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Article *in* Global Change Biology · July 2016

DOI: 10.1111/gcb.13406

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Received Date : 16-Feb-2016
Revised Date : 09-Jun-2016
Accepted Date : 13-Jun-2016
Article type : Research Review

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Keywords: viticulture, wine, climate change, grapevine, phenology, risk, adaptation, provenance

Abstract

The cultivation of grapevines for winemaking, known as viticulture, is widely cited as a climate-sensitive agricultural system that has been used as an indicator of both historic and contemporary climate change. Numerous studies have questioned the viability of major viticulture regions under future climate projections. We review the methods used to study the impacts of climate change on viticulture in the light of what is known about the effects of climate and weather on the yields and quality of vineyard harvests. Many potential impacts of climate change on viticulture, particularly those associated with a change in climate variability or seasonal weather patterns, are rarely captured. Key biophysical characteristics of viticulture are often unaccounted for, including the variability of grapevine phenology and the exploitation of microclimatic niches that permit successful cultivation under sub-optimal macroclimatic conditions. We consider how these same biophysical characteristics permit a variety of strategies by which viticulture can adapt to changing climatic conditions. The ability to realise these strategies, however, is affected by uneven exposure to risks across the winemaking sector, and the evolving capacity for decision-making within and across organizational boundaries. The role grape provenance plays in shaping perceptions of wine value and quality, illustrates how conflicts of interest influence decisions about adaptive strategies within the industry. We conclude by considering what lessons can be taken from viticulture for studies of climate change impacts and the capacity for adaptation in other agricultural and natural systems.

Introduction

Climate change poses a threat to the long-term viability of both agricultural and natural systems (Porter *et al*., 2014; Thomas *et al*., 2004). The biological and physical characteristics of these systems will affect their exposure and response to climatic change (Maclean *et al.*, 2015), but so too will management practices (Howden *et al.* 2007, Greenwood *et al.* 2016), social-economic and cultural factors (Grothmann & Patt, 2005; Adger *et al*., 2008).

The methods used to downscale the projections of climate models and assess their impacts have been subject to frequent review (Mearns *et al.*, 2001; Rosenzweig *et al.*, 2013; Wilby & Dawson, 2013 Ashcroft et al., 2009; Kearney & Porter, 2009; Pacifici *et al.*, 2015). However, the suitability of different methods and approaches can only be fully assessed within the context of particular ecological or agricultural systems. Methodological recommendations require an understanding of how well they capture system characteristics that mediate the adverse impacts of climate change and offer mechanisms of adaptation. Furthermore, the credibility of information about climate change is reduced in the eyes of practitioners and decision-makers by any failure to identify key effects of climate on specific systems or to recognize the requirements and implications of adaptation.

In this review we critically examine the methods used to capture the impacts and implications of climate change on a specific agricultural system widely cited within the global change literature. The cultivation of grapevines for wine production, or 'viticulture', provides an excellent case study, not only because of over thirty years of publications on the effects of climate change, but also because of the variety of methodological approaches taken and the socio-economic transformation of the industry over recent decades.

The gross domestic product worth of the global wine sector has been estimated at 58,600 billion USD (Anderson & Nelgen 2011) and plays a significant role in several national economies. The major world viticulture regions (predominantly of *Vitis vinifera* L.) are found at latitudes lying between the mean annual 10 ºC and 20 ºC isotherms (de Blij, 1983), although viticulture is also found outside of this range, including the tropics where grapevines may exhibit no winter dormancy and produce more than one crop per year

(Conceição and Tonietto, 2005). Individual grapevine cultivars, many of which are associated with particular wine styles that have endured over centuries (Bowers *et al.*, 1999; This *et al.*, 2006; Myles *et al.*, 2011), possess more restricted distributions. Winemaking has been described as a natural resource–based industry organized around site-specific characteristics (Centonze, 2010) that are seen as intimately associated with wine quality, and find expression in the importance often given to wine provenance and the concept of 'terroir', of which climate is an integral part (Vaudour, 2002; van Leeuwen & Seguin, 2006; White *et al.*, 2009). Seasonal variability in the prevailing climate is also important in determining year-on-year variation in the yield, quality and value of harvests (Ramirez, 2008), reflected in the concept of wine vintages of varying quality.

Viticulture has been used as an indicator of both historic (Chuine *et al.*, 2004; Meier *et al.*, 2007) and contemporary climate change (Rodo & Comin, 2000; Duchêne & Schneider 2005; Bock et al 2011), and has become a *cause célébre* within the global change biology literature. Studies suggest major changes to the suitability of existing viticulture regions or grapevine cultivars, which implies significant social and economic consequences for a global industry in which cultivar and provenance are key indicators of product value and typicity (Bailly 2000; Schamel & Anderson 2003).

The wine industry also exemplifies the impacts of globalization (Anderson, 2003, Hussein et al., 2008), with the development of new regions of production and consumption, expansion in international trade and technological innovation**.** Despite the evolving socioeconomic context of winemaking, many studies continue to adopt a primarily biophysical approach with limited consideration of how climate change impacts interact with the wider risk context. Conflicting evidence on the adoption of measures by the winemaking and viticulture industries to reduce future impacts (Galbreath, 2014; Alonso & O'Neill, 2011; Lereboullet *et al.*, 2013a) raises questions about the relevance of climate change information and how it is communicated to the industry (Lemos *et al.*, 2012).

In this review we eschew particular theoretical frameworks to consider how research from across disciplinary divides both complements and challenges their respective findings. We draw upon the scientific literature and industry experience to (i) review the methods used to assess the biophysical impacts of climate change on viticulture; (ii) outline significant limitations to these methods in the light of the multiple determinants of harvest quality and yield, grapevine phenology and the association of viticulture with topographical niches; (iii) explore the capacity for adaptation within the industry and the importance of key socioeconomic factors on adaptive decision-making; and (iv) examine what lessons may be drawn for assessing impacts on ecological and agricultural systems, and how information on the impacts of climate change can be made more relevant to the industry.

Measuring climate change impacts on viticulture

The impacts of climate change on viticulture are projected to vary between different winemaking regions. Where viticulture is restricted by a shorter growing season and/or low summer temperatures, such as higher latitude or elevation regions, suitability is expected to improve under future climate conditions as higher temperatures permit the growing of a wider range of cultivars, more reliable yields and the production of better quality wines (Lough *et al.*, 1983; Kenny & Harrison, 1992; Jones *et al.*, 2005). In contrast, major reductions in quality and in the area suitable for premium grape production are anticipated in several existing winemaking regions, primarily due to projected increased summer temperatures and lower precipitation (White *et al.*, 2006; Webb *et al.*, 2008; Mira de Orduña, 2010; Hannah *et al.*, 2013). The adoption of new varieties and/or the migration of vineyards to new regions and/or higher elevations have been suggested as likely consequences of climate change (White *et al.*, 2006; Hall & Jones, 2009; Salinger, 1987; Jones *et al.*, 2005; Lobell *et al.*, 2006; Hannah *et al.*, 2013; Moriondo *et al.*, 2013; Fraga *et al.*, 2014b). However, the implications drawn by many studies have been challenged and doubts expressed about how well the methodologies and metrics used to describe the effects of future climate conditions capture key aspects of viticulture that may augment or mitigate the impacts of change (Keller, 2010; Sadras & Moran, 2013; van Leeuwen *et al.*, 2013).

Climate determinants of yield, quality and phenology

The economic viability of viticulture depends not only on the size and variability of yields but also on harvest quality and suitability for winemaking, which are unrelated to overall biomass production (Ollat *et al.*, 2002). The physical and chemical composition of harvested grapes interacts with the winemaking and conservation process to determine wine quality: a concept difficult to quantify but which has an important sensory aspect determined in part by grape composition which in turn is affected by grapevine genotype, environmental conditions and cultivation practices (Jackson & Lombard, 1993; Verdú Jover, 2004; Lund & Bohlmann, 2006).

Adequate growing season temperature is recognized as essential to vineyard yields (Sánchez & Dokoozlian, 2005), fruit quality (Bonada & Sadras, 2015) and grapevine phenology (Chuine *et al.*, 2004; Petrie & Sadras, 2008; Xu *et al.*, 2012), but a range of other climatic variables and weather events can also act as limiting factors, the importance of which varies between different climatic conditions and types of viticulture (Nesbitt *et al.*, 2016).

Harvest yields are determined by the number and size of grape clusters formed (Petrie and Clingeleffer 2005), which are affected not only by average seasonal conditions but also by weather conditions at key stages of vine development that include bud initiation in the previous season (Pratt, 1971; Keller & Koblet, 1995; Watt *et al.*, 2008), budbreak (Pouget, 1981; Petrie & Clingeleffer, 2005) and flowering (Koblet, 1966, May, 2000). The effects of extreme temperature and water stress on crop yields vary according to the stage of grape development (Kliewer, 1977) as does the impact of extreme weather events such as heavy rainfall or hail that can cause the complete loss of harvests (Willsher, 2013).

In terms of quality, higher growing season temperatures promote the accumulation of grape sugars and breakdown of organic acids: the traditional measures of grape maturity. Inadequate growing season temperatures will result in immature berries that are unsuitable for winemaking. Conversely, very high ripening temperatures can also reduce quality due to excessive sugar levels and low acidity, anthocyanin and flavonoid concentrations (Haselgrove *et al.*, 2000; Downey *et al.*, 2006; Sadras & Moran 2012) which in turn reduce the aromatic properties of wines (Jackson & Lombard, 1993; Mira de Orduña, 2010). Other facets of climate, such as solar radiation and precipitation, can affect the evolution of berry properties that may be quantitatively less significant but have a major effect on quality (Gonzalez-Barreiro *et al.*, 2013, Pereira *et al.*, 2006). Asynchronous fruit development associated with cold or rainy weather at flowering can also be a major cause of reduced harvest quality and/or yields. Optimal ripening conditions vary according to the varietal flavours of different cultivars and the requirements of different wine styles: as a result, different climates favour the production of grapes for particular types of wine.

Many of the effects of climate on viticulture are mediated by grapevine phenology, which varies between grapevine cultivars (McIntyre *et al.*, 1982) but is also responsive to temperature. More advanced phenology is observed under warmer growing conditions. Changes in the timing of budbreak or flowering will alter the conditions of later development according to seasonal weather patterns and the magnitude of the phenological shift. Phenological advancement may therefore augment the detrimental effects of climate change in Mediterranean regions by exposing ripening grapes to the higher temperatures and water stress that occur earlier in the season (Lereboullet *et al.*, 2013b; Ramos *et al.*, 2008). Conversely, phenological advance could enhance the benefits of higher temperature in cool-climates by allowing grape ripening and harvest to occur in earlier, more favourable conditions.

The mediating effect of phenology can have surprising implications under some climate change scenarios. Exposure to late spring frosts, for example, has been projected to increase under some future climate-warming scenarios despite warmer temperatures due to an advance in budbreak (Molitor *et al.*, 2014a; Mosedale *et al.*, 2015). Exposure to many grapevine pathogens and pests, such as the European grapevine moth (*Lobesia botrana*), will also be affected by any change to the phenology of grapevines or the pest species (Caffarra *et al.*, 2012).

Biophysical modelling approaches

Unlike many agricultural systems where crop yield models have dominated impact studies, many different measures of impact have been used to describe the effects of climate change on viticulture. The impacts of climate change have been most commonly described using (i) bioclimatic indices to map changes in land suitability for viticulture, (ii) the application of empirical models to future climate projections, or (iii) dynamic models that seek to simulate the effect of climate on the processes of crop growth and development.

i. **Suitability maps** provide spatial representations of bioclimatic indices to describe changes in the suitability of land for viticulture under future climate conditions. Indices are often chosen *a priori* on the basis of their use in systems to classify different types of viticulture, such as those described by Amerine & Winkler (1944), Gladstones (1992), Kenny & Harrison (1992) and Tonietto & Carbonneau (2004) among others. Alternatively indices may be selected from correlation analysis of a wide range of climatic variables with existing distributions of viticulture (Hannah *et al.*, 2013; Moriondo *et al.*, 2013), using methods similar to those applied in 'species distribution' and 'climate envelope' models used to assess impacts on ecosystem composition and species ranges (Guisan & Thuiller, 2005; Hijmans & Graham, 2006; Pacifici *et al.*, 2015). Such methods have exploited the availability of gridded climate datasets (Hijmans *et al.*, 2005; Haylock *et al.*, 2008) to describe the implications of future climate projections across a national (Fraga *et al.* 2014b), continental (Kenny & Harrison, 1992; White *et al.*, 2006; Moriondo *et al.*, 2013) or global scale (Hannah *et al.*, 2013).

ii. **Empirical models** describing the statistical relationship observed between climate and viticulture variables have been applied to future climate projections. Empirical models can be used to relate variables across spatial and temporal scales, describing how macroclimate and large-scale atmospheric circulation patterns can be significant determinants of vineyard yields (Fraga *et al.* 2014c) conditions (Nemani *et al.*, 2001; Santos *et al.*, 2012), grapevine phenology (Marta *et al.*, 2010; Webb *et al.*, 2012) and the quality of wines (Jones & Davis, 2000; Rodo & Comin, 2000; Grifoni *et al.*, 2006). Alternatively, models relating macroclimate to local climate parameters are used to statistically downscale (Hewitson et al., 2014) climate model outputs before applying models of the relationship between local climate and viticulture (Santos et al., 2011). Statistical models have been applied to measure climate change impacts on yield (Santos *et al.*, 2011), grapevine pathogens (Francesca *et al.*, 2006, Calonnec *et al.*, 2008), and on various measures of harvest quality from vintage ratings (Jones *et al.*, 2005; Moriondo *et al.*, 2011) and harvest prices (Webb et al., 2008) to sugar content (Urhausen *et al.*, 2011; Neumann & Matzarakis, 2014) and other physicochemical properties of berries (Barnuud *et al.*, 2013).

iii. **Dynamic, or process-based, crop growth models** have been widely used for measuring climate impacts on annual crops (Rötter & Geijn, 1999; Rosenzweig et al., 2013) but have been less often applied to studies on viticulture. Dynamic models of grapevine growth range from growing season, field-scale simulation models primarily used as decision-support and forecasting tools, to functional models offering insight into specific plant physiological processes (Moriondo *et al.*, 2015).

Several of the most widely used crop growth models have been applied to assess impacts of, and adaptation to, future climate projections. The general crop model STICS (Brisson *et al.*, 2003) was adapted to assess impacts on viticulture at a national and regional scale (de Cortazar-Atauri, 2006; Brisson and Levrault, 2010; Muresu, 2012) and CropSyst (Stöckle *et al.* 2003) has also been used in several regional studies (Marsal and Utset, 2008; Mukaetov *et al.* 2013) focussing on implications for irrigation and water balance. VineLOGIC (Godwin *et al.*, 2002) has been applied to assess impacts on Australian viticulture, particularly on phenology (Webb *et al.*, 2007).

Although they vary in complexity, these crop growth models are composed of distinct but inter-related sub-models. Heat summation models of phenology have been widely used to model the effects of temperature on the timing of key phases of grapevine development such as budbreak, flowering and the onset of fruit ripening and colouration (‘veraison’) (Chuine *et al.*, 2003; Duchene & Schneider, 2005; Williams *et al.*, 1985; Caffarra & Eccel, 2011; Moncur *et al.*, 1989; Xu *et al.*, 2012). Other key elements of the main crop growth models include sub-models of canopy light (or photosynthetically active radiation) interception, biomass synthesis (using Radiation and/or Water Use Efficiency coefficients) and partitioning among vegetative, fruit and root organs either as a function of the phenological stage or as dynamic partitioning as a function of the ‘sink’ size and activity of different organs (White *et al.*, 2016). Climatic effects are generally captured by daily precipitation, radiation and maximum and minimum temperature variables. Environmental stresses, such as water or nutrient stress, are typically captured by empirical calibration of their effect on crop parameters such as RUE, or by the correction of biomass accumulation.

Dynamic grapevine models focussing on specific applications such as canopy development and branching (Pallas *et al.*, 2010), nitrogen dynamics (Nendel and Kersebaum, 2004), the effects of salinity (Ben Asher *et al.*, 2006), soil water balance and intercropping (Celette *et al.*, 2010) also offer the possibility of being adapted for use with future climate projections.

Limitations to existing approaches

The many different factors that can restrict harvest yields or quality vary across temporal and spatial scales. An increase in mean growing season temperature may allow global viticulture to extend into higher latitude regions and permit a wider variety of cultivars to be grown in cool-climate regions. However, on a regional scale, other factors such as the risk of adverse flowering weather or frost events can limit yields in many years and thereby restrict the economic viability of viticulture. Furthermore, existing distributions of cultivars or viticulture do not correlate with biological tolerance limits, but are also a product of historical and social factors. Cited tolerance limits, in terms of average growing season temperatures of cultivars, have been exceeded in several viticulture regions (van Leeuwen et al., 2013) as a result of historic warming. Phenotypic plasticity, including phenological response to temperature, viticulture management and the requirements of different winemaking styles will all affect the climatic limits within which viticulture is viable. Therefore bioclimatic indices used in suitability mapping, whether chosen a priori or from the analysis of existing distributions, will only capture a few aspects of future climate change the importance of which will vary between viticulture regions.

Viticulture is an example of a 'niche crop' (Challinor et al., 2015) with vineyards often associated with topographical features that shape local, mesoclimatic conditions and permit viable viticulture under marginal macroclimatic conditions. In higher latitude regions, therefore, vineyards are typically located on south-facing slopes to maximise growing season temperatures and solar radiation, while reducing frost risk. Aspect, slope, elevation or the proximity of a large water body modify not conditions to which crops are exposed including temperature, wind exposure and soil drainage (van Leeuwen et al., 2004; Bonnardot et al., 2005; Jones, 2006; Bonnardot & Cautenet, 2009; Bonnefoy et al., 2013; Fraga et al., 2014a). Where vineyards are associated with particular topography, even mean viticulture conditions will diverge from regional and macroclimatic norms. Suitability maps based on uncorrected, low resolution climate projections are therefore liable to underestimate the fine-scale variability of conditions that might permit viticulture to remain viable under changing macroclimatic conditions.

The widespread use of empirical models in impact studies on viticulture is largely explained by their computational simplicity, less demanding data requirements than dynamic models and their ability to relate variables across temporal and spatial resolutions. Limitations include the difficulty of deriving causal effects from statistical correlations and whether the relationships they describe will apply under future climate projections given the multiple determinants of yield and quality.

The ability of empirical models to capture impacts relating to weather conditions at key stages of crop development depends upon their spatial and temporal resolution. Seasonal or monthly metrics can capture the impacts of a change to inter-seasonal climate variability, including the frequency of extreme events, but are less suited to capture the effects of any shift in seasonal weather patterns or the indirect effects of a change in grapevine phenology, both of which are likely to invalidate empirical models developed under current climatic conditions.

The 'decoupling' of local mesoclimate change from macroclimate change, together with the non-linear relationship between climatic conditions measured at different resolutions, can also restrict the validity of empirical models when applied across different temporal or spatial scales. For example the reliability of phenology models calibrated from regional temperatures or local weather station data when applied to vineyard conditions will depend on the heterogeneity of the landscape and other factors determining variation in local temperatures (Ollson & Jönsson 2015) or phenological response. Divergence between vineyard conditions and macroclimatic or regional climates can vary diurnally and seasonally, and is often greatest during extreme weather events such as frosts or heatwaves (Madelin & Beltrando, 2005; Bonnefoy et al., 2013). The rate of historic warming displays spatial variation (Ashcroft et al., 2009; Maclean et al., 2016) as a result of topography and terrain, and therefore future changes in the climatic conditions affecting viticulture will not necessarily be proportionate to changes forecast from global and/or regional climate models.

The theoretical benefits of dynamic models (Costa et al., 2015, Moriondo et al. 2015) include their ability to capture non-linear interactions between weather and viticulture, their basis on biological, causal processes and their potential to integrate the effects of climate with other factors including soil profiles, crop management practices, and perhaps most importantly for future climate change scenarios, the effects of elevated CO_2 levels on grapevine growth and development (Bindi et al. 1996, Poni et al., 2006).

However, comparison studies of dynamic growth models of annual crops have reported variation in the yields predicted by different models (Rötter et al., 2012; Eitzinger et al., 2013). A greater proportion of the uncertainty in climate change impact projections has been attributed to variations among crop models than to variation among downscaled general circulation models (Asseng et al., 2013).

Plant growth and development differs under environmental stress, including water stress or extreme temperatures, and dynamic models vary in how they integrate the effects of environmental stress on model coefficients, such as RUE, or the partitioning of resources among plant organs. Synergistic and antagonistic interactions between different aspects of climate change adds to the complexity of simulating crop growth, with for example elevated CO2 levels increasing the optimal temperature for photosynthesis (Schultz and Stoll, 2009; Salazar-Parra et al., 2012) and decreasing transpiration (Ewert et al. 2002). The greater complexity of the vineyard system, compared with annual crops, presents additional challenges to the dynamic modelling of climate impacts.

There is no absolute distinction between the three approaches we have described. Dynamic models depend on statistically described empirical relationships of the processes they describe. Key elements of many crop growth models, including the use of ‘growing degree days’ to model changes in grapevine phenology, have a limited grounding in biological processes and are derived from statistical analysis of historic time-series. The suitability of heat summation models of grapevine phenology, whether applied in isolation or as a component of dynamic growth models, remains unclear due to inherent limitations of daily summation measures (Due et al., 1993; Gu, 2015). Experimental studies (Sadras & Moran, 2013) have failed to replicate the high sensitivity to temperature (typically a 4-9 day advance in maturity per °C increase) of linear models based on the analysis of historic time series (Tomasi et al., 2011; Petrie & Sadras, 2008; Kast & Rupp, 2009; Sadras & Petrie, 2011). The incorporation of a winter chilling requirement to simulate grapevine vernalization, correction for daylength or applying upper limits to daily temperature summation does not always improve model performance (de Cortázar-Atauri et al., 2009; Fila et al., 2014). Attempts to develop robust growing degree models (Caffarra & Eccel, 2010; Parker et al., 2011) applicable to cultivars or conditions beyond those under which they have been calibrated, have had varying success. In some cases statistical models using monthly temperature averages have been found to outperform classic growing degree day models applied across winemaking regions (Malheiro et al., 2013; Fraga et al. 2016).

Both empirical and dynamic models of discrete phenological events or even of discrete growing seasons cannot capture the continuity of phenological development and the interplay between development and vegetative growth (Sadras & Moran, 2013). Few models replicate an entire season of growth (Molitor et al., 2014b), let alone the full two-year grapevine reproductive cycle (Pratt, 1971). Bud initiation, biomass synthesis and storage during previous years can be important factors affecting grape yields and quality, and can play an important role in crop responses to environmental stress such as extended periods of high temperature or drought (Lobell et al. 2006).

In summary, different modelling approaches share many common challenges when it comes to assessing the impacts of climate change on viticulture, key among which are (i) the multiple and interacting climatic determinants of harvest yields and quality, (ii) the contingency of many impacts on grapevine phenology, and (iii) the divergence between vineyard and macroclimatic conditions.

Many weather events restricting yields or quality display high spatial and temporal resolutions, and viticulture has long exploited fine-scale topographic niches affecting local conditions. The metrics and approaches used to model climate impacts need to reflect the factors that really matter to viticulture under current conditions, which vary between different climatic and winemaking regions. Studies need to be informed about how these factors are likely to vary under future climatic conditions not only by models but by consideration of grapevine biology and viticulture in regions with analogous conditions to future projections.

Mechanisms and strategies of adaptation

Biophysical models, despite their shortcomings, reveal how the impacts of future climate change on viticulture will affect not only harvest yields but also the suitability of different cultivars, grape qualities and the type of wines produced. Viticulture, however, has proved itself viable under a range of sub-optimal climates. The same mechanisms that render grapevine cultivation sensitive to climatic conditions also provide methods by which viticulture can adapt to future climate change by the selection and manipulation of vineyard conditions, plant responses and winemaking techniques.

Studies mapping changes in the suitability of existing viticulture regions under future climate projections can imply that adaptation requires the migration of entire viticulture regions towards higher elevation and/or higher latitude regions (White *et al.*, 2006; Moriondo *et al.*, 2013; Hannah *et al.*, 2013). Less consideration is given to how the macroclimatic conditions under which viticulture can succeed are influenced by long and short-term adaptation of viticulture and winemaking techniques (Fraga *et al.*, 2012; Fleming *et al.*, 2015b).

Vineyard conditions and canopy microclimates are influenced not only by vineyard topography but also by the orientation of vine rows (Grifoni *et al.*, 2008), planting density, ground cover (Celette *et al.*, 2009), grapevine training and canopy management systems (Smart, 1985; Smart *et al.*, 1990; Dry, 2000; Pieri & Gaudillère, 2015). Crop protection against extreme temperatures is possible through the use of shading nets (Castellano *et al.*, 2008; Shakak *et al.*, 2008; Greer *et al.*, 2011) or foliar sunscreens (Glenn *et al.*, 2010). Exposure to risks contingent on phenology, such as late frost, can be reduced by a change of cultivars but also by changes to viticulture practices. Late pruning is used to delay budbreak to mitigate the risk of spring frost damage (Friend & Trought, 2007). Changes to the leaf area to fruit weight ratio (Petrie & Clingeleffer, 2006; Poni *et al.*, 2009), by the removal of grape clusters or canopy pruning, can modify the speed of fruit development in response to excessively low or high temperatures (Keller, 2010; Parker *et al.*, 2014). The adaptation of wine styles and winemaking techniques can help ensure that the requirements of winemaking better match the maturity and properties of fruit produced under changing climatic conditions. Longer-term, the maintenance of genetic diversity and the breeding and selection of more tolerant cultivars and rootstocks (Duchene *et al.*, 2010) could improve viability under future climate projections.

Adaptive decision-making

To support adaptive decision-making within the winemaking industry there is a need not only for information on the impacts of climate change and mechanisms of adaptation, but also recognition of the uneven distribution of the costs and benefits of adaptation among industry participants.

Any adaptive strategy has implications that extend beyond the management of climate-related risks, and resistance to change cannot be overcome simply by the provision of better information about the likelihood or consequences of climate change. The decision to adopt a particular adaptive strategy by an individual or an organisation will depend upon their capacity to change, the perception of their vulnerability to climate change relative to other sources of risk, and the risks and opportunities associated with adaptation.

The capacity to change is determined not only by the potential of the underlying biophysical mechanisms, such as the phenological plasticity of grapevine cultivars or the potential to manipulate vineyard conditions, but also by socio-economic and cultural factors. Different strategies require different resources and impose uneven costs among participants within the winemaking industry. Adaptation strategies based upon changes to the cultivars grown or areas under cultivation have greater financial implications for viticulture than for most agricultural crops, due to the high capital costs of vineyard establishment and slow return on investment. Such strategies imply substantial or 'transformative' change (Rickards & Howden, 2012) to the industry with widespread consequences. Changes to viticulture practice offer more incremental strategies of adaptation, but can place significant demands on the skills and resources of individual organisations and businesses. The high value of winegrapes permits more costly interventions to mitigate the impacts of unfavourable weather events than might be feasible for many crops. Nevertheless, the achievement of a more adaptable and responsive viticulture often depends upon improved risk monitoring and more tailored interventions that require investment in technological assets and skills, as well as increased production costs (Burrell *et al.*, 2004; Hall *et al.*, 2002; Holland & Smit, 2010).

The perceived importance of climate change relative to other risks (Grothmann & Patt, 2005) is shaped not only by the available information and resources but also by values rooted in cognitive, social and cultural factors (Slovic, 1987; Adger *et al.*, 2003, 2008). The greater scepticism about the need for adaptation among Australian grape-growers compared with winemakers (Fleming *et al.*, 2015a) reflects the heightened exposure of grape-growers to a variety of socioeconomic risks (Kiem & Austin, 2013; Bryant & Garnham, 2013) which claim priority over the risks associated with future climate change. Likewise the stronger practical and emotional attachment to place of grape-growers (Fleming et al, 2015b), compared with wineries, magnifies the risks of any shift in vineyard locations (Galbreath, 2014).

Risks extend beyond the immediate cost implications associated with adaptation, particularly where they imply changes to key indicators of market value and quality such as the grapevine cultivar or provenance of grapes. The capacity of viticulture to adapt to climate change is determined not only by the resources and attitudes of *individual* businesses and organizations, but also by the wider capacity for innovation within value chains (Park *et al.*, 2012) or the geographical ‘clusters’ (Porter, 1998) of enterprises and supporting organizations that typify winemaking regions. The risks and benefits associated with adaptation are contingent on the resources and decisions of many different organizations and individuals within the sector. The time required to build supply-chain expertise and market demand for new varieties in Australia, for example, has been estimated to be of the order of 20 to 30 years (Anderson *et al.*, 2008; Paterson, 2004).

The structures and relationships that affect the distribution of risks across the industry and decision-making within and across organizational boundaries are key to the adaptive capacity of viticulture and the winemaking industry as a whole. Many of these structures and relationships have been transformed by globalization of the wine industry, including the creation of new regions of production and consumption, as well as the growing involvement of multinational companies throughout the supply chain (Anderson *et al.*, 2003). Nevertheless, the perception of wine and winemaking as intimately related to the provenance of grape cultivation is not entirely without justification and there remains a strong regional identity to much of the industry, most evident in the reputation of certain winemaking regions and localities. If the relationship between provenance and quality has weakened over recent decades (Moran, 1993; Giraud-Heraud *et al.*, 1998; Vaudour, 2002), it remains widely used by consumers to differentiate between wines not only from traditional European winemaking regions, but also from those regions that pioneered the use of alternative indicators of quality such as cultivars and wine brands to shape consumer expectations (Bailly, 2000; Schamel & Anderson 2003).

Provenance and adaptive decision-making

The importance of provenance to many wines and winemaking regions, and the methods used to maintain its value as an indicator of wine character and quality, provides an example of the complex way in which regulatory and institutional structures (or the lack of them) can affect decision-making and the adaptive capacity of the industry.

The association of provenance with wines of particular quality and character represents considerable investments not only to individual businesses but also to regional industries. Like physical common-pool resources, provenance risks being exploited and reduced in value if the quality or type of products fails to accord with expectations (Patchell, 2008; Ostrom, 2015). Whereas such concerns have been strongest in the long-established European winemaking regions, similar concerns have been expressed about areas central to the expansion and reputation of more recent winemaking nations, for example Napa Valley in the USA and Marlborough Sauvignon Blanc in the New Zealand wine industry (Hayward & Lewis, 2008; Overton, 2010).

Protection of this common 'resource' is often provided by regulations governing the use of geographical indicators of provenance, which now exist in most major winemaking nations (Banks & Sharpe, 2006; Josling, 2006; Overton & Heitger, 2008). The most elaborate of such systems remains the French AOC system, established in 1935, that seeks to ensure provenance is a coherent indicator of wine value and character by not only restricting grape provenance, but also the cultivars, methods of production and yields for particular *appellations*. The restrictions imposed by the French AOC system, however, can impede the ability of the industry to adapt to future climate change (Lereboullet *et al.*, 2013b) by requiring the cultivation of vine cultivars in locations of declining suitability, and by impeding the adoption of innovative viticulture and winemaking practices. The fine geographical scale at which many *appellations* are defined can augment the economic impact of extreme weather events (Belliveau *et al.*, 2006), while the implications for product value create major land price differentials within and between viticulture regions that inhibit changes in land use. Although producers may opt out of the AOC system – and France has seen significant growth in premium wines not belonging to reputed AOC designations (Garcia-Parpet, 2008) – the risks of such a strategy to market value are major deterrents for established producers.

Critiques of the AOC and similar regulatory systems can reflect an opposition to market regulation in principle. Unregulated markets, however, offer no guarantee of more adaptive decision-making. A relatively small number of grape cultivars dominate the global wine market (This *et al.*, 2006) which inhibits the adoption of less familiar cultivars better suited to emerging climatic conditions (Shaw, 1999; Belliveau *et al.*, 2006; Hope-Ross *et al.*, 2006; Holland & Smit, 2010) irrespective of regulatory barriers.

Likewise, there can also be an implicit favouring of individual businesses and producers as the optimal scale for adaptive decision-making. Yet adaptive and maladaptive strategies can be realized at many different scales beyond the individual actor or organisation if there is the motivation and mechanisms available for collective decision-making (Eakin & Patt, 2011). The importance of provenance and the systems that protect geographical indicators of origin can, at least in principal, provide the regulatory tools and institutions whereby collective strategies can be implanted at a regional scale across the production chain (Patchell, 2008). Regional trade associations, government structures and other supporting organisations and industry bodies might similarly provide mechanisms to facilitate decision-making and innovation, and (re)distribute the benefits and risks of adaptive strategies (Porter, 1998; Giuliani et al., 2011).

New regions and participants to the industry are the most likely to view the removal of institutional frameworks and regulations governing provenance as facilitating the innovation required for successful adaptation. Established businesses and regions are more likely to see the same ‘de-regulation’ as undermining decades of investment and the preservation of regional qualities and reputations as essential to adaptation. In both cases, these views will influence perceptions about the desirability of different adaptive strategies. The protection of provenance as an indicator of wine quality can therefore inhibit innovation and adaptation within the industry, but recognition of provenance as a communal asset provides an incentive for decision-making to extend beyond individual businesses and organisations, thereby permitting the realization of a wider range of adaptive strategies.

The concept of wine quality, of which provenance acts as an indicator, is itself subject to evolution and this in turn will change the requirements of viticulture. ‘Consumer naivety’, particularly in the rapidly growing Asian markets (Lee, 2009) can reinforce the value of traditional indicators of quality, such as provenance, and of alternative indicators such as the quality ratings of a select few global wine critics (Gibbs *et al.*, 2009). Equally, however, the development of new markets may hasten an evolution in consumer tastes and transform perceptions of wine quality, which in turn will determine the requirements of viticulture under changing climate conditions.

Lessons from the vineyard

Viticulture provides not only an example of an agriculture that is highly sensitive to changes in climate conditions, but also of a system on which the impacts of climate change are wide-ranging, and the capacity for adaptation subject to global and regional, social-economic and cultural determinants. But what lessons can be drawn that might be applied to other systems vulnerable to future climate change?

Capturing the impacts of climate change

Firstly, many of the potential impacts of climate change on the yield, timing and quality of vineyard harvests occur at high temporal and spatial resolutions that have not been well captured by the metrics and models used to assess climate change impacts. Viticulture therefore illustrates the widely debated effects of a mismatch between the spatial resolution at which climate data are collected and that experienced by organisms (Araújo & New, 2007; Lobell *et al.*, 2006; Wiens *et al.*, 2009; Willis & Bhagwat, 2009; Potter *et al.*, 2013; Bennie *et al.*, 2014; Harwood *et al.*, 2014). Just as vineyards prevail in unsuitable climates through association with distinctive topographical niches, so too the exposure of other species to the effects of climate change can be buffered by a combination of fine-scale microclimate variation and changes in habitat association (Suggitt *et al.*, 2011; Maclean *et al.*, 2015). The temporal resolution of data affects the capacity to capture climate change impacts relating to a change in weather conditions at key stages of species development (Wilson *et al.*, 2007; Morin & Chuine, 2014).

Secondly, viticulture illustrates that the projections of geographical shifts in crop suitability or species ranges resulting from climate change, risk undervaluing the potential of in-situ management and fine-scale habitat variability to reduce impacts, not only on crop systems but also on natural and semi-natural ecosystems (Greenwood *et al.*, 2016). Quantitative information about natural variation and the capacity to manipulate local conditions is required if the potential of in-situ management and adaptation strategies is to be incorporated into impact studies.

Thirdly, there is a need for greater empirical testing and comparison of impact models in terms of their choice of impact metrics and the reliability of models (Rotter *et al.*, 2011). Doubts about the reliability of time series analyses that underpin many models of grapevine phenology also apply to other plant species (Wolkovich *et al.*, 2012). More generally, it is important to demonstrate the limiting factors on species distribution, crop yield or other key characteristics that operate at different scales and resolutions.

Developments in data provision, analytical tools and computing capacity offer an opportunity to widen the application of dynamic crop models in impact studies on viticulture. Stochastic weather generators (Semenov & Barrow, 1997) have been used as a climate downscaling technique in studies on viticulture (Moriondo *et al.*, 2011), but their capacity to model unique time series of daily or hourly weather under future climate scenarios also permits study of changes to risks associated with the timing and frequency of weather events at key stages of development (Mosedale *et al.*, 2015).

Wider application of dynamic models is to be expected (Cola *et al.*, 2014) but requires adopting the lessons learnt from other crop systems, including developing methods for estimating uncertainty, the use of model ensembles, and methods for field-level simulations to account for variation in landscape and management across larger areas (Rotter *et al.*, 2011, Palosuo *et al.* 2011). The integration of statistical and dynamic modelling approaches may well prove the most fruitful approach. Statistical models can help inform about the scale of application of dynamic models (Challinor *et al.* 2003), or distinct statistical models can be applied as a function of phenological modelling (Landau *et al.* 2000). Dynamic models could allow the mapping of cultivar suitability for different cultivars, not just on thermal basis, but also on their tolerance to different stress factors (Costa et al 2015).

A combined approach can also be applied to downscaling weather data to higher levels of resolution. Regional weather station and remote sensing data has been used to construct physical variables capturing landscape effects that are used to calibrate a statistical model of fine-scale regional variations (<100 metres resolution) in temperature for a variety of landscapes (Bennie *et al.*, 2008; Hannah *et al.*, 2014; Kearney *et al.*, 2014; Maclean *et al.*, 2016). The ability of such tools to simulate local conditions can be combined with grapevine canopy models (Louarn *et al.*, 2008; López-Lozano et al., 2011) and radiative transfer models (Chelle & Andrieu, 1998) to simulate irradiance levels and other conditions for whole canopies. Such dynamic model systems offer the potential to calculate the primary production of whole crop systems (Prieto *et al.*, 2012) under different climatic conditions, integrate the effects of future increases in CO2 concentrations on grapevine growth (Bindi *et al.*, 2001; Tognetti *et al.*, 2005) and assess the adaptive capacity of changes in crop management.

Informing decision-making

The provision of climate change information should be driven by the needs of decision-makers and not solely by the availability of improved data and models. Climate change affects exposure to multiple risks, the relative importance of which varies between viticulture regions. The risk of frost or poor flowering conditions may be negligible for most regions but critical to a few for which climate change information will lack relevance if these risks are ignored.

Studies of perceptions and attitudes can help inform impact studies, but it is direct participation of the users of information in the 'co-production' (Lemos & Morehouse, 2005; Pohl *et al.*, 2010) of climate change information that is most effective in ensuring relevance. Several regional studies have demonstrated how engagement with local practitioners can help researchers identify key impacts of climate change, as well as better understanding the wider risk context and factors affecting adaptation options (Belliveau *et al.*, 2006; Holland & Smit, 2010; Lereboullet *et al.*, 2013a). The transparency of the methods and metrics used is also important. Describing the effects of climate change on vintage ratings or harvest prices appears to have direct financial relevance to decision-makers within the industry, but the opacity of the models used can render the results less informative than simple climate-related metrics and risks that can be readily interpreted. Industry knowledge and expertise can often be exploited by the way in which information is presented such as citing existing climate analogues to future conditions (Dunn *et al.*, 2015).

Impact studies also lack salience if there is a mismatch between the resolution of information provided and the scale of effective adaptation and decision-making (Cash *et al.*, 2006; Bodin *et al.*, 2014). Many impact studies do not capture the potential of adaptive strategies that exploit variation in local climatic conditions or grapevine phenology. Likewise the scope of impact studies often reflects the geography of bioclimatic factors rather than the geography of decision-making mechanisms, regulatory systems or indicators of product value. In the case of viticulture, the identification of effective decision-making mechanisms within the industry – whether at the level of individual businesses or co-operatives, regional *appellations* or national regulatory or trade bodies – can help to provide more useful information of appropriate resolution and scope.

Finally, viticulture provides a reminder that the adaptive capacity of agri*cultural* systems is contingent upon the value attributed to inherent characteristics of the system and the products they provide. The high value of premium wines permits a wider range of adaptive strategies for viticulture than would be feasible for lower value crops. What we value, however, is subject to change. Many grape qualities required for the production of highly valued wines can be defined, but both the types of wines that are most valued and the grape qualities required to produce them are not fixed over time. Rather they emerge from the combination of biophysical and technical characteristics with cultural expectations, social and economic factors. Likewise, the values we attribute to other natural and managed systems, are neither constant nor ubiquitous, but shaped by culture and values whose evolution will affect the capacity and incentives to improve the resilience of these systems.

Conclusion

Improved analysis of the impacts of climate change and the mechanisms of adaptation will benefit but will not of itself ensure adaptive decision-making. Viticulture illustrates how agreement about the biophysical consequences of climate change does not imply agreement about the need or strategy of adaptation.

Impact studies have tended to focus on large-scale, transformative changes by which the industry may adapt to climate change – strategies that imply significant and unequal risks to industry participants. As a crop system, however, viticulture has proved viable across a wide range of climatic conditions through the adaptation of vineyard locations, establishment, management and the style of wine produced. The same characteristics offer the potential for reducing exposure and sensitivity to the impacts of future climate change.

Improvements to the adaptive capacity of the industry depend not only upon decisions by individual participants and organisations, but on a capacity for collective adaptive decision-making across organisational boundaries. Climate change is only one of many factors affecting the risk environment of participants in the winemaking industry – an environment that is continually evolving from changes to the global wine market, regulatory regimes and continued developments in technology and consumer demands. Ultimately the viability of viticulture under future climate change scenarios is a cultural decision set within a context of changing socio-economic and biological viability.

Acknowledgements

We are grateful for the constructive comments and suggestions of both reviewers of the original text.

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