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ORIGINAL ARTICLE

Assessing local climate vulnerability and winegrowers' adaptive processes in the context of climate change

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Abstract Adaptation to climate change is a major challenge facing the viticulture sector. Temporally, adaptation strategies and policies have to address potential impacts in both the short- and long term, whereas spatially, place-based and context-specific adaptations are essential. To help inform decision-making on climate change adaptation, this study adopted a bottom-up approach to assess local climate vulnerability and winegrowers' adaptive processes in two regulated wine-producing areas in the Anjou-Saumur wine growing sub-region, France. The data used for this study were collected through individual semi-structured interviews with 30 winegrowers. With a focus on wine quality, climate-related exposure, and sensitivity were dependent on many contextual factors (e.g., northern geographical position, wine regulatory frameworks, local environmental features) interacting with the regional oceanic climate. Climate and other non-climate-related variables brought about important changes in winegrowers' management practices, varying in time and space. This ongoing process in decision-making enhanced winegrowers' adaptive responses, which were primarily reactive (e.g., harvesting, winemaking) or anticipatory (e.g., canopy and soil management) to short-term climate conditions. Winegrowers described changing trends in climate- and grapevine (*Vitis)* -related variables, with the latter attributed to regional climate changes and evolving management practices. Regarding future climate trends, winegrowers' displayed great uncertainty, placing the most urgent adaptation priority on short-term strategies, while changing grapevine varieties and using irrigation were identified as last resort strategies. The study concluded by discussing the implications of these findings in the context of climate change adaptation in viticulture.

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1 Introduction

Climate change, its causes and impacts have received considerable attention in the last few years. For most parts of the world, long-term climate records have shown rising land and ocean temperatures together with shifting patterns in rainfall and extreme weather events (Easterling et al. 2000; Alexander et al. 2006; Jones et al. 2012; IPCC 2014). Attributed to natural and anthropogenic forcings, the observed changes in climate, especially warming trends, are projected to become more apparent and severe with time (IPCC 2014). With the effects of a changing climate already visible on many natural and human systems, mitigation and adaptation arise as two key policy responses to climate change (Smit et al. 1999; IPCC 2014), operating at different spatial and temporal scales (Tol 2005; Füssel and Klein 2006). As mitigation deals with reducing greenhouse gas emissions, it is more beneficial, lessening the causes and impacts of climate change on a global scale (Füssel 2007). Yet, because of the long time lags involved in climate processes and feedbacks, the effects of mitigation efforts may take many years to manifest, irrespective of their extent and intensity (Meehl et al. 2012; IPCC 2014). Adaptation to climate change is therefore unavoidable, becoming an immediate priority across all climate-sensitive sectors (Smit et al. 1999; Füssel 2007; IPCC 2007).

Viticulture is one of those sectors most sensitive to both short- and long-term climate changes (Jones and Webb 2010). A wine growing region's long-term climate structure largely determines its grape *(Vitis)* growing and winemaking potential (Tonietto and Carbonneau 2004), where short-term climate variations are key factors influencing seasonal grape and wine production (Jackson and Lombard 1993). For many wine-growing regions, significant trends in regional climates have already been described (Jones and Davis 2000; Duchêne and Schneider 2005; Jones et al. 2005; Ramos et al. 2008; Bock et al. 2011; Tomasi et al. 2011; Webb et al. 2011; Neethling et al. 2012; Sturman and Quénol 2013; Koufos et al. 2014). These studies also indicated important changes in grapevine phenology (i.e., timing of growth stages) and grape composition, with the latter leading to increased alcohol levels and altered wine sensory profiles (Orduna 2010; Fraga et al. 2012). Although these changes in grapevine behavior are partly attributed to evolving practices, recent warming trends and declining soil water contents have been major causal factors (Webb et al. 2012). Hence, continued climate change is very likely to have significant effects on regional wine quality and style, which over the long term may cause geographical shifts in suitable grapevine varieties and production areas (Kenny and Harrison 1992; Schultz and Jones 2010; Mozell and Thach 2014). Rising temperatures, especially during winter months, could also increase pest and disease risks (Porter et al. 1991; Salinari et al. 2006; Caffarra et al. 2012), to which grapevines are very susceptible.

Climate change therefore brings about many potential environmental and socio-economic risks, or opportunities for cool climate regions, to which winegrowers are increasingly required to respond (Holland and Smit 2010, Quénol 2014). While the practice of adaptation has always been a characteristic feature of viticulture (Metzger and Rounsevell 2011), adaptation to climate change remains a relatively new and uncertain process, involving complex temporal and spatial challenges. Due to the perennial nature of grapevines, adaptation strategies and policies must account for both short- and long-term impacts of climate change, where adjustments undertaken will need to be place-based and context-specific (Quénol 2014). In dealing with these cross-scale issues, the understanding of a system's vulnerability to climate change is essential to facilitate and enhance the process of planning adaptation (Kelly and Adger 2000; Ford and Smit 2004). Depending on how vulnerability is interpreted, the resulting understanding of vulnerability and, in particular, that of its interrelated components (exposure, sensitivity and adaptive capacity) will provide decision-makers (e.g., farmers, local governments) with a framework to help identify and prioritize adaptation strategies and policies (Adger 2006; IPCC 2007; O'Brien et al. 2007).

Within this perspective, many outcome vulnerability assessments have been carried out in wine-growing regions (Webb et al. 2007; Duchêne et al. 2010; Malheiro et al. 2010; Hannah et al. 2013; Fraga et al. 2015). Following a top down approach that involves a sequence of successive steps, these assessments place high dependence on regional climate projections and biophysical impacts analyses to evaluate adaptation options to climate change (Dessai and Hulme 2004; O'Brien et al. 2007). In dealing mainly with the natural aspects of a system, such assessments minimize the social and human dimensions of vulnerability (O'Brien et al. 2007), indicating therefore a wide range of potential rather than actual adaptation options (Smit and Wandel 2006; Crane et al. 2011). Accordingly, contextual vulnerability assessments have emerge as a key concept to inform adaptation to climate variability and change (Kelly and Adger 2000; Brooks 2003; Ford and Smit 2004; Smit and Wandel 2006). Variations of these assessments have also more recently been conducted in a few wine-growing regions (Belliveau et al. 2006; Hadarits et al. 2010; Webb et al. 2010; Nicholas and Durham 2012; Holland and Smit 2013; Lereboullet et al. 2013). Using a bottom-up approach (Dessai and Hulme 2004), they account more explicitly for the internal and external factors and processes (e.g., physical, social, economic) defining exposure, sensitivity, and adaptive capacity to changing conditions (Ford and Smit 2004; Crane et al. 2011). This is of particular importance in the viticulture sector as grape and wine quality are much attributable to the unique and local characteristics of its geographical location (White et al. 2009; Metzger and Rounsevell 2011), where winegrowers' decision-making play a significant role (Van Leeuwen and Seguin 2006; Van Leeuwen et al. 2013).

In order to assist the viticulture sector more accurately in planning adaptation to climate change, there is a need for more detailed understanding of contextual vulnerability (Holland and Smit 2010). Therefore, by adopting a bottom-up approach, the aim of this study is to assess local climate vulnerability and winegrowers' adaptive processes in two regulated wine-producing areas in the Anjou-Saumur wine-growing sub-region, France. The study starts by presenting the multifaceted and dynamic nature of decision-making processes in viticulture (Fig. 1). This conceptual framework illustrates the structure and timing of perennial and annual management practices, along with the characteristics of the ongoing adaptation process. Then, from the qualitative data obtained through semi-structured interviews with 30 winegrowers, the study results are divided in four separate sections. The first section deals with the exposure and sensitivity of wine quality to past and current climate conditions. The second and third sections analyses, respectively, the changes in viticultural practices over recent decades and winegrowers' adaptive responses to climate conditions. Finally, for the fourth section, the perceptions and adaptation priorities of winegrowers to potential future climate changes are evaluated. The study concludes by discussing the implications of these findings in the context of climate change adaptation in viticulture.

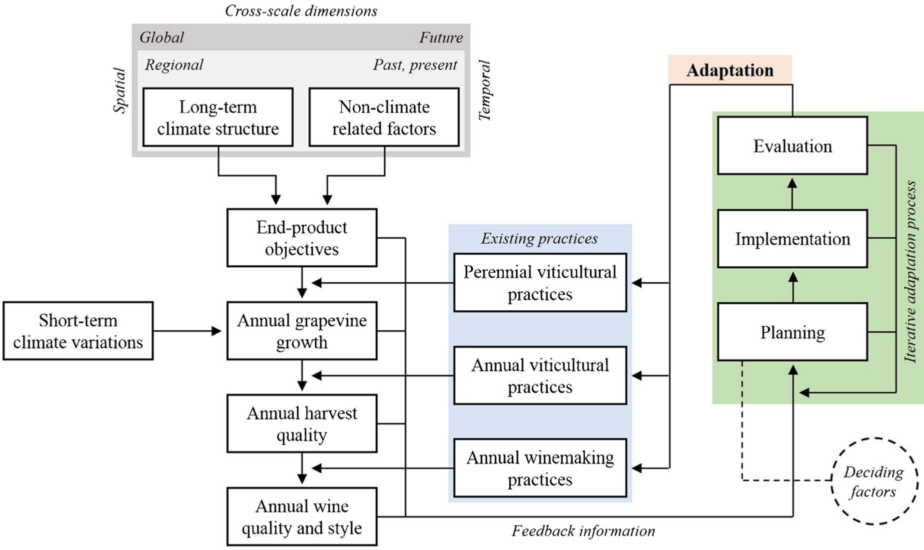

Fig. 1 Conceptual framework of the multifaceted and dynamic nature of decision-making processes in viticulture (adapted from Klein et al. 1999; Coulon-Leroy et al. 2012)

2 Conceptual framework

The grapevine is cultivated over a wide range of environmental conditions, where its fruit is primarily used for winemaking (OIV 2015). As a perennial specie, the grapevine requires a few years to reach reproductive maturity, remaining then economically productive for many years (Orlandini et al. 2009). Therefore, prior to planting, winegrowers' decisions in terms of perennial practices are very important, e.g., selection of planting site, vineyard layout, and choice in grapevine or rootstock varieties (Coulon-Leroy et al. 2012). At this level, decision-making is closely related to how winegrowers conceptually perceive their end-product objectives (Fig. 1), i.e., a wine with a distinct structure, style, and sensory profile (Cadot et al. 2012). This conceptual perception is a function of the long-term climate structure of a wine-growing region, as each grapevine variety has specific climate requirements to reach optimal ripeness. In general, cool climate regions are best suited for early ripening varieties and warm climate regions for late ripening varieties (Huglin and Schneider 1998). Climate inevitably play an important role, yet winegrowers' decision-making is likewise strongly driven by the role of multiple non-climate-related variables (Belliveau et al. 2006), such as global or national market trends, regional production regulations, local historical contexts, etc. Indeed, quality-orientated wine production is only achieved by considering both environmental and socio-economic conditions (Van Leeuwen and Seguin 2006). Once winegrowers have decided upon their conceptual end-product objectives, they will take the necessary measures to implement the most appropriate perennial practices that should favor grapevine growing, grape ripening and therefore, quality wine production.

Thereafter, annual viticultural practices, e.g., soil, disease and canopy management, are constantly required to manage, among other factors, seasonal climate variability (Jackson and Lombard 1993; Hunter et al. 2010; Coulon-Leroy et al. 2012). Over time, short-term variations in climate factors, such as sunshine hours, heat units, rainfall amounts, or frost events, strongly influence grapevine growth and development (Tesic et al. 2002; Van Leeuwen et al. 2004;

Carey et al. 2008; Hunter and Bonnardot 2011). For instance, in the absence of adverse events (e.g., droughts, diseases), heat unit accumulation plays a decisive role in the seasonal rhythm of grapevine phenology and grape ripeness (Jones and Davis 2000; Parker et al. 2013). Under a same regional climate, grapevine behavior is also much dependent, directly or indirectly, on the differences in local environmental features. The rate of biochemical change in grape berries (e.g., sugar accumulation, decline in acidity) is likewise a function of climate conditions during grape ripening (Keller 2010). As wine structure and flavor are much dependent on grape attributes at harvest (Cadot et al. 2012; Bindon et al. 2013), winegrowers closely follow the grape-ripening process in order to adjust their harvest management practices (i.e., harvest timing and technique) and pick grapes at the most adequate period. Finally, within the conceptual perception of end-product objectives, winegrowers will use an array of winemaking techniques to produce quality wines with distinct styles (Coulon-Leroy et al. 2012).

Over time and across space, winegrowers are continually dealing with multiple environmental and socio-economic issues (Belliveau et al. 2006). Decision making in viticulture is an ongoing process, where winegrowers perform various forms and types of autonomous adaptation measures, through adjusting existing practices (Fig. 1). Adaptation is an iterative process, following several steps (Klein et al. 1999). The first step involves collecting feedback information, which will either confirm or refute the assumptions made prior to planting. For instance, comparing actual, produced wine quality with conceptual, planned wine quality (Coulon-Leroy et al. 2012). Feedback information can also include changing external factors (e.g., market conditions or trends), which may have incidences on the conceptual perception of end-product objectives. As feedback information is collected at different outcome levels, the next step is to plan or design an appropriate response that depends on many deciding factors (Klein et al. 1999). They are, e.g., the technical, economic and legal feasibility of identified adaptation initiatives. The final two steps involves respectively implementation and evaluation, allowing further corrections or improvements to be made, before winegrowers eventually bring about an adjustment to the corresponding existing practice.

3 Study area and methodology

3.1 The Anjou-Saumur wine-growing sub-region

Located at the 47-degree northern latitude, the Loire Valley wine-growing region stretches east to west from the center of France to the Atlantic Ocean, following the course of the Loire River. In France, it is the third largest regulated wine-producing region, the principal producer for white wine and the second for sparkling wine (Barbeau 2008). The Loire Valley is divided into five wine-growing sub-regions. From west to east, they are Pays Nantais, Anjou-Saumur, Touraine, Centre-Loire, and Auvergne. Anjou-Saumur is the largest sub-region with a vineyard surface area of 19,700 ha and an annual production of around 135 million bottles of wine. It accounts for 37 % of the Loire Valley's total surface area and 31 % of its total wine production (InterLoire 2010). Diversity is one of the main strengths of Anjou-Saumur. With distinctive landscape features, the presence of the Loire River and its tributaries, contrasting geo-pedological situations and eight different grapevine varieties, winegrowers produce high quality red, white or rosé, still or sparking, dry or sweet wines (Barbeau 2008). Therefore, 30 different wine-producing appellations are recognized within this sub-region, where Chenin and Cabernet Franc are respectively the main white and red varieties. Wine-producing appellations in France are called "Appellation d'Origine Protégée" (AOP), meaning "protected designation of origin." Created in 1935, French wine appellations are managed by the National Institute for Quality and Origin (INAO), assuring the produced wine's origin and its compliance with the quality requirements determined by each appellation. Wine-producing appellations define and regulate production area boundaries, acceptable grapevine varieties, viticultural practices (e.g., planting density, grape yield), and wine production in terms of quality and typicality. The latter refers to the concept of family resemblance, where the produced wine should have a set of biochemical and sensory attributes that are strongly related to its geographical origin (Cadot et al. 2012). These strict regulatory frameworks play an important role in Anjou-Saumur, where 90 % of its total vineyard surface is produced within the regulations of the 30 wine appellations (InterLoire 2010).

3.2 Study areas

In order to take into account contrasting environmental conditions, management practices, and regulatory frameworks, two wine-producing appellations in Anjou-Saumur were selected for this study, namely the AOP Coteaux du Layon and AOP Saumur Champigny (Fig. 2). The AOP Coteaux du Layon, established in 1950, is situated on moderate to steep slopes, following the course of the Layon River (Table 1). Although the demarcated geographical area stretches over 27 villages, the demarcated vineyard area only covers 1400 ha. These vineyards are mainly planted on shallow slate soils, containing low to moderate water reserves. Appellation regulations only allow sweet white wines to be produced from Chenin grapes, harvested after an over-ripening process. As is often the case within the French wine classification system, the AOP Coteaux du Layon is subdivided into smaller wine appellations, where quality and production regulations increase with the appellation hierarchy. For the same grape variety (i.e., Chenin), the appellation classifications in ascending order are as follows: Generic Coteaux du Layon, Communal Coteaux du Layon, Premier Cru Chaume, Bonnezeaux, and Grand Cru Quarts de Chaume. The AOP Saumur Champigny was established in 1957 and covers a demarcated vineyard area of 1500 ha that consists mainly of flat plains and moderate slopes, next to the Loire River. This sedimentary basin is primarily characterized by deeper

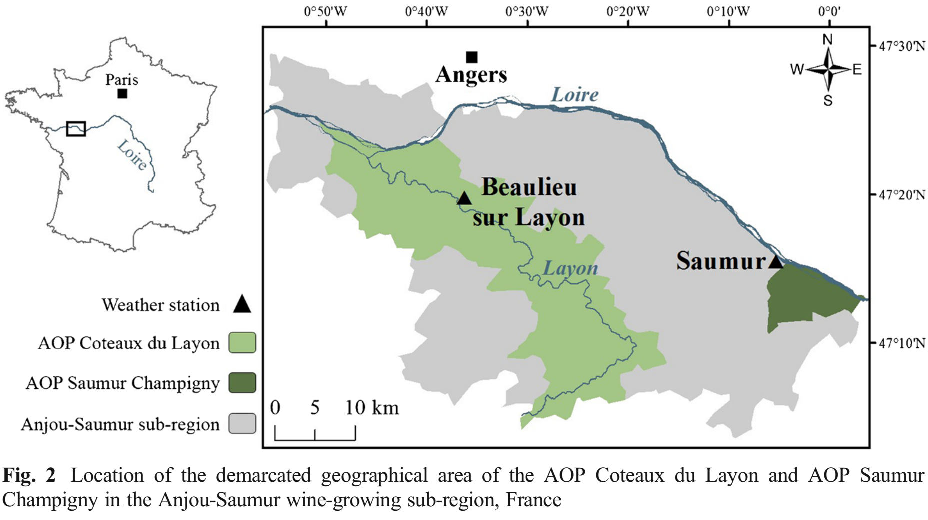

Fig. 2 Location of the demarcated geographical area of the AOP Coteaux du Layon and AOP Saumur Champigny in the Anjou-Saumur wine-growing sub-region, France

Table 1 Primary environmental and regulatory characteristics for the AOP Coteaux du Layon and AOP Saumur Champigny

Study areas	Surface (ha)	Rock formation	Soil properties	Landscape features	Grapevine variety	Wine style
AOP Coteaux du Layon	1400	Metamorphic and volcanic	Shallow slate soil	Steep to moderate slopes	Chenin	Sweet white wine
AOP Saumur Champigny	1500	Sedimentary	Deep calcareous soil	Flat plains and moderate slopes	Cabernet Franc	Dry red wine

calcareous soils, containing moderate to high water reserves, where appellation regulations only allow the production of dry red wines. These wines are produced essentially from Cabernet Franc, with a permitted addition of up to 15 % of Cabernet Sauvignon or Pineau d'Aunis.

For the Anjou-Saumur sub-region, the demarcated geographical boundaries of the different wine-producing appellations overlap. The latter means that winegrowers from Coteaux du Layon may produce dry white or sparkling wines from Chenin, while winegrowers from Saumur Champigny can produce generic red, rosé or sparkling wines from Cabernet Franc. Moreover, both study areas also provide relevant information on grape growing for neighboring wine-producing appellations in Anjou-Saumur, as well as for neighboring sub-regions in the Loire Valley. While winemaking techniques and regulatory frameworks are unique for each wine appellation, the environmental characteristics (rock formation, soil properties, landscape features) of Coteaux du Layon are similar to the conditions and constraints for grape growing in the western part of Anjou-Saumur and in the Pays-Nantais sub-region. On the other hand, the sedimentary basin of Saumur Champigny is a good representation of the conditions and constraints for grape growing in the eastern part of Anjou-Saumur and in the sub-regions of Touraine and Centre-Loire.

3.3 Climate structure, variability, and trends

The Anjou-Saumur wine-growing sub-region, encompassing the vineyards of the two study areas, benefits from a temperate oceanic climate, with mild winters, cool summers, low annual temperature ranges, and a regular rainfall pattern throughout the year (Peel et al. 2007; Quénol et al. 2008). As with Anjou-Saumur, both study areas have a warmer and particularly drier climate, compared to the rest of the Loire Valley (Dubreuil 1996). The Mauges hills, located towards the southwest, partially shelter the vineyards from incoming Atlantic disturbances and lead to a lower annual rainfall. From 1988 to 2012, the growing season average temperature (i.e., GST, April-September) was 17.0 °C in Beaulieu sur Layon and 17.4 °C in Saumur, while the growing season average rainfall (i.e., GSR) was 263 mm in Beaulieu sur Layon and 279 mm in Saumur. These two weather stations are closely located to the vineyards of both study areas, forming part of the regional network of Météo France (Fig. 2). Historical climate records in Beaulieu sur Layon and Saumur illustrate a strong climate variability from 1988 to 2012 (Fig. 3). For both locations, the warmest season was in 2003, the coolest in 1988, and the

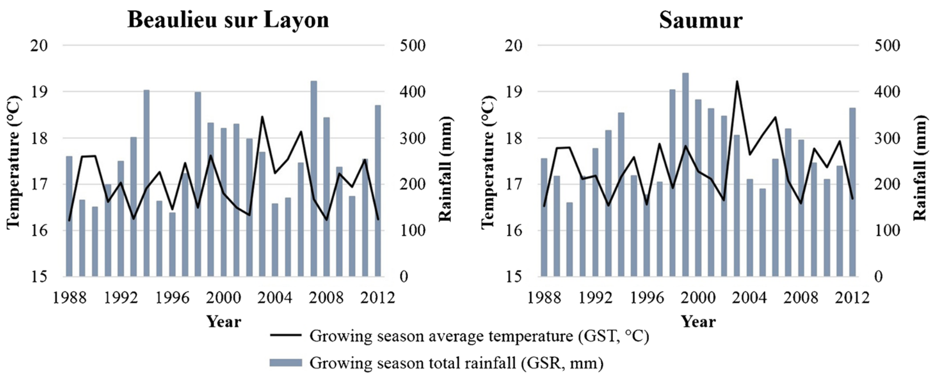

Fig. 3 Growing season (April-September) average temperature and total rainfall in Beaulieu sur Layon and Saumur from 1988 to 2012 (Data source, Météo France)

driest in 1990, whereas the wettest was observed in 2007 in Beaulieu sur Layon, and in 1998 in Saumur.

During the second half of the twentieth century, significant warming trends were observed for the Anjou-Saumur wine-growing sub-region (Bonnefoy et al. 2012; Neethling et al. 2012). In Angers (Fig. 2), annual and growing season average temperatures increased by 1.5 and 1.7 °C, respectively, from 1950 to 2010. Rising temperatures meant that the 30-year GST in Angers increased from 15.6 °C (1951–1980) to 16.6 °C (1981–2010). Trends in average temperatures were accompanied by a decrease in spring frost days and an increase in hot summer days. Although total annual and seasonal rainfall strongly varied over time, no significant long-term shifts in rainfall patterns were documented. A warmer regional climate affected grapevine behavior for the main white and red grapevine varieties cultivated in Anjou-Saumur (Neethling et al. 2012). For these varieties, earlier phenological stages and harvest dates (14 days earlier on average) were observed, along with higher sugar contents and lower acidity levels in grape berries at harvest. Overall, recent temperature increases have been favorable for grapevine behavior and wine quality in Anjou-Saumur, especially for the moderate-late ripening varieties Chenin and Cabernet Franc.

3.4 Data collection and analysis

3.4.1 Participating winegrowers

Thirty winegrowers (i.e., producers of both grapes and wines) participated in this study. From each study area, 15 winegrowers were selected according to their seniority, geographical position, farm size, and whether the companies were family owned or privately held. Farm sizes varied from 6 to 55 ha for Coteaux du Layon and from 12 to 48 ha for Saumur Champigny, whereas for differences in production strategies, there were four conventional, seven integrated, and four organic farms from Coteaux du Layon and five conventional, seven integrated, and three organic farms from Saumur Champigny. Among the winegrowers selected from Saumur Champigny, five were also members of the regional cellar cooperative. In terms of their geographical position, the winegrowers selected from Saumur Champigny represented all nine villages of this wine-producing appellation. For the study area in Coteaux du Layon, winegrowers were mainly selected from the six villages that characterize the communal Coteaux du Layon appellation. This selection criterion gave the opportunity to interview winegrowers who produce both generic Coteaux du Layon and higher quality wines with more strict production regulations within the appellation hierarchy.

3.4.2 Semi-structured interviews

The study conducted individual semi-structured interviews with the selected winegrowers. This research technique consists of many open-ended questions (e.g., "what", "how"), with the objective of collecting and understanding participants' experiences and opinions on a particular event or topic (Rubin and Rubin 2005). While open-ended questions are prepared beforehand, some may arise naturally during the interview. Semi-structured interviews are efficient, resourceful (i.e., detailed information concerning complex questions), and flexible, as the interviewer can explain or rephrase any difficult or misunderstood questions. Semi-structured interviews are nevertheless time consuming, where the quality of the data collected strongly depends on the skill of the interviewer and the trust inspired in participants. Prior to fieldwork, pre-test interviews were completed with two additional winegrowers to ensure that the questionnaire met research goals. Thereafter, individual interviews were conducted at participants' wine farms, firstly in 2012 with winegrowers from Coteaux du Layon, and secondly in 2013 with winegrowers from Saumur Champigny. Each interview lasted about an hour and a half, recorded with the participant's consent and carried out by the same interviewer.

The questionnaire developed had a framework of four themes. The first theme focused on general wine farm information (e.g., grapevine varieties, wine styles). The second theme focused on changing viticultural practices over recent decades. Winegrowers were asked to describe how annual (e.g., pruning techniques; vigor, disease and pest control; soil, yield and harvest management) and perennial practices (e.g., varietal material; site selection; planting system) have evolved at farm- and plot-level, including identifying the possible causal factors for those changes. The third theme focused on climate-related perceptions and experiences over the last 20 years. Our interest in climate was therefore not revealed until here. Winegrowers were asked to identify the favorable and unfavorable climate conditions for grapevine behavior and wine production. In addition, they were asked to describe their adaptive responses to those conditions, which according to Smit and Skinner (2002) vary depending on their timing (i.e., reactive or anticipatory) and duration (i.e., tactical/short-term or strategic/long-term). The final theme focused on winegrowers' perceptions of climate change. Winegrowers were asked to comment on recent climate changes and their impacts on grapevine behavior and wine production. From here, they were asked about future climate changes, its potential impact, and their view on necessary adaptation strategies. Using a list of viticultural practices defined beforehand, winegrowers had to organize them in an ascending order, from urgent to low adaptation priority, according to a temporal scale, ranging from short to long term over the twenty-first century.

3.4.3 Qualitative content analysis

Winegrowers' interviews were analyzed through qualitative content analysis (Graneheim and Lundman 2004). Hsieh and Shannon (2005) defined qualitative content analysis as "a research method for the subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns." Qualitative content analysis focuses on interpreting or making sense of rather than quantifying the content of data. This research method involves a process of preparation (e.g., transcribing interviews), analysis (e.g., coding, categorizing), and reporting (Graneheim and Lundman 2004; Elo and Kyngäs 2008). Each interview recorded was transcribed verbatim and the transcribed texts were then read through several times to obtain an overall understanding of the raw qualitative data. Following the preparation phase, an inductive approach was used to analyze the data obtained from the open-ended questions (Elo and Kyngäs 2008). The whole analysis process is not linear but instead iterative, meaning that there is repeated movement back and forth between raw data, codes, categories, and themes to ensure that all aspects of the content are described and identified (i.e., trends, similarities, and differences). Based on the recurrent and emergent patterns and themes obtained from winegrowers' responses, study findings were identified and described. As with semi-structured interviews, qualitative content analysis is time-consuming and results are more susceptible to selective or biased interpretation.

4 Results

4.1 Exposure and sensitivity of wine quality to past and current climate conditions

One winegrower explained that “it is the vintage effect that leaves its signature every year,” giving the example of 2002 and 2003, two successive yet very contrasting climatic seasons. For the former, cool and wet, wines had low alcohol and high acidity levels with unripe flavors, whereas for 2003, which was very warm and relatively dry, wines had high alcohol and very low acidity levels with overripe flavors. All winegrowers defined inter- and intra-seasonal climate variations to be key variables influencing grapevine behavior and wine production (Table 2). There was good coherence among winegrowers as they described the wine quality of growing seasons over recent years. For both study areas, most winegrowers

Table 2 Winegrowers’ descriptions of wine quality along with the associated perceptions of seasonal climate characteristics and their impacts on grapevine behavior and wine production

Wine quality	Growing season	Growing season climate characteristics	Examples of impacts on grapevine behavior and wine production
Excellent	1989, 1990, 2005, 2010	Sunny, warm, dry season	Early vine phenology
		Rain at the right moment	Regular budburst and bloom
		Warm, dry ripening period	Grapes fully ripened
Very good	1995	Sunny, warm, dry season	Grapes fully ripened
	1996	Sunny spring, dry season	High sugar, phenolic content
	1997	Warm, dry ripening period	Grapes fully ripened
	2011	Dry spring, wet summer	Very early vine phenology
		Warm, dry ripening period	Grapes fully ripened
Very good but atypical	2003	Very warm summer	Very early vine phenology
		Heatwave	Overripe grapes
		Fairly dry season	Atypical wine profile
Good	2007	Warm spring, Wet season	Downy Mildew outbreaks
		Dry ripening period	Lower yield, good grape quality
	2009	Warm summer	High yields, good grape quality
Normal	1993	Cool season	Fruity, light structured wines
	1998	Heat wave in August	Sunburn of grapes
	2001, 2002	Wet, cool season	Low sugar, high acidity content
	2004	Dry spring, wet August	Adequate grape ripeness
Poor	1999, 2006	Warm season	High level of grey rot
		Wet ripening period	Short harvesting period
	2000, 2012	Wet, cool season	High Downy Mildew outbreaks
		Wet ripening period	Late vine phenology, unripe grapes
	2008	Late-spring frost	Late vine phenology
		Wet, cool season	Low yields, unripe grapes
Very poor	1991	Late-spring frost	Very low yields
			Irregular grapevine behavior
	1994	Wet ripening period	High level of grey rot
	1992	Wet, cool season	Very high yields, unripe grapes

(80 %) identified the highest quality wines to have been produced in 1989, 1990, 2005, and 2010. Almost all winegrowers (90 %) agreed that the lowest quality wines were produced in 1991, 1992 and more than a half (65 %) also mentioned 1994. Winegrowers' capacity to recall detailed descriptions of wine quality (i.e., structure, flavor) along with their understanding of climate/vine/wine interactions structured their perceptions of climate characteristics during past growing seasons. Winegrowers underlined that quality wines are produced when climate conditions allowed for an early grapevine phenology, regular budburst and bloom, uniform berry ripening, and fully ripened grapes (Table 2). As they differentiated between favorable and unfavorable climate conditions, three variables emerged as the most significant: the amount of heat units, the seasonal amount and timing of rainfall, and the incidence of late-spring frosts.

4.1.1 Amount of heat units

Both study areas cultivate moderate-late ripening varieties at a northern latitude, generally less suitable for these varieties. Indeed, French wine-growing regions at the same latitude, namely Burgundy and Alsace, cultivate early ripening varieties (e.g., Pinot Noir, Riesling), which require less heat to reach adequate ripeness levels (Huglin and Schneider 1998). For both study areas, winegrowers identified favorable conditions as sunny days with warm temperatures, which will cause higher heat unit accumulation. Firstly, more heat during spring is essential for an early grapevine behavioral response. In northern latitude vineyards, vine earliness shifts the ripening period to a warmer period of the year, favoring grape ripening and wine quality (Barbeau et al. 1998). Secondly, more heat necessarily generates greater ripening potential for both Chenin and Cabernet Franc.

Cool seasons are challenging as the amount of heat units is lower than the specific culture requirements, resulting in delayed vine phenology and unripe grapes (i.e., low sugar contents, high acidity levels). An insufficient amount of heat units also affects the physiological ripeness of Cabernet Franc, leading to unripe phenolic and flavor compounds. For Saumur Champigny, winegrowers explained that unripe grapes result in "low quality, acidic wines with green herbaceous flavors and aggressive tannins." The effect of heat units on sugar loading implies that during cool seasons, grapes will struggle to achieve the necessary sugar content as required under appellation regulations. For Saumur Champigny, regulations require a minimum sugar content of 180 g/L for Cabernet Franc, while for Coteaux du Layon, the minimum sugar content is 221 g/L for Chenin. With a greater sensitivity to lower heat units in Coteaux du Layon, winegrowers explained that by waiting for adequate sugar contents during cool seasons, they are exposed to other climatic risks, particularly the arrival of autumn rain.

For both study areas, higher heat units favor vine phenology, grape ripening, and wine quality. However, winegrowers stressed that with too many heat units (e.g., 2003) vine phenology and grape ripening evolves very rapidly. In 2003, the seasonal temperature in Beaulieu sur Layon and Saumur was respectively 1.4 and 1.8 °C warmer than average conditions (Fig. 3). While wine quality was very good in 2003, wine structure and flavor were described as atypical (Table 2). All winegrowers explained that with very high sugar loading and rapid acid degradation during grape ripening, wines had high alcohol contents, low acidity levels, and unfamiliar flavor profiles. Winegrowers from Saumur Champigny described wines in 2003 to be "more typical of wines produced in Southern France, than typical Saumur Champigny." Winegrowers from Coteaux du Layon also observed very little infection by *Botrytis cinerea* in 2003. The latter is a fungal pathogen, which under specific environmental conditions during ripening produces noble rot, causing berries to shrivel and concentrate the sugars (Barbeau et al. 2001; Carey et al. 2004; Jackson 2008). In addition to the beneficial role of noble rot on concentrating sugars, it helps maintain an optimal acidity level and plays a key role in wine structure and flavor. With the absence of noble rot in 2003, the typicality of Coteaux du Layon wines was very different.

4.1.2 Seasonal amount and timing of rainfall

Winegrowers described the regional oceanic influence to bring about a regular rainfall pattern. With rainfall expected all year around, desired vine growth and health, grape yield and quality were underlined as strongly dependent on the seasonal amount and timing of rainfall. The former was emphasized as playing a central role in vine water supply and fungal pathogen outbreaks, whereas rainfall timing was associated with vine phenology.

Vine water supply is a key factor in grapevine behavior and potential wine quality (Matthews et al. 1990; Kennedy et al. 2002; Van Leeuwen et al. 2009). For both study areas, dry growing seasons were identified to be the most favorable for desired vine water supply. Indeed, all quality wines were produced during drier than normal seasons (Fig. 3 and Table 2). Despite low rainfall amounts during these dry growing seasons (e.g., 1990, 2005), the regular rainfall pattern was described to be beneficial, bringing “rain at the right moment.” Wet seasons caused non-restricted vine water supply, which lead to extended and excessive vegetative growth, delayed grape ripening, and inadequate ripeness levels. Together with seasonal rainfall amounts, vine water supply varies depending on soil properties, varietal material, and viticultural practices (Coulon-Leroy et al. 2012). Winegrowers from Coteaux du Layon recognized that their vineyards, planted on shallow slate soils, tend to be more exposed to restricted vine water supply, which is challenging during dry seasons. For Saumur Champigny, the deep calcareous soils were defined as causing higher exposure to regular and non-restricted vine water supply. Although challenging during wet seasons, these soil properties in Saumur Champigny were described as favorable for grapevine behavior under dry conditions. Winegrowers further identified Cabernet Franc to be more sensitive to drought than Chenin, while also describing rootstocks that induce moderate to high vigor to be more drought tolerant than low vigor rootstocks, which induces an early vine phenology (e.g., Riparia Gloire). As with vine water supply, dry growing seasons were identified as most favorable with regard to fungal pathogen outbreaks. Grapevines are very susceptible to fungal pathogens, which disrupt vine physiology and affect grape yield and quality (Jackson 2008). While weather conditions and optimal thresholds vary across fungal pathogens, wet conditions enhance their sporulation and infection on vine leaves and fruit clusters. Accordingly, the highest outbreaks, especially for Downy mildew, were described during wet growing seasons (e.g., 2000, 2012).

Lastly, with a regular rainfall pattern throughout the year, winegrowers described that rainfall is prone to occur during bloom or grape ripening, when dry conditions are crucial. Rainfall during bloom delays or inhibits the pollination and fertilization of grape flowers, which is detrimental for fruit set and productivity (Jackson 2008). In 2012, winegrowers explained that wet and cool conditions during bloom caused a greater occurrence of “coulure” (no fruit set) and “millerandage” (irregular and poor fruit set). Consequently, the yield losses observed for Cabernet Franc and Chenin were around 15 to 30 %. As for bloom, rainy ripening periods are detrimental for grape yield and quality. Rainfall during ripening leads to increased berry size, diluting grape composition and flavor (Coombe and McCarthy 2000; Van Leeuwen et al. 2009). With high water uptake, berries can even split, causing further yield losses. Winegrowers described that wet conditions during ripening also result in greater incidences of grey rot (e.g., 1999, 2006) (Table 2). The Coteaux du Layon is particularly sensitive to these conditions as winegrowers pursue the infection of *B. cinerea* to produce noble rot. With wet conditions, the *Botrytis* infection will however turn into gray rot and be detrimental for grape yield and quality. Climate conditions during ripening are therefore vital for optimal grape quality. Winegrowers said that "even if seasonal conditions are not ideal, a warm and dry ripening period will allow for quality wine production, as in 2011."

4.1.3 Incidence of late-spring frosts

All winegrowers described that spring frosts are the most significant agro-climatic hazards, according to their northern geographical position. Since bud break generally takes place in April for Chenin and Cabernet Franc, the incidence of late-spring frosts was defined as extremely harmful. The most damaging late-spring frost occurred on April 21, 1991, where the minimum-recorded temperature in Beaulieu sur Layon and Saumur was −2.0 °C. This single frost event caused severe leaf and bud injuries (Table 2). With frost injury to the primary shoots, winegrowers explained that shoots developed from secondary or tertiary buds, which resulted in irregular vine and grape development. These differences in grapevine behavior together with very low grape yields resulted in brought about very poor quality wines.

Two types of frost are recognized: advection and radiation (Quénol et al. 2004; Madelin and Beltrando 2005; Poling 2008). When exposed to radiation frost, as in 1991, the local topography is closely associated with the spatial distribution of frost damage. In Coteaux du Layon, most damage was observed for low-lying vineyards, at the bottom of slopes. Indeed, as energy is lost through radiation upward from the soil surface at night, the colder air, denser and heavier than the warmer air, flows from higher to lower elevations due to gravity (Quénol et al. 2004; Poling 2008). The accumulation of cold air at these low-lying areas increases the risk of frost, while temperatures remain warmer at higher elevations. Bonnefoy et al (2012) studied the spatial variation of minimum temperatures in Coteaux du Layon during a radiation frost, illustrating that temperatures ranged from 1.3 °C at high elevations to −3.1 °C at low elevations. For Saumur Champigny, winegrowers similarly described the most severe frost damage to have occurred in low-lying vineyards. Frost damage was also influenced by the proximity of vineyards to the Loire River and to nearby vegetative obstacles. While the latter altered the flow of cold air, the Loire River played a moderating role, as water streams regulate temperatures and slow down nocturnal radiation cooling (Reynier 2007). Winegrowers described how vineyards located next to the Loire River demonstrated much less to no frost damage, whereas the most severe damage was observed for low-lying vineyards, located further from the Loire River. Saumur Champigny is particularly sensitive to frost events, as many vineyards are planted in low-lying areas. Historical harvest records reveal this greater sensitivity. The volume of red wine produced in Saumur Champigny was 26,363 hectoliters (hl) in 1991, compared to the average volume of 76,197 hl (1981–2010). Losses in 1991 were therefore around 65 %. For Coteaux du Layon, 19,521 hl of sweet wine was produced in 1991, resulting in losses closer to 50 % when compared to the average volume of 40,929 hl (1981–2010).

Frost damage also depends on the vine's ability to withstand strong nocturnal cooling. For grapevines, the threshold of frost susceptibility rises from −8 °C in pre-budburst to −2 °C in budburst stage (Reynier 2007). Winegrowers underlined that the severe damage caused by the late-spring frost in 1991 was also a result of an early vine phenology due to warm spring temperatures. In France, the late-spring frost of 1991 caused severe damage in Bordeaux and Languedoc-Roussillon. For these regions, an early vine phenology was also observed, while in Champagne and Burgundy, where the onset of vine phenology was later, damage was less significant (Insee 1992).

4.2 Changing viticultural practices in response to climate- and non-climate-related variables

Important changes in viticultural practices occurred for both study areas over recent decades. During the 1970 to 1980s, vineyards were vigorous, producing high yields and less-mature grapes. While climate conditions during those years were mostly cold-wet and less favorable for higher ripeness levels, common viticultural practices also consisted of selecting vigorous, high yielding varietal material and adding fertilizers and soil amendments at regular intervals. Winegrowers from Saumur Champigny explained that those practices were linked with their end-product goals and market demands, i.e., “to produce light and easy to drink red wines for brasserie type restaurants.” The 1990s marked a turning point, initiated by the high quality seasons of 1989 and 1990, followed then by the poor seasons of 1991 and 1992 (Table 2). A winegrower explained, “With 1989–90, we realized that we could produce something more than table or average wine.” With the aim of producing quality wines more constantly and not only under favorable climate conditions, winegrowers understood that they had to reconsider their viticultural practices in order to better manage climate-related risks and opportunities.

From here, winegrowers focused mainly on three areas in their vineyards to improve wine quality. Firstly, vine vigor and grape yield were recognized as important features of grape ripeness and quality. Adjustments were made to existing practices (e.g., bud number per cane, soil amendments) along with the introduction of cover cropping, leaf and crop thinning practices. These practices allowed winegrowers to manage better vine vigor and grape yield depending on seasonal climate conditions. Secondly, greater interest was taken in understanding the influence of soil on vine and grape development. During the 1990s, the French national institute of agricultural research (INRA-URVV) in Angers developed a method to characterize vineyard soil properties (Morlat 2001; Bodin and Morlat 2006). Thanks to this scientific work, high-resolution soil data was freely available to winegrowers, in order to adapt and optimize plot-level management practices and to select the most suitable vineyards for wine production. Lastly, the concepts of grape ripening and optimal harvest dates evolved. For winegrowers from Coteaux du Layon, this meant a better understanding of the processes of over-ripening and noble rot development, while for winegrowers from Saumur Champigny, greater balance was pursued between technological (sugar/acidity) and physiological (phenolic compounds) ripeness levels. This transition towards producing higher grape and wine quality (i.e., from quantity to quality) had significant implications across soil, canopy, and harvest management practices. Among those practices, vine inter-row management practices changed the most significantly for all winegrowers. It was also the most dynamic practice, changing at different temporal and spatial scales in response to climate and non-climate-related variables.

4.2.1 Vine inter-row management practices: trends, scales, and causal factors

During the 1970s to mid-1980s, chemical weeding was commonly used, replacing horse-drawn cultivators (Fig. 4). Winegrowers rapidly implemented chemical weeding, as it was less

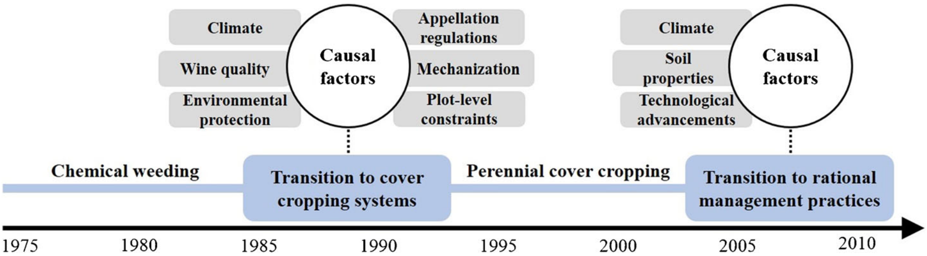

Fig. 4 Temporal trends and causal factors identified for vine inter-row management practices

labor intensive and more cost effective. The mid-1980s to mid-1990s marked a transitional period towards perennial cover cropping systems. At that time, INRA-URVV, along with extension officers of Anjou-Saumur, carried out trials, demonstrating the role of cover cropping in managing vegetative growth for vineyards with ample soil depth and moisture (Morlat and Jacquet 2003). Indeed, cover crops compete with vines for soil, water and nutrients, reducing vine vigor and grape yield. Other advantages of cover crops include improved vine earliness, enhanced environmental protection, and increased soil fertility, structure, and tractability (Morlat and Jacquet 2003; Ingels et al. 2005; Tesic et al. 2007). Cover crops also reduce fungal pathogen and soil erosion risks. Initially, winegrowers planted perennial grass cover crops in young or vigorous vineyards, but then from the 1990s, systemically in all vineyards, whatever the soil property. In response to multiple exposures, the various advantages induced by cover crops lead winegrowers to identify perennial cover cropping as the most appropriate practice for vine inter-rows (Fig. 4). Indeed, favorable climate conditions in 1989 and 1990 (i.e., sunny, warm, and dry) contributed to winegrowers' evolving perceptions of potential grape and wine quality. At that time, environmental protection agencies and appellation regulations were imposing more constraints on the use of chemical weeding. Likewise, the first mechanical harvesters were introduced to Saumur Champigny in the late 1980s, demanding good soil tractability, while for Coteaux du Layon, previously abandoned steep slopes with high erosion risks were once again cultivated.

From the mid-2000s, a transition took place towards more rational inter-row management. Perennial cover crops, especially the grass species, perennial ryegrass (*Lolium perenne* L.) and tall fescue (*Festuca arundinacea Schreber*), became too competitive with vines. Winegrowers described how vineyards displayed less winter-pruning wood, greatly reduced vine vigor and grape yield, low vine nitrogen levels, and slow or delayed sugar loading. Grape musts with low nitrogen contents also caused slow or stuck alcohol fermentation and limited the potential intensity of wine aromas. Despite the various advantages of cover crops, winegrowers recognized that they had "gone too far in their cover cropping systems, allowing too much competition." An important factor was that vine inter-row management practices were not reasoned according to the variations in soil properties at plot levels. Winegrowers from Coteaux du Layon notably emphasized that their vineyards are less suited to perennial cover cropping systems, due to their specific soil properties (Table 1) in an already dry regional climate (seasonal rainfall ±260 mm). Warmer and dryer than normal conditions over the last decade were also identified as having intensified competition between cover crops and vines. For vineyards with poor soil depth and moisture, shallow soil-tillage practices were introduced in each or every second vine inter-row. Technological advancements in soil-tillage tools, which vary in tillage depth, width, and intensity, were underlined to have facilitated their application in vine inter-rows. In other cases, less competitive grass and legumes species were selected, or natural vegetation was allowed to grow. However, for vigorous vineyards with ample soil depth and moisture, perennial grass cover crops remained in each vine inter-row.

4.3 Winegrowers' adaptive responses to climate conditions

For both study areas, winegrowers identified most adaptive responses to occur during harvest and winemaking (i.e., tactical and reactive). Depending on the evolution of grape ripening, coinciding climate conditions and grey rot risks, winegrowers adapt by adjusting harvest management practices. This is especially true for wet ripening periods, where winegrowers defined harvest "windows" to be relatively small. While winegrowers from Saumur Champigny can intervene rapidly with harvesting machines (i.e., day/night), winegrowers from Coteaux du Layon are more restricted. Indeed, regulations only allow manual harvesting (i.e., slow and labor intensive) where winegrowers pass several times in vineyards to hand select grape bunches having reached optimum ripeness. During harvest, winegrowers similarly have to manage the diversity in grape yield and quality, as local environmental properties will cause geographically spread-out vineyards to perform differently. Winegrowers highlighted this diversity to be beneficial, where blending wines made from different but complementary vineyards lets them maintain wine quality and style under diverse climate conditions. For example, grapes from cool vineyard sites bring acidity during hot growing seasons, while for frost or hail (i.e., local extreme events), undamaged vineyards ensure grape yield and quality. Among winemaking techniques, winegrowers can further change planned wine styles (e.g., due to inadequate grape ripeness). A winegrower from Saumur Champigny explained that, "Instead of producing average red wines, it is better to produce rosé wines, thanks to a good rosé market that exists."

Still, the impacts of climate variations are not new and adapting to those conditions has always been a constant challenge faced by winegrowers. Winegrowers underlined that through various learning experiences, shared knowledge (i.e., practical and scientific) and changing viticultural practices, they enhance their adaptive responses (i.e., tactical or strategic). A winegrower said, "It takes bad vintages to judge a good winegrower and to improve viticultural practices. During good vintages, everyone makes quality wines." Accordingly, winegrowers have developed various adaptive responses (Table 3), in particular to manage those climate conditions related to exposure and sensitivity of wine quality.

4.3.1 Managing heat accumulation

Canopy management practices (i.e., tactical responses) control the amount of sunlight exposure on leaves and grapes and the amount of airflow within the vine canopy (Marais et al. 1999; Hunter 2000; Bergqvist et al. 2001; Spayd et al. 2002). During cool growing seasons, winegrowers advance canopy management practices (anticipatory) or use more severe leaf, shoot, and crop thinning (reactive). These tactical responses to cool conditions will improve canopy structure and create a warmer microclimate, which enhances the heating of grapes and the synthesis and concentration of berry compounds (e.g., sugars, anthocyanins). Although removing leaves and shoots has several benefits during cool seasons, winegrowers highlighted the potential risk for sunburn.

Table 3 Types of adaptive responses used by winegrowers to manage diverse climate conditions

Adaptive responses	Climatic stimuli	Examples of viticultural practices
Tactical, reactive	Cool, wet	More severe leaf, shoot, crop thinning
	Warm, dry	Less severe leaf, shoot thinning
		Foliar nitrogen fertilization
	Wet ripening period	Several harvests via bunch selection
		Harvesting at night by machine
	Frost	Requesting crop insurance
		Turning on heaters/wind machines
Tactical, anticipatory	Cool, wet	Advancing canopy management practices
		Allowing natural vegetation to grow
		Higher number of fungicide treatments
	Warm, dry	Delaying canopy management practices
		Shallow soil tillage
	Frost	Delaying winter pruning
		Mowing cover crops
Strategic, reactive	Cool, wet	Longer cane pruning
	Warm, dry	Changing perennial cover crop species
		Increasing the trellis system height
Strategic, anticipatory	Cool, wet	Site selection
	Dry	Choice of rootstock variety
	Frost	Site selection, choice of grapevine variety

During the cool and wet growing season of 1998 (Fig. 3), the month of August was characterized by a heat wave with daily temperatures exceeding 35 °C. As cool spring and summer temperatures brought about early and severe leaf and shoot thinning, grapes were exposed to unexpected high August temperatures that caused significant sunburn damage. This resulted in grape berries shriveling and drying out, which was detrimental to both grape yield and quality. Winegrowers underlined that grape susceptibility to heat damage or sunburn increases with grape ripening and berry softening, identifying Chenin to be more sensitive than Cabernet Franc. Within this perspective, winegrowers implement a two-step adaptive response to reduce the potential for sunburn, i.e., first removing leaves on the morning sun side (cooler sun) and depending on the climate conditions, a second leaf thinning on the afternoon sun side towards the end of summer.

During warm growing seasons, winegrowers conversely delay canopy management practices or apply less severe leaf and shoot thinning. These tactical responses to warm conditions will reduce sunlight exposure on grapes, favoring a cooler microclimate that allows grapes to retain more acidity. Winegrowers also described strategic responses to manage heat accumulation, namely adjusting trellis system height and pruning length (i.e., reactive) or via site selection (i.e., anticipatory). At high latitudes in the northern hemisphere, south facing slopes will receive more direct sunlight than north facing slopes (Huglin and Schneider 1998). Accordingly, winegrowers from Coteaux du Layon mainly select steep south-, southeast-, or east-facing slopes for planting vineyards, since Chenin requires high amounts of heat units to reach adequate sugar contents for sweet wine production.

4.3.2 Managing vine water supply

Over the short term, winegrowers manage temporal variations in vine water supply through vine inter-row practices (i.e., tactical), where anticipatory responses were defined to be essential. Contrary to reactive responses, anticipatory responses let actions be taken before critical thresholds are reached (e.g., severely restricted water supply), which can lead to irreversible impacts on grapevine behavior. For vineyards with tilled or cultivated vine inter-rows, winegrowers will allow weeds and natural grasses to grow during wet growing seasons. In addition to regulating vine vigor and improving vine earliness, weeds and natural grasses ensure good soil tractability for treatment, as wet conditions inevitably imply higher disease risks. Under normal and dry conditions, winegrowers will return to a clean cultivation or shallow soil tillage.

For vineyards with annual or perennial cover cropping systems, winegrowers will perform a shallow soil tillage in each/every second vine inter-row during dry growing seasons. As cover crops, in particular perennial species, require a long time to grow and establish themselves, winegrowers underlined the difficulty and great uncertainty in removing cover crops when confronted with strong inter- and intra-seasonal climate variations. For example, cover crops may be required within the same or following growing season to provide good soil tractability for harvesting machines or to reduce soil erosion with winter rainfall. In this context, two winegrowers from Coteaux du Layon demonstrated innovative practices to manage climate variations. The first planted an annual cereal crop in vine inter-rows. This cover crop will provide good soil tractability, while reaching maturity early during the growing season in order not to compete with vines during grape development and ripening. The second winegrower introduced a mechanical tool, called "rolo-faca." Instead of mowing or removing natural vegetation and weeds in vine inter-rows during dry growing seasons, the "rolo-faca" will roll over the vegetation, creating a sort of living mulch layer allowing its self-reproduction through seeds.

Over the long term, winegrowers manage vine water supply through the choice of annual and perennial cover crop species (i.e., strategic and reactive) or via site selection and choice of rootstock varieties before planting (i.e., strategic and anticipatory). In response to warm and dry trends over the last few decades, winegrowers from Coteaux du Layon have selected increasingly drought-resistant rootstock varieties, namely Gravesac, 1103 Paulsen, and 110 Richter. However, winegrowers from Saumur Champigny are more restricted in the choice of rootstock varieties, as they have to select rootstocks suited to calcareous soils (i.e., Fercal/SO4). In situations where active calcium carbonate levels are lower or for non-calcareous soils, winegrowers primarily plant Couderc 3309.

4.3.3 Managing fungal pathogen outbreaks

Winegrowers use physical, biological, or chemical adaptive responses to manage fungal pathogen risks or outbreaks (Nicholas and Durham 2012). Physical responses involve regulating vine growth directly or indirectly through canopy and vine inter-row management practices, respectively, where winegrowers defined a well-ventilated vine canopy to be less susceptible to disease. Biological and chemical responses were a function of winegrowers' disease management strategies, which Barbeau et al. (2014) similarly reported. Organic winegrowers only use contact fungicides, while conventional and integrated winegrowers may alternate between contact and systemic fungicides. Organic winegrowers explained that while maintaining an optimal foliar coverage is relatively simple under dry conditions, wet seasons are very difficult. Unlike systemic fungicides, contact fungicides must be applied correctly with expected rainfall (i.e., anticipatory), as this washes the treatment from vine leaves and limits vine protection. As a result, organic winegrowers underlined the importance of reliable rainfall predictions (i.e., duration and intensity), whereas integrated winegrowers will take fewer risks during wet seasons, following a more conventional strategy. Across all winegrowers, regular vineyard visits were essential to monitor fungal pathogen risks or to follow-up and evaluate treatment actions.

4.3.4 Managing late-spring frosts

The close relationship between local topography and frost damage meant that winegrowers' frost protection methods varied spatially and were either passive or active. Passive protection includes indirect methods (e.g., site selection, pruning techniques) carried out in advance to reduce the vineyards' susceptibility to frost damage (Poling 2008). Active protection is the use of direct methods (e.g., wind machines, heaters, over-vine sprinklers), applied just before or during frost events. For both study areas, the most important strategic responses to late-spring frosts were passive methods, namely site selection and choice of grapevine variety. Winegrowers will avoid planting vineyards in frost-prone areas (e.g., low-lying) or select late-ripening varieties for those areas (e.g., Cabernet Sauvignon). Because late-ripening varieties require more heat to trigger bud break, a delayed vine growth reduces the potential exposure to spring frosts. Nevertheless, winegrowers explained that since these varieties with high heat requirements generally do not reach adequate grape ripeness, they are mainly used to produce sparkling wines.

As the incidence of late-spring frosts is also highly variable over time, winegrowers take risks in planting Chenin or Cabernet Franc in frost-prone areas. Yet, only a few winegrowers had fuel heaters in vineyards and one winegrower from Saumur Champigny invested in a wind machine. During radiation frost conditions, wind machines mix warmer air aloft with colder air nearest to the soil surface, consequently increasing the air temperature around vines. The absence of these active protection methods for most winegrowers was because their vineyards are geographically spread out. They explained that installing heaters, and especially wind machines, should be a collective strategic response. Indeed, the installation and operating costs for wind machines are high and the investment is only justified for large vineyard surfaces (Poling 2008).

Accordingly, winegrowers similarly depend on passive protection for Chenin and Cabernet Franc vineyards, planted in frost-prone areas. Passive protection methods included the adjustment of vine inter-row management practices (i.e., tactical responses). The amount of heat absorbed during the day and radiated at night depends on soil properties (e.g., texture, porosity) and surface cover. Cover crops restrict heat absorption, resulting in lower night temperatures during spring frosts (Donaldson et al. 1993; O'Connell and Snyder 1999). For vineyards in frost-prone areas, winegrowers therefore described that early spring mowing of cover crops is undertaken. This increases soil surface exposure to sunlight, allowing more heat absorption that will enhance heat release at night and reduce frost susceptibility. Winegrowers also underlined that soil tillage or cultivation should be avoided prior to frost events. Shallow tillage or cultivation loosens the soil structure, leaving more pore space for air (Jackson 2008). As air is a poor conductor of heat, these practices carried out in spring may increase the potential for frost damage. Through pruning management practices, winegrowers similarly reduce the vineyards' susceptibility to frost. For vineyards in frost-prone areas, the main strategy is to postpone winter pruning. Late pruning will delay the onset of bud break and vine growth (Reynier 2007; Jackson 2008), reducing the exposure to frost damage. Some winegrowers also increased the vine training height or delayed the downward bending of the fruiting cane during spring (i.e., from which annual vine growth and grape clusters emerge). Indeed, night temperatures are the coldest near the soil surface during radiation frost conditions (Quénol et al. 2004; Poling 2008). As night temperatures rise with the height above ground, the higher position of sensitive vine parts will improve frost protection.

4.4 Winegrowers' perceptions and adaptation priorities to potential future climate changes

In France and Europe, winegrowers from several wine-growing regions have observed regional climate changes and their impacts on vine phenology and grape quality (Battaglini et al. 2009; Rochard et al. 2010). For both study areas, most winegrowers (80 %) also described a changing climate together with observed changes in phenological stages, harvest dates, grape compositions, and to a lesser extent, altered manifestations of vine pests and diseases. They highlighted that due to higher sugar contents, the common winemaking practice of adding sugar for must enrichment had rarely been used since 2003. Recent climate changes were identified as having been favorable for grapevine behavior, with positive impacts on overall grape and wine quality. One winegrower said, "Since 1990, there have been a series of good vintages compared to those of my parents. Previously, quality vintages were mostly limited to one or two per decade." Winegrowers were nevertheless careful not to identify climate change as the main causal factor, stressing that their evolving viticultural practices have played a significant role in improving grapevine behavior and wine quality. For the Loire Valley, temperature trends have been shown to explain only about 60 % of the changes in grape quality from 1981 to 2010 (Neethling et al. 2012).

Concerning the persistence and future direction of regional climate changes, all winegrowers described a great uncertainty. They perceive climate conditions to be more dependent on natural variability, i.e., variations between cold and wet periods as in the 1960s to 1970s, followed by warm and dry periods since 1990. The cold and wet climate conditions of 2012 were highlighted as an indication that the regional climate could return to a cold and wet period. Winegrowers agreed that if conditions become warmer and drier over the twenty-first century, these climate changes could bring about various opportunities as well as risks for grape growing and winemaking in both study areas. They associated future climate-related opportunities with improved conditions for grape ripening and wine quality, whereas climate-related risks were particularly linked with the potential impacts on regional wine typicality. They explained that a different wine structure and flavor, such as in 2003, could cause confusion to consumers who are familiar with their wines.

For both study areas, winegrowers' uncertainties about future climate changes were reflected in their outlook on adaptation priorities over the twenty-first century. As the perception of risk influence adaptation priorities at individual or community levels, greater uncertainty or less believe in potential future risks may be a limiting factor for strategic adaptation measures to long-term climate changes (Reid et al. 2007; Adger et al. 2009). As a result, winegrowers placed the highest priority on harvest management practices and winemaking techniques, while changing grapevine varieties and using irrigation for vine water supply received the lowest priority (Fig. 5). Winegrowers said that before changing the grapevine

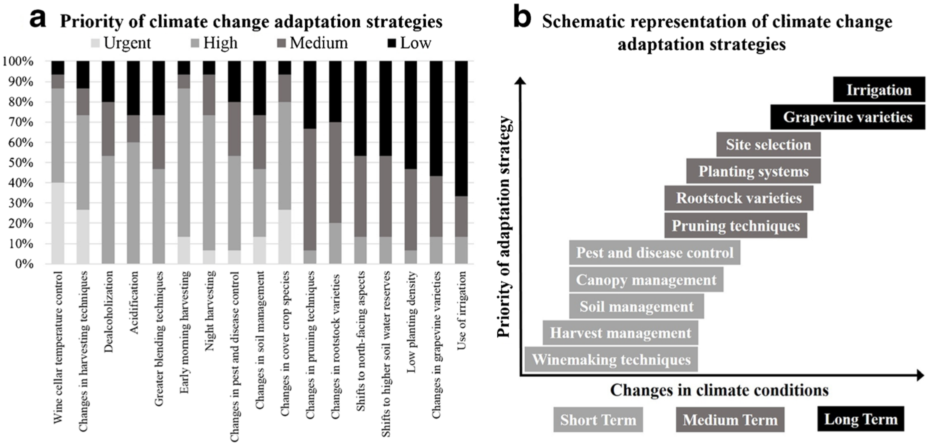

Fig. 5 Based on the responses of winegrowers from Saumur Champigny, **a** the priority of climate change adaptation strategies and **b** its schematic representation in the short, medium, and long term over the twenty-first century

varieties currently grown in both study areas, it is first necessary to intensify soil and canopy management practices or to introduce new innovative practices such as the "rolo-faca." From here, they underlined that with further changes to climate conditions (e.g., warmer and drier), it will subsequently become necessary to adapt by changing rootstock varieties or planting vineyards on soils with greater depth and moisture. Goulet and Morlat (2010) illustrated that very few vineyards in the middle Loire Valley are planted with the most suitable rootstock variety for their specific soil properties. Winegrowers pointed out that small vineyard surfaces could now be planted with varieties more suited to warm and dry conditions, in order to understand the grape growing and winemaking potential of the varieties in their environmental conditions. As for the use of irrigation, producing wines from these varieties is not permitted under appellation regulations, which means that this becomes a collective discussion with policymakers. Irrigation was identified as the best alternative response to drought (i.e., after soil management practices or choice in rootstock variety), yet winegrowers explained that because their vineyards are highly spread out, implementing irrigation systems would likewise be a collective adaptation measure. From winegrowers' responses, it is possible to classify the various adaptation strategies at different temporal scales, from short to long term, knowing that these strategies will vary, depending on vineyard-scale characteristics (e.g., soil properties, topographical features, grapevine, and rootstock varieties).

5 Conclusions

This case study was conducted in two regulated wine-producing areas in the Anjou-Saumur wine growing sub-region, France. Using data collected through semi-structured interviews with 30 selected winegrowers, study findings have provided important insights on local climate vulnerability and winegrowers' adaptive processes. Within the context of climate change and the key issues surrounding adaptation, this study highlights the importance of local, contextual knowledge in framing vulnerability and understanding its differences across and within wine growing regions. With a focus on wine quality, study findings have shown that in addition to the regional prevailing climate, local environmental features and socio-economic aspects are key determining factors of exposure and sensitivity. As each wine-growing region consist of unique contexts (e.g., physical, environmental, social, economic), knowledge and understanding of those contextual factors, and their interaction with the regional climate, will be essential for winegrowers to identify and prioritize adaptation initiatives. Indeed, dealing with current exposure and sensitivity constitute a first step towards adapting to future vulnerability to long-term climate changes. Through constant learning experiences and a range of management practices, study findings have also shown that winegrowers' decision-making is an ongoing process, depending on many climate and non-climate-related factors. Assessment approaches, as in this study, are therefore essential to outline those deciding factors that assist or constrain the process of autonomous adaptations. Alongside winegrowers' autonomous adaptations, there is a need for policy and research to assist winegrowers in planning adaptation responses to uncertain long-term climate changes, as the latter is likely to be overshadowed by short-term climate variability and limited by winegrowers uncertainties in future climate trends. High-resolution climate change projections along with a more detailed understanding of local vulnerability will provide winegrowers' with better perspectives of potential future agro-climatic potentials and adaptation strategies necessary at different temporal (short to long-term) and spatial scales (local to regional). Nevertheless, local climate vulnerability remains a complex process, where the influence of non-climatic factors will have important consequences on the nature of future vulnerability.

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