et al., 2015; Xia et al., 2020)
Physical properties of vineyard	- Terrain characteristics (nominal) - Slope (%, continuous) - Lack of water? (binary) - Soil erosion? (binary) - Low soil quality? (binary)	(Hadarits et al., 2010; Kallas et al., 2010; Neethling et al., 2017; Schütte and Bergmann, 2019)
Management properties	- Total utilised area of agriculture for viticulture (discrete) - Harvesting method (nominal) - Management type (nominal) - Producing for a label? (binary) - Do you receive agricultural subsidies? (binary) - Do you offer activities for tourists on your vineyard? (binary) - Number of varieties (discrete)	(Kallas et al., 2010; Winter et al., 2018)

the five languages spoken in the study regions. Responses of the questionnaire were first collected in Spain, where winegrowers provided feedback regarding the layout, order, and clarity of the questionnaire. We then added one more question to the same questionnaire for all the remaining case studies. This added question concerns an environmental attitude (i.e., to consider trees and hedges in the surroundings) which can be relevant for winegrowers in those regions.

3.2.2. *Questionnaire distribution*

The survey was conducted in three different ways between 2019 and 2020, including i) local focus group meetings on other topics within the same project where also the questionnaire was distributed, ii) on-farm visits, and iii) online questionnaires (Table 4). All questionnaires were self-administered. To increase the number of responses, we started conducting farm visits for distributing the questionnaires, starting with Austria. However, as the COVID-19 pandemic hit our case study regions, farm visits were no longer possible. To adapt to the situation, we then created an online version of the questionnaire. Links to questionnaires were sent to winegrowers known in our team as well as through newsletters. Table 4 summarises the number of responses per data collection method. The rate of valid online responses ranged from 37% to 73%. No follow-up interviews were conducted.

3.3. *Data analyses*

3.3.1. *Behavioural differences across case studies*

We first checked normality for all behaviours that were represented by continuous variables. As most of them violated normal distribution, we tested if medians across case studies are significantly different using Independent-Samples Median Test and used Kruskal-Wallis Test to examine whether distributions of numerical values were significantly different for case studies of Palatinate (DE), Leithaberg (AT), Tarnave (RO) and Bordeaux (FR) and if so, what pairs of comparison constituted the difference by the adjusted p-value with the *post-hoc* method Bonferroni correction (which divides the threshold value — that one measures p-values against — by the number of comparisons).

3.3.2. *Exploring attitudes and beliefs towards behaviour*

The reported levels of importance of attitudes did not follow normal distributions. For each attitude, we used the Kruskal-Wallis Test as a non-parametric alternative to the one-way ANOVA to test if the reported level of importance had significantly different medians across case studies (DE, AT, RO and FR) and reported the significantly different pairwise comparisons (when the adjusted p-value $< .05$).

3.3.3. *Decision trees to explain behaviours with drivers*

The number of respondents in Palatinate (DE), Leithaberg (AT), Tarnave (RO), and all cases across case studies (G) allowed us to explore statistical analyses to explain behaviour with drivers. We used decision trees which are more easily communicable to stakeholders (Kotsiantis, 2013) and can be used with missing values and various variable distributions (Song and Lu, 2015). To overcome the tendency of overfitting, we limited the maximum depth of each decision tree to five (Bramer, 2013). We used IBM SPSS Decision Tree 25 and the algorithm of Exhaustive Chi-square Automatic Interaction Detector (CHAID) (Milanović and Stamenković, 2016) and kept record of the random seed used in each run of the decision tree for tractability and reproducibility.

Specifically, for each behaviour, we fed the decision tree model with all candidate drivers listed in Table 3 and ran the decision tree model 100 times (see in Table 5). Behavioural variables can be either categorical (nominal) or continuous, implying that different performance indicators are required — accuracy for behaviour measured as nominal variable, and risk estimate for behaviour measured as continuous variable. The accuracies of the decision trees for categorical variables can theoretically range between 0 and 100%, as each correctly predicted case accounts for 1/N (N is sample size) of the accuracy. For continuous

Table 4
Collected responses from various platforms across the case studies.

CASE STUDY	FOCUS GROUP DISCUSSION	FARM VISIT	VALID ONLINE RESPONSES	RATE OF VALID ONLINE RESPONSES	TOTAL
PALATINATE, GERMANY	3		24	73%	27
LEITHABERG, AUSTRIA	4	18	16	64%	38
TARNAVE, ROMANIA	10		24	71%	34
BORDEAUX, FRANCE	8		7	37%	15
MONTILLA-MORILES, SPAIN	10		–	–	10

Table 5
Implementation details of decision tree for each behaviour.

	Method implementation
Decision tree method	Exhaustive CHAID (IBM, 2017; Milanović and Stamenković, 2016)
Tree growth and split specifications	Maximum depth: 5; minimal parent size: 5; minimal child size: 2; required significance level for splitting: 0.05 (corrected with Bonferroni method)
Candidate drivers	39 candidate drivers (see Table 3).
Training vs. testing	Training: 80% Testing: 20%
Iterations	100
Model performance indicator	Categorical dependent variable: accuracy (%) Continuous dependent variable: risk estimate (within-node variance)

variables, comparing the classification of test data does not work, so a risk estimate is used instead. The risk estimate can theoretically range from 0 to infinity. When a case with a small value is wrongly predicted as a large one, it penalises the model performance by increasing the risk estimate, i.e., the within-group variance. Herbicide and pheromone dispenser use were modelled as binary decisions: as herbicide applications showed low frequency across the case studies and winegrowers used different types of pheromone dispensers, requiring different numbers per hectare across the case studies.

Per behaviour, we identified the best decision tree based on the following criteria: for a categorical dependent variable, a candidate decision tree needs to have an accuracy better than a random model, the candidate with the highest accuracy for the testing sample is selected; for a continuous dependent variable, a candidate decision tree needs to have a risk estimate lower than a random model, the candidate with the smallest risk estimate for the testing sample is selected.

Model performance indicators (accuracy for categorical dependent variable, and risk estimate for continuous dependent variable) from the random models were generated in two ways: 1) When the tree model failed to meet the specified criteria at the root node level, no decision tree was generated. A "null model" was generated to predict cases in the testing sample (randomly for categorical values and mean of the training sample for continuous values). Model performance indicators from such runs were used as references during the selection process. 2) When there was no null model generated within the 100 iterations, we manually created a random model to generate the reference.

4. Results

In the following, we first report how inter-row management and pesticide use vary across case studies (section 4.1), followed by differences in winegrowers' attitudes and beliefs (section 4.2). Finally, we present our findings on drivers of behaviour (section 4.3). Appendix B provides an overview of the characteristics of winegrowers (such as age and experience in viticulture) and the characteristics of their vineyards (such as farm size, slope, cultivated varieties, management type, problems with soil and water, etc.).

4.1. *Different inter-row management and pesticide use across case studies*

Winegrowers across the case studies have heterogenous inter-row management, including the choice between vegetation vs. bare soil in the inter-row, the duration and type of vegetation, and frequency of soil tillage (Fig. 3). Vegetation is either growing in every or every second inter-row, with the former being the dominant type in Palatinate (DE), Leithaberg (AT) and Bordeaux (FR). A few winegrowers from Leithaberg (AT) report that some of their plots have vegetation in every inter-row, and some have vegetation in every second inter-row (light green in Fig. 3a). Bare soil inter-rows are reported from Tarnave (RO) and dominating the vineyards from Montilla-Moriles (ES). In inter-rows with vegetation, the duration of the vegetation is more often year-round in the German, Austrian and Romanian case studies (Fig. 3b). Seed mixtures are only used in the German, Austrian and French case studies whereas Tarnave (RO) and Montilla-Moriles (ES) winegrowers only reported spontaneous vegetation in the inter-rows. Spanish winegrowers tend to till the inter-row soils more frequently than those from other case studies (Fig. 3d). Statistical tests between the German, Austrian, Romanian and French case studies show that their medians in soil tillage frequency per year are not significantly different but with different distributions (Table 6). To summarise, the desired management regime of "inter-row vegetation in every inter-row, as year-round cover and with seed mixtures" appears more frequently in Palatinate (DE), Leithaberg (AT), and Bordeaux (FR) than in Tarnave (RO) and Montilla-Moriles (ES).

Pesticide use across case studies is also very heterogenous. Herbicide use in the inter-rows is only occasionally reported in the German, Romanian and Spanish case studies (Fig. 4a and b) and not at all for the French and Austrian case studies. Cross-tabulation showed no relationship between herbicide use in the inter-rows and inter-row management except for Tarnave (RO) where not using herbicides is associated with more inter-row vegetation (Appendix C). Insecticide sprayings (Fig. 4c and d) are most frequent in Tarnave (RO), and pheromone dispensers (Fig. 4e and f) are used in all case studies but with large variation in the number of dispensers per hectare (note that different types of dispensers can be installed requiring different number of devices per hectare). Both insecticide sprayings and the use of pheromone dispensers appear unrelated to inter-row management (Appendix C). Overall, winegrowers from Palatinate (DE) and Leithaberg (AT) apply fewer insecticides and use more pheromone dispensers than winegrowers from other case studies. All winegrowers use fungicides (Fig. 4g and h), and differences in usage of fungicide for organic viticulture vs. synthetic fungicides are considerable. More vegetation in the inter-rows is related with more sulphur-copper-based fungicides and less synthetic fungicides (Appendix C).

Statistical tests for four case studies (Table 6) suggest that both the median and the distribution of each pesticide use are significantly different: Winegrowers in Tarnave (RO) used more herbicides, insecticides, synthetic fungicides, and less pheromone dispensers and organic fungicides than their counterparts in Leithaberg (AT). Winegrowers in Bordeaux (FR) spray more insecticides than their colleagues in Leithaberg (AT). Winegrowers in Palatinate (DE) spray less insecticides and use more pheromone dispensers per hectare than those in Bordeaux (FR) and Tarnave (RO).

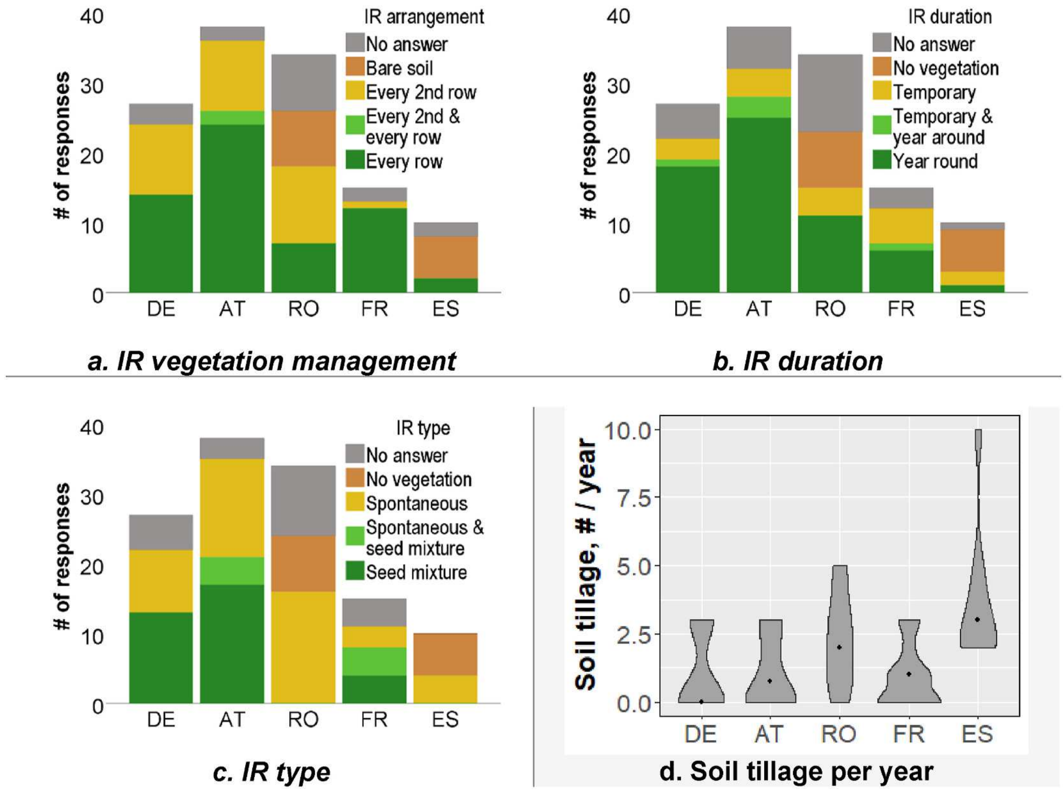

Fig. 3. (a–d): Reported behaviour on inter-row (IR) management (including vegetation and soil tillage) across the case studies. Please note that soil tillage is reported as the frequency of soil tillage in the inter-row within a year, which can result in decimals, e.g., when a winegrower tills 3 times within a 2-year period. The point within the violin plot indicates the median.

4.2. Winegrowers show differences in their attitudes and beliefs towards their behaviour across case studies

Looking at the overall pattern of attitudes and beliefs towards behaviour, we found striking similarities as well as differences between the case studies (Fig. 5). In general, winegrowers state that attitudes and beliefs on the environment and their adaptive capacities are rather important for their decision-making, but economic and social attitudes less so. We hypothesized that inter-row management and pesticide use are inter-related, and indeed, winegrowers mostly strive to make sure their behaviours fit with how their vineyard is managed.

Winegrowers from different case studies (DE, AT, RO, and FR) have different attitudes and beliefs regarding their behaviour on viticultural practices (Table 7) as measured with pair-wise comparisons. These differences mostly relate to the social attitudes and beliefs (10 statistically significant pair-wise comparisons) and less for adaptive capacity (5), economic attitudes and beliefs (1) or environmental attitudes and beliefs (1). Most differences can be traced to differences between Tarnave (RO) and the other case studies, i.e. with Leithaberg (AT) (35%), with Bordeaux (FR) (24%) and with Palatinate (DE) (12%). Regarding the social attitudes and adaptive capacity, differences are also detected between Palatinate (DE), Leithaberg (AT) and Bordeaux (FR) on the one hand and Tarnave (RO) on the other hand. Specifically for the attitude “Follow the behaviour of other winegrowers”, differences exist between almost all pairs. As would be expected, avoiding water competition between inter-row vegetation and vines is very important for winegrowers in Montilla-Moriles (ES) but – surprisingly, also for those in Palatinate (DE) while not for winegrowers in Bordeaux (FR).

4.3. Different drivers of behaviour found across case studies

For each behaviour considered in this research, we identified its driver(s) in a normal year based on the best performing decision tree (Table 8). We did not model the decision-making of herbicides and insecticides for the German and Austrian case studies since these pesticides are rarely used. Neither did we model the use of pheromone dispensers in Palatinate (DE) as almost all surveyed winegrowers use them. To illustrate how the decision trees look like, we provide exemplary trees for a categorical variable and a continuous variable (Fig. 6). All trees with detailed statistics can be found in Appendix E. Appendix D summarises the assessment of prediction performance: Almost all trees perform well with substantial improvements over random models; the exceptions are inter-row vegetation management and number of soil tillage events for RO; duration of inter-row vegetation, number of soil tillage events for DE; and number of soil tillage events for all regions (G).

First, the complexity of trees is lower for a specific case study than for the general cross-region trees. Whereas all behaviours can be explained with very simple trees for the three individual case studies (DE, AT, and RO), more complicated trees resulted for the trees covering all regions (G) (as per number of highlighted variables in Table 8). The increased complexity — from one tree explaining a specific case study to another explaining the generic situation across all case studies — is consistent across all the behaviours examined.

Second, the driver(s) identified to best explain the same behaviour for the three individual case studies (DE, AT, and RO) are mostly different. One of the two exceptions is the behaviour “Inter-row vegetation duration”, for which the explanatory variable inter-row vegetation management (i.e., every row, every second row, or bare soil) is used in both trees for AT and RO. The other is the behaviour “Synthetic fungicide spraying”, for which the variable “Management type” is used for both trees for DE and AT.

Third, winegrowers’ attitudes and beliefs and management properties by far drive most behaviour. Attitudes and beliefs appeared in total 36 times as explanatory variables; management properties followed with 26 times. Winegrowers’ personal characteristics and physical properties of the vineyards each appeared only three times. Specifically,

Table 6
Tests on the median and distribution of the numerical values of different behaviours across respondents from Palatinate (DE), Leithaberg (AT), Tarnave (RO) and Bordeaux (FR). The null hypotheses are **1) The medians** of the values for the behaviour under investigation are the same across case studies, tested using Independent-Samples Median Test; **2) The distribution** of the values for the behaviour under investigation is the same across case studies, tested using Independent-Samples Kruskal-Wallis Test. Significantly different (adjusted p-value at .05 level) pair-wise comparisons from post-hoc analyses with Kruskal-Wallis Test are included in the last column.

Behaviour	Test results on null hypothesis	Post-hoc (Bonferroni correction)
Soil tillage per year	Median ($p = .118$, retain null) Distribution ($p = .033$, rejected)	
Herbicide sprayings per year	Median ($p = .026$, rejected) Distribution ($p = .029$, rejected)	AT-RO ($p = .036$)
Insecticide sprayings per year	Median ($p < .001$, rejected) Distribution ($p < .001$, rejected)	AT-FR ($p = .002$) AT-RO ($p < .001$) DE-FR ($p = .002$) DE-RO ($p < .001$)
Pheromone dispensers per hectare	Median ($p < .001$, rejected) Distribution ($p < .001$, rejected)	AT-RO ($p = .016$) AT-DE ($p = .001$) DE-RO ($p < .001$) DE-FR ($p < .001$)
Fungicide for organic viticulture (copper, sulphur), sprayings per year	Median ($p = .036$, rejected) Distribution ($p = .017$, rejected)	AT-RO ($p = .009$)
Synthetic fungicide sprayings per year	Median ($p = .021$, rejected) Distribution ($p = .022$, rejected)	

some drivers appeared more frequently in the best performing trees than other drivers. “Producing for a label?” was found most frequently (seven times), followed by “Management type” (six times) and “Follow the advice of extension services” (four times).

The results above show the drivers that best explain winegrowers' behaviours in a normal year. Exceptional circumstances may influence pesticide use. Thus, we also included open-ended questions on exceptional pesticide use in the questionnaire. Overall, winegrowers reported weather conditions as drivers for exceptional pesticide use: increased rainfall was reported to result in higher than usual spraying frequencies for all pesticides and decreased rainfall resulted in the opposite; temperature rise increased sprayings for insecticides and fungicides but decreased the use of herbicides (Appendix F).

5. Discussion

With the behaviours and the drivers of behaviours found to differ drastically across European winegrowers, we discuss in the following, how these heterogeneous behaviours and drivers can be understood given their contexts (section 5.1 and 5.2), how farmers' decision-making is better understood by explicitly considering their attitudes and beliefs (section 5.3), and policy implications of our results (section 5.4).

5.1. Reflection on the reported behaviour

Differences in inter-row management (Fig. 3) might reflect a mixture of policy effects, soil properties and climatic conditions, which influence water stress severity. For example, inter-row vegetation in the winter is standard in Palatinate (DE), Leithaberg (AT), and Bordeaux (FR), and some local labels and distribution channels require year-round cover (Table 2). However, despite the subsidy for green cover in Montilla-Moriles (ES), bare soils are dominating the landscape. This is most likely linked to the hot climate and is further backed by the high level of importance to the attitude and belief “Avoid water competition between vines and inter-row vegetation” rated by winegrowers from Montilla-Moriles (Fig. 5). The result is in line with the observation that winegrowers from this area are reluctant to risk their grapevine yield by maintaining vegetation in the inter-rows (Schütte and Bergmann, 2019). Surprisingly, the ratings were less clear in Bordeaux but are also difficult to interpret due to the low number of responses.

The reported use of various pesticides is generally in line with the current regulations (see Fig. 4 and Table 2). One reason for no report of herbicide use in Bordeaux (FR) and Leithaberg (AT) could be linked to the ban of herbicide use in several appellations in Bordeaux (FR) and financial compensation (for not using) in Leithaberg (AT). In addition, the use of the dominant systemic herbicide glyphosate is prohibited by at least one distribution channel and by the local label DAC Leithaberg (AT). In Palatinate (DE) the use of herbicides in the interrow is forbidden and only a small strip under the vine can be treated (in-row application). The few reported cases with herbicide use in the inter-rows from Palatinate (DE) came out surprising, with two possible explanations: either some winegrowers violated the regulation, or they were not aware that the herbicide application was asked for the inter-rows but not the in-rows (the vines).

The fewer applications of insecticides and widespread use of pheromone dispensers in Palatinate (DE) and Leithaberg (AT) could be understood by their policy instruments. In Palatinate (DE) the use of pheromones for mating disruption against grape berry moths is subsidised with 50 €/ha and year if the use of insecticides is avoided. This means de facto insecticide free viticulture on 90% of the vineyard area. In Leithaberg (AT), where only a minority of winegrowers reported insecticide use, winegrowers are financially compensated for not using insecticides. The Austrian agri-environmental programme seemed to be successful in initiating a shift towards less insecticide and herbicide use for many winegrowers (Kieninger et al., 2018). On the contrary, in several locations of the Bordeaux (FR), the use of insecticides against the widespread American grapevine leafhopper (*Scaphoideus titanus)* is mandatory (as it is the vector of a phytoplasma categorized as quarantine pest in the EU), and the majority of the winegrowers there also reported using insecticides against this vector.

For fungicides, the relative lower use in Montilla-Moriles (ES) can be explained by the local climatic conditions where only powdery mildew (*Erisyphe necator*) is a problem so that the number of treatments can be significantly reduced compared to other areas where powdery and downy mildew (*Plasmopara viticola*) can be expected at any time of the growing season.

To summarise, bottlenecks for sustainability are locally different and must be discussed for each behaviour. For fungicide use, Spanish winegrowers are more sustainable than German or Austrian winegrowers, despite the higher share of organic viticulture in the latter two case studies. For insecticides and inter-row management, it is the other way around. Therefore, support programs (such as AESs) must identify and address these locally different bottlenecks and to design targeted instruments.

5.2. Reflection on the reported attitudes and beliefs, and other drivers

Viticulture in Europe is an agricultural practice in which constant adaptations to soil, weather and pest conditions, and the knowledge of human-environment interactions are required to ensure quality production. This is reflected in the overall high importance of winegrowers' attitudes and beliefs towards the environmental and their adaptive capacity (Fig. 5). For adaptive capacity attitudes and beliefs, the high importance of “Respond to current weather conditions” is probably due to the fact that pest species and fungal diseases are highly weather sensitive. For environmental attitudes and beliefs, the most important one is to “Preserve soil quality”. There is room to further improve the awareness of winegrowers on to “Have natural enemies against pests”,

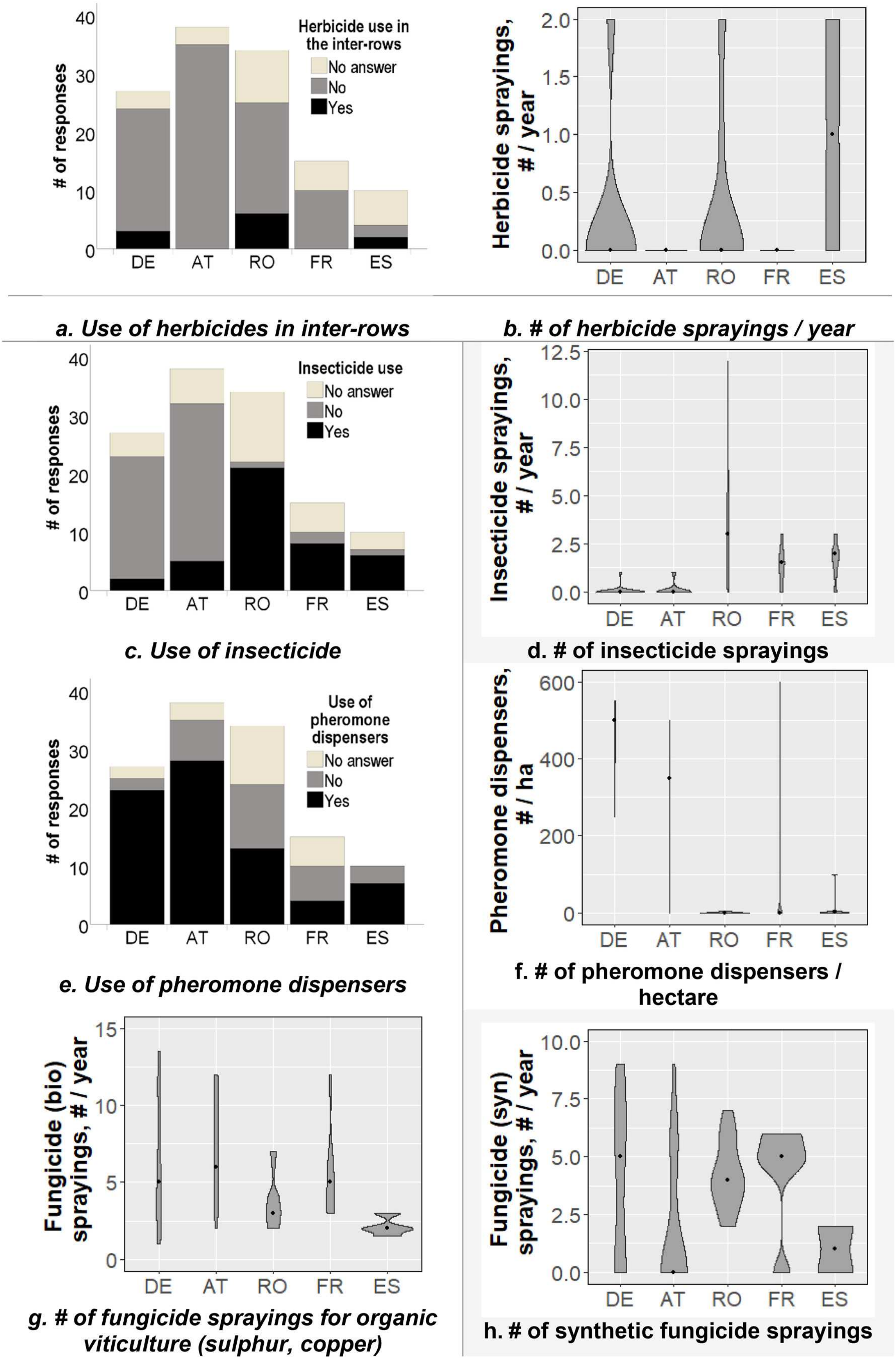

Fig. 4. (a–h): Reported behaviour on various types of pesticide use across the case studies. The points in the violin plots indicate the median.

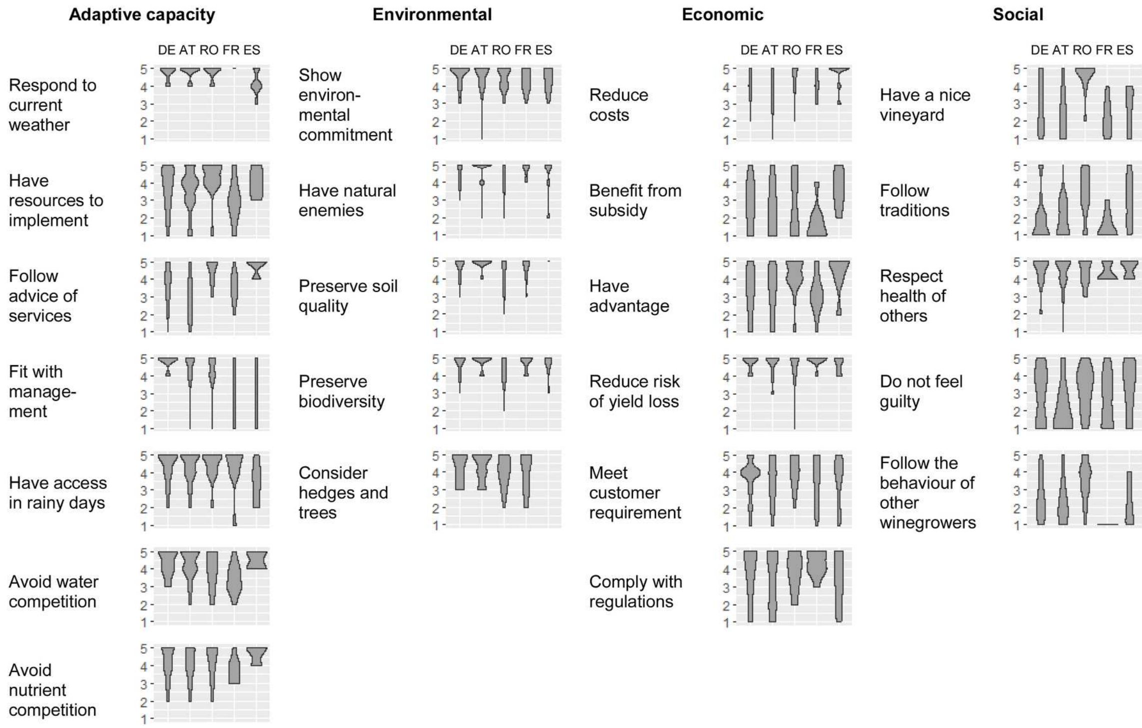

Fig. 5. Violin plots of attitudes and beliefs towards viticultural practices. All plots have a scale (vertical axis) from 1 to 5, representing level of importance. The sequence of plot is from left to right: Palatinate (DE), Leithaberg (AT), Tarnave (RO), Bordeaux (FR), and Montilla-Moriles (ES).

"Preserve biodiversity", and "Consider hedges and trees". For economic attitudes and beliefs, the high importance of "Reduce risk of yield loss" may imply their aversion of large yield reduction and the tendency of preventive pesticide sprayings. For social attitudes and beliefs, the high importance of "Respect health of others" may suggest that the recent debates on public health concerns of pesticide use have raised the awareness among winegrowers (Barbière, 2019; Robert, 2019; Villemaine et al., 2020). Winegrowers could value environmental and certain social attitudes higher than they truly are to them, due to the fact that some winegrowers are also winemakers and direct marketers of their own products.

The outstanding situation for Tarnave (RO) winegrowers with their attitudes and beliefs mostly differing from the rest may indicate a different objective focusing rather on quantity than quality-oriented production. For instance, one Tarnave (RO) winegrower shared they feel a lack of access to materials and knowledge that could improve their viticultural practices (personal communication, January 10, 2020). In this region many small winegrowers sell their grapes to a cooperative and therefore do not invest in marketing activities. Besides, they are the least experienced in viticulture comparing to winegrowers from other case studies (Appendix B), which may cause differences in their attitudes and beliefs. Furthermore, agri-environmental schemes which support pesticide reduction and vegetation cover are until now only rarely implemented in Romanian viticulture. However, we do not exclude the possibility that both winegrowers and their customers in our Romania case study have systemically different attitudes and beliefs towards viticultural practices.

Out of the 23 attitudes and beliefs, 19 of them appear at least once in the best decision trees to explain winegrowers' behaviour (Table 8). The attitudes and beliefs "Follow the advice of extension services", "Fit with how my vineyard is managed", "Have natural enemies against pests", "Preserve biodiversity", and "Reduce costs in material, labour, and machinery" appeared more frequently and therefore have important policy implications (see section 5.4). The importance of knowledge transfer via extension services is argued by Marques et al. (2015), reporting overall a negative opinion of extension services perceived by winegrowers in central Spain and consequently affecting to what extent they can identify soil problems in their vineyards. The extent to which winegrowers perceive behavioural options fit with their current management reflects their adaptation strategies. Neethling et al. (2017) found that French winegrowers prioritised short-term adaptation strategies (via inter-row practices) over long-term options such as to change grapevine varieties and use irrigation. "Preserve biodiversity" relates to "Have natural enemies against pests" and they showed very similar patterns in our case studies (Fig. 5). Márquez-García and colleagues (2019) reported that Chilean winegrowers identified positive relations between winegrowing and biodiversity via pest and disease control. Lastly, viticulture is an economic activity and one way to ensure profitability is via cost reduction. Hadarits et al. (2010) showed that many of the interviewed Chilean winegrowers reported rising cost as a concern while they cannot influence the price. Unwillingness to establish cover crops in the inter-rows due to the costs of seed mixtures and seeding was also expressed by French winegrowers especially when the benefits are unclear to them (Schütte and Bergmann, 2019).

Note that an attitude can still be important for winegrowers but not necessarily useful in distinguishing their behaviours. For example, "Respond to current weather conditions" and "Reduce risk of yield loss" are two very important attitudes and beliefs as reported by winegrowers from our case studies (Fig. 5) and they reflect the empirical evidence from other studies showing the need of adaptation from winegrowers to the environment (Nicholas and Durham, 2012) and their risk aversion (Aka et al., 2018). Another example is the social attitude and belief "Respect health of others", for which winegrowers across our case studies reported a very high importance. We expected this factor to explain winegrowers' behaviour, given the recent debates on public health and societal pressure (Barbière, 2019; Robert, 2019; Villemaine et al., 2020). However, when an attitude (also for other candidate drivers) is perceived rather homogeneously among farmers, it has little use in explaining heterogeneity in their behaviour. For example, we only found the social attitude and belief "Respect health of others" as a driver for winegrowers' use of copper-sulphur based fungicide in Leithaberg (AT), see Table 8. In other case studies, winegrowers indicated very high

Table 7
Kruskal-Wallis tests on the attitude and belief variables with post-hoc analyses showing significantly different pair-wise comparisons (adjusted P < .05). Cases from Montilla-Moriles (ES) were excluded.

Groups	Attitudes and beliefs	Significantly different pair-wise comparison
Adaptive capacity	Respond to current weather conditions	
	Have resources to implement (money, machinery, ...)	FR-RO.
	Follow the advice of extension services	AT-RO, AT-DE.
	Fit with how my vineyard is managed	FR-DE, FR-AT.
	Have access to vineyard in rainy days to spray or to harvest	
	Avoid water competition between inter-row and vine	
	Avoid nutrient competition between inter-row and vine	
Environmental	Show environmental commitment	
	Have natural enemies against pests	
	Preserve soil quality	
	Preserve biodiversity	AT-RO.
	Consider hedges and trees in the surroundings	
Economic	Reduce costs in labour, material (seeds), and machinery	AT-RO.
	Benefit from subsidies	
	Have competitive advantage	
	Reduce risk of yield loss	
	Meet customer requirements	
	Comply with regulations	
Social	Have a nice vineyard	AT-RO, DE-RO, FR-RO.
	Follow traditions	AT-RO, DE-RO, FR-RO.
	Respect health of workers, tourists, neighbours, etc	
	Do not feel guilty	
	Follow the behaviour of other winegrowers	FR-AT, FR-DE, FR-RO, AT-RO.

importance rather homogeneously to this attitude and belief (see Fig. 5). This means that most winegrowers still find respecting the health of others very important (see our earlier discussion), but such importance just did not affect the way they manage their inter-rows and use pesticides. A possible explanation could be that winegrowers do not associate inter-row management options with health risks, and their pesticide use – regardless of the product and frequency – is allowed and justified by current regulations, which does not lead them to feel disrespectful to others. Besides, heterogeneity of a candidate driver is not a guarantee for its explanation power. For example, we expected that differences in how Palatinate (DE) winegrowers manage their inter-rows could be explained by their appreciation of the technical advantages, reflected by the attitudes "Have access to vineyards in rainy days" and "Preserve soil quality" as these advantages are described in every grower's handbook in that region. However, results show that winegrowers' age, whether they produce for a label, and attitudes of "Preserve biodiversity" and "Comply with regulations" were found with the best explanation power.

Besides winegrowers' attitudes, various other drivers were also found to explain their behaviour (Table 8). We draw attention to the following: "Producing for a label" and "Management type", as they appear more frequently than other drivers. Labels are supposed to be indicators of quality and a label can set various protocols for viticultural practices. The management type (organic, integrated, conventional, in transition to organic) has been extensively studied in agricultural systems when it comes to adoption of environmental friendly practices (Kallas et al., 2010; Kuhfuss et al., 2016; Mzoughi, 2011; Siepmann and Nicholas, 2018), and also here is important in understanding the behaviour of winegrowers.

Climate change has important implications for our case studies. Many winegrowers indicated that unusual temperature and precipitation affect how they use pesticides. As most of our case studies are projected to have increased temperature (Malheiro et al., 2010; Santos et al., 2020), increases in the use of insecticides and fungicides are expected. Another effect of climate change is increasingly mild winters. They enable the survival and spread of the invasive alien pest species such as *Scaphoideus titanus* or *Drosophila suzukii*, which originated in America and Asia respectively and are already widespread in European vineyards (Chuche and Thiéry, 2014; Rombaut et al., 2021; Santos et al., 2020). Invading alien pests may trigger an increase in the use of pesticides, especially if they are categorized as quarantine pest transmitting vectors (like *Scaphoideus titanus*) which oblige all winegrowers to use insecticides. Therefore, the effects of climate change for European viticulture concern not only possible shift in growing regions (Santos et al., 2020) and changes in grapevine yields (Fraga et al., 2016) but also increasing pest/disease control pressure for the current viticultural landscape.

Overall, the selected drivers (Table 8) were based on the best performing decision trees. These decision trees in general have not only good model performance (Appendix D) but also reasonable logic behind. For example, winegrowers from Leithaberg (AT) who value "Preserve soil quality" more are more likely to have vegetation in every row instead of every second row; winegrowers from Tarnave (RO) who offer tourism activities are more likely to have vegetation in every row than those who do not; winegrowers from Palatinate (DE) who value "Have natural enemies against pests" more are more likely to have year round vegetation cover in the inter-rows instead of having temporary vegetation; and winegrowers from Tarnave (RO) who value "Reduce costs" more report to spray insecticide less frequently (see tree 1.2, 1.3, 2.1, and 6.3 respectively in Appendix E). Such good model performance and logic confirm our choice of method and create potential for further applications of these models.

5.3. Understanding farmers' decision-making

This study demonstrates how winegrowers' decision-making can be understood via their personal characteristics including attitudes and beliefs, as well as physical and management characteristics of their vineyards. Results contribute to the literature on farmers' decision-making (Bartkowski and Bartke, 2018; Dessart et al., 2019) by explicitly connecting attitudes and beliefs (Demartini et al., 2017; Fruitos et al., 2019; Marques et al., 2015; Siepmann and Nicholas, 2018; Urquijo and De Stefano, 2016) with actual behaviour (Forbes and de Silva, 2012; Kallas et al., 2010; Marquez-García et al., 2019; Micha et al., 2015; Schütte and Bergmann, 2019). Much of the previous studies deals with a binary decision – e.g., converting to organic farming, enrolling in an agri-environmental scheme (AES) – that is usually long-term or within a certain time window of intervention. Such knowledge is important because there are prescribed behavioural rules (for organic farmers and AES participants) which have benefits for environmental sustainability. Our study enriches the literature by zooming into specific behaviours (i. e., inter-row management and pesticide use) that need to be practised by winegrowers regularly (e.g., at least yearly for inter-row management and within the growing season for pesticide use). The behaviours investigated in this study are only partially bounded by organic farming (banning herbicides, insecticides, and synthetic fungicides) and AESs (which may have different focuses on soil, water, biodiversity, etc; and consequent indication for inter-row management). Therefore, it would be insufficient to understand differences in how winegrowers manage their inter-rows and use pesticides by only looking at if they are organic

Table 8

Overview of drivers to explain behaviours for Palatinate (DE), Leithaberg (AT), Tarnave (RO), and all regions (G) based on the best performing tree, grouped by personal (grey), physical (blue), management (orange) and attitudes and beliefs in adaptive capacity, environmental, economic, and social (shades of green). Each driver is provided with the number of times it appears in the 31 best performing decision trees. IR: Inter-row vegetation. Bio.: copper-sulphur based fungicide. Syn.: synthetic. *: only used as candidate drivers for IR duration and type. Results are from 31 best performing decision trees out of 3100 iterations.

	IR management				IR duration				IR type				Tillage				Herbicide		Insecticide		Pheromone			Bio. fungicide				Syn. fungicide			
	DE	AT	RO	G	DE	AT	RO	G	DE	AT	RO	G	DE	AT	RO	G	RO	G	RO	G	AT	RO	G	DE	AT	RO	G	DE	AT	RO	G
Age (1)	■																														
Experience in viticulture (2)				■																■											
Average slope (1)				■																											
Lack of water? (1)																							■								
Soil erosion? (1)																															■
Management type (6)												■												■			■	■	■		■
Number of varieties (2)																	■			■											
UAA for viticulture (2)												■								■											
Do you offer activities for tourists? (3)			■																			■	■								
Harvesting method (1)														■																	
Producing for a label? (7)					■					■		■	■												■		■			■	
IR management* (5)						■	■	■			■	■																			
Follow the advice of extension services (4)				■												■	■								■						
Fit with how vineyard is managed (3)								■									■										■				
Have access in rainy days (2)								■										■													
Avoid water competition (2)				■																	■										
Avoid nutrient competition (1)										■																					
Have natural enemies against pests (3)				■	■																										■
Preserve soil quality (2)		■													■																
Preserve biodiversity (3)								■	■				■																		
Show environmental commitment (1)				■																											
Reduce costs (3)																			■				■				■				
Benefit from subsidies (2)															■					■											
Have competitive advantage (1)															■																
Meet customer requirement (1)							■																								
Reduce risk of yield loss (2)								■				■																			
Comply with regulations (1)									■																						
Have a nice vineyard (1)																										■					
Follow traditions (2)																		■										■			
Respect health of others (1)																									■						
Do not feel guilty (1)														■																	

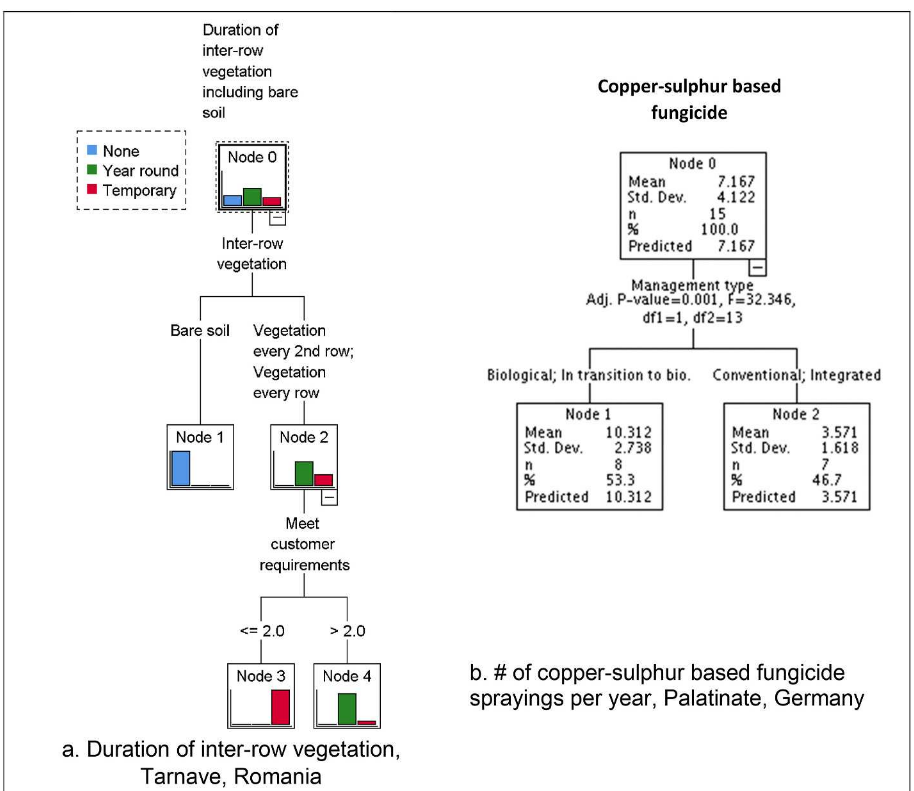

Fig. 6. (a–b). Examples of decision trees. Note for b) organic winegrowers can only use copper-sulphur based fungicides; non-organic winegrowers may also use such fungicides to reduce their applications of synthetic fungicides.

or AES participants. When investigating how winegrowers manage their inter-rows and use pesticides in five European viticultural landscapes, we find large variability beyond a simple distinguishing of conventional vs. organic farmers.

By explicitly accounting for 23 attitudes and beliefs in four groups (adaptive capacity, environmental, social, and economic) of winegrowers, we have the following reflections. First, despite that winegrowers overall reported higher importance for their environmental attitudes than the economic ones (Fig. 5), the biodiversity-friendly measures such as year-round vegetation in the inter-rows and using seed mixtures are not yet widely adopted (Fig. 3). This may result from the interaction effect due to differences in their adaptive capacity and social attitudes (Fig. 5), current policy (Table 2) and management properties (Appendix B). Second, it is known that many winegrowers, such as in Germany, Austria and part of France artificially reduce grapevine yields to achieve better quality, as in these regions vines are very productive. In regions with yield limitations or when winegrowers are only selling grapes or bulk wine, such as in part of Romania and Spain, they usually can not afford to suffer from yield loss. This is commonly recognised by local experts from our case studies. One might expect the reported importance for the attitude "Reduce risk of yield loss" to reflect such difference. However, winegrowers across the case studies ranked overall high importance to this attitude (Fig. 5), indicating their risk aversion. This is because the attitude was asked in association with their bad past experiences (see Appendix A) but not under normal circumstances. Such risk aversion (to yield loss) can also be reasonably claimed for their aversion to grapevine quality loss, when it comes to inter-row management and pesticide use for winegrowers who prioritise quality production over quantity. Therefore, undesired loss (of yield and quality) in grapevine due to the implementation of the desired greener inter-rows and less pesticide-intensive viticulture should be addressed by future regulations.

As we move from one case study to another, factors that best explain a behaviour change. Consequently, as we aggregate all case studies to find a generic European model that explains their behaviour, more factors are needed in comparison to the model that only explains an individual case study. The increase in complexity reflects differences of climate, soil, socio-economic, and regulation across the European vineyards. Such heterogeneity and complexity have implications for policies.

5.4. Policy implications

Increasing the adoption of (diverse) vegetation cover in the inter-rows and reducing the use of pesticides of European vineyards is a challenging task towards environmental sustainability. Results from our case studies show that there is room for further adoption of vegetation cover and reduction of pesticide use. The EU has the goal to halve the use of pesticides and to increase the share of organic farming to 25% by 2030 (European Commission, 2020a). Based on our results, we can indicate that labels and appellations might be influential to achieve these goals, as well as targeting winegrowers' attitudes. However, since considerable heterogeneity exists between cases, context-specific adaptations of EU policies may be needed.

Our results suggest that certification, i.e. producing for a label, can strongly affect winegrowers' decisions on inter-rows and pesticides for different behaviours in all cases. This is in line with a recent study on the French Languedoc-Roussillon region where inter-row vegetation management appeared not to be linked to water stress or soil quality but rather with labels of quality wine production (Fernández-Mena et al., 2021). Certifications include those labels that stand for both quality and origin, such as the French system of *Appellation d'Origine Contrôlée* (AOC), the Austrian system of *Districtus Austriae Controllatus* (DAC), both as country-level quality categories of the EU wine labels of *Protected Designation of Origin* (PDO), and labels that indicates environmentally-friendly viticulture such as organic wine produced according to the Regulation of the European Commission no. 203/2012, or biodynamic labels such as Demeter and BIODYVIN. Each of these labels has specific rules for winegrowing and winemaking and may adapt to changing situations. Therefore, certified production including organic viticulture could be used to complement state-led policy instruments to steer behaviour of winegrowers if no other major barriers exist locally.

Despite the desired increase of organic farming in EU viticultural landscapes, it does not solve the problem of reducing fungicide use. Under the current regime, synthetical fungicides used by conventional winegrowers require less frequent sprayings and quantity of active substances per hectare, compared to the use of copper and sulphur by organic winegrowers which also have detrimental effects on different soil organisms and natural enemy groups like predatory mites (Costello, 2007). Therefore, stakeholders should not expect that pesticides use as a whole can be reduced easily in European viticulture as a significant part of the pesticides used are fungicides. Alternative approaches - outside the scope of this analysis - could be to improve current decision support systems reporting infection risks (Redl et al., 2021) and to adopt mildew-resistant grape varieties (Pertot et al., 2017). Mildew-resistant varieties which significantly reduce fungicide use, however, are very rarely planted in the EU and reported by our surveyed winegrowers. This may be due to appellations mostly not allowing the use of resistant varieties; for example, in France, wines produced with such varieties can only be labelled as "Vins de France" but not as other popular local appellations. As we find that much of winegrowers' behaviours are affected by labels and certifications, their regulations are currently also barriers to achieve less fungicide intensive viticulture.

Our study shows that attitudes and beliefs also contribute to explaining - and potentially changing - winegrowers' behaviour. Other studies indicated that environmental awareness and additionally the behaviour of other farmers may positively affect farmers' intention to reduce pesticides and offset the consequently increased perception of risk (Bakker et al., 2021; Kieninger et al., 2018). While our results confirm the importance of environmental attitudes, we do not see a strong influence of the behaviour of others (i.e., descriptive norms) on explaining their behaviours, possibly because we do not specifically ask for the importance of pioneers' behaviour.

In this study we do not report on the full spectrum of winegrowers' behaviours and drivers of behaviour in Europe. We have not covered all European wine-producing regions and did not study variation of behaviours and drivers within a country in our study, as we only analysed one case study region per country. Furthermore, the COVID-19 pandemic restricted our data collection and might have introduced self-selection bias, especially into our online sample, as winegrowers already interested in environmental issues might be more likely to answer such a questionnaire.

6. Conclusions

European viticulture is evolving at the interplay of many factors including traditions, edaphoclimatic conditions, climate change, public awareness, and pressure on environmental sustainability. By investigating differences in, and drivers of, inter-row management and pesticide use across five European winegrowing regions, we demonstrate the importance of including attitudes and beliefs to understand farmers' behaviours and find that differences in their behaviours are explained by different drivers cross these regions. Our results also show that there is still scope for further increasing the extent (surface area and duration) and diversity of vegetation cover and reducing the use of pesticides to improve ecosystem service provision and increase biodiversity. However, it will be important to take local bottlenecks for more sustainable behaviours, such as climatic conditions, into consideration when designing policies. As a greener and less pesticide-intensive viticulture is envisioned for Europe via the Green Deal, both challenges and opportunities exist given the current regulations, label requirements (certified organic viticulture, labels of quality wine or protected origin), climate change, and the trade-off between winegrowers' economic and environmental objectives. In the long term, the goal to further increase vegetation cover in the inter-rows and reduce pesticide use require efforts from more stakeholders than winegrowers themselves. To summarise, we provide two take-home messages for European viticulture. First, winegrowers' behaviours can differ significantly both within and across regions, and behaviour can be better understood by including their attitudes and beliefs. Second, policy instruments need to take local bottlenecks for more sustainable behaviours into consideration, likely moving beyond the current NAPs. Further research should investigate to what extent these findings can be generalised to other types of agricultural production, given the specifics of viticulture such as tradition and less importance of prices.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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