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Adaptation to climate change in the UK wine sector

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ABSTRACT

This research contributes to literature on private sector adaptation, examining business-level adaptation to climate change in the UK wine sector. The research adopts a temporal and relational view of adaptation, through a sector-wide, value chain lens and through considering adaptation to both climate variability and longer-term change. Using the lens of 'a good year' and 'a bad year' in the sector, we consider the role of extreme events in adaptation decision-making and learning. We focus, unusually, on both opportunities and risks of climate change. Results show businesses increasingly see climate change as an opportunity for the UK wine sector. Yet climate risks remain and propagate along value chains, through supply and demand. This produces winners and losers in 'good years' and 'bad years', as well as over longer timescales. We find businesses along the value chain take steps to engage in extensive proactive adaptation behaviour, often right from business design and development. Business relationships condition climate risk exposure and adaptive capacity and adaptation decisions within one business can influence risks and opportunities throughout the value chain. Our results also reflect and develop organisational adaptation theories. We find businesses continually refine their adaptation strategies in response to climate variability and extreme events. They enhance adaptation learning by experimenting with new technologies and strategies. Irregular and extreme events can become important focal or tipping points in creative iteration and innovation of adaptation strategies, including for longer-term climate change. Our results stand in contrast to earlier literatures which suggest that businesses consider climate change to be too uncertain, or long-term, to engage in adaptation. Instead, climate change has become a master-narrative within the wine industry, through which sector actors often interpret their experiences and orient their business design and activities. Results indicate a strong dependence on own experience in adaptation decision making, that risks creating adaptation lock-in. We propose a typology of proactive private sector adaptation responses.

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1. Introduction

Most climate change adaptation decisions are undertaken by individuals, households, businesses and other organisations, who directly experience climate impacts and take actions to maximise opportunities and manage their exposure to risks (Fankhauser, 2017; Gannon et al., 2020). There is increasing evidence of human adaptation to climate change within academic literature, especially within food and agriculture (Berrang-Ford et al., 2021). Yet evidence focused on private sector engagement in adaptation has, until recently, been limited (ibid).

Conventional wisdom within the literature on private sector adaptation has been that, outside of specific, particularly vulnerable industries such as insurance (Adger et al., 2005), adaptation action – particularly *proactive* anticipatory adaptation, undertaken before impacts are apparent (Smit and Skinner, 2002) – is rare within the private sector. Indeed scholarship has commonly concluded that businesses find climate change to be too uncertain or long-term to warrant significant investment (Agrawala et al., 2011; Averchenkova et al., 2016; Berkhout et al., 2006; Biagini and Miller, 2013; Wheeler and Lobley, 2021). As the impacts of climate change intensify, however, adaptation literatures are increasingly documenting new pathways of exposure and impact for urban and rural businesses. In parallel, recent empirical enquiry has observed private sector actors, from diverse sectors and varying sized businesses, undertaking a range of climate change adaptation actions in response to both expected and experienced climate risks (Canevari-Luzardo, 2019a; Crick et al., 2018; Gannon et al., 2018; Goldstein et al., 2019; Kom et al., 2020; Leitold et al., 2021).

In this context, we have been studying business-level climate change adaptation in the UK wine sector. The overall direction of change in long-term climate trends has been positive for UK wine production. Warming growing season average temperatures (GST) have brought large areas of the UK into the ideal climatic range for several commercially popular wine grape varieties. This has led to massive expansion of the sector, focused on production of English sparkling wine using the classic Champagne grapes of Chardonnay and Pinot Noir (Nesbitt et al., 2022,2016) (Fig. 1).

Wine production in the UK nevertheless remains highly exposed to climate risk. Ongoing warming is likely to necessitate further variety and/or wine style changes in the medium-term (Nesbitt et al., 2022). Moreover, continuing and potentially increasing variability in interannual suitability of growing conditions, alongside ongoing risks from extreme events such as spring frosts and high rainfall during the growing season, shapes large fluctuations in yields (Fig. 1) that present a major challenge for the viability of the sector (Nesbitt et al., 2016).

There is little academic literature on adaptation behaviour at the 'lower-end' of suitability, in cool-climate viticultural contexts. However, literatures have observed adaptation responses in viticulture in warm-climate contexts (e.g. Neethling et al., 2017; Lereboullet et al., 2014; Nicholas and Durham, 2012; Webb et al., 2009). Examining adaptation behaviour of businesses in the UK wine sector enabled us, unusually, to consider adaptation to both opportunities and risks of climate change. Literature increasingly highlights the complex and integrated ways in which climate risks and adaptive capacity cascade, interact and amplify across social systems and over time (e.g. Adger et al., 2018; Thornton et al., 2014; Challinor et al., 2018). Thus, to account for the array of stimuli, interactions and temporal scales pertinent to holistic analysis of adaptation in the sector we designed the research to account for two further key analytical dimensions to guide our exploration of adaptation. These included: Consideration of *relational dimensions* of adaptation, through sector-wide examination of climate risks and adaptation behaviour along viticultural value chains; and a focus on different *temporal dimensions* of adaptation, through consideration of adaptation to longer-term climate trends, as well as to climate variability and extreme events.

From these foci, the central questions addressed in this study are: How does climate risk and opportunity impact UK wine sector value chains and how do businesses in this climate sensitive sector adapt to climate variability and longer-term change? We explore these questions through three sub-questions:

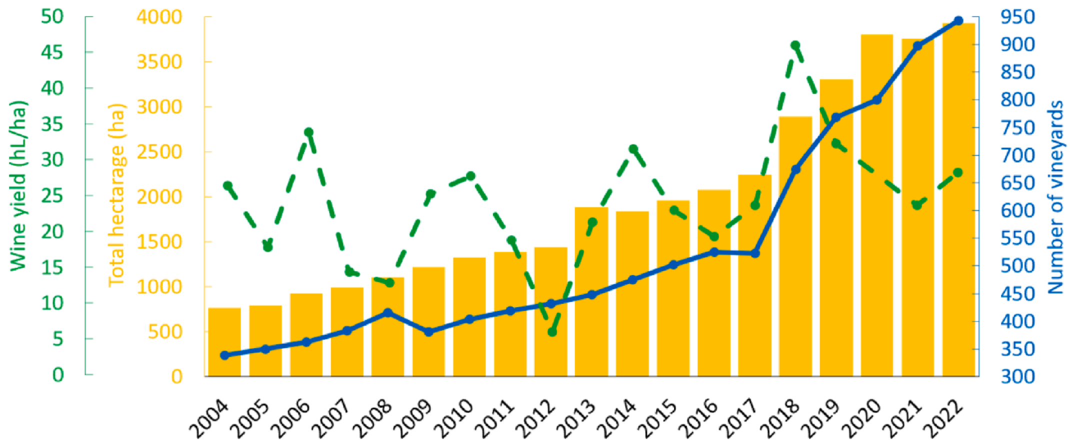

Fig. 1. 2004–2022 UK Vineyard numbers, total hectarage and national wine yield*.
Data sources: Skelton, 2020; WineGB, 2022a,2021a,2021b. Updated from Nesbitt et al. (2022). * No wine yield data currently available for 2020.

– How is climate change perceived and what do sector actors identify as the key opportunities and challenges?
– How do businesses manage climate variability and the occurrence of extreme events?
– How are businesses preparing for longer-term climate change?

1.1. A road map through this study

To set the scene for our examination of how adaptation occurs within the UK wine sector, we need to clarify the parallel questions of 'adaptation *to* what' and 'adaptation *of* what' (c.f. Smit et al., 2000). In the sections that follow, we first summarise the academic literature on climate risk and opportunity in the UK wine sector, to clarify the effects of recent climate trends on UK viticulture and how near-term projected climatic trends may impact the sector. After summarising the conceptual basis through which we incorporate temporal and relational dimensions of adaptation into our study, we outline methods. We then summarise findings from UK wine sector value chain mapping; identifying the range of actors, activities and flows of goods and services that go into transforming grapes into wine supplied to customers.

Next, we outline perspectives from actors involved in activities across the UK wine sector on the risks and opportunities surrounding climate change and present analysis of adaptation behaviours described by respondents. To do this, we identify the proactive adaptation behaviours that respondents report undertaking within their businesses to prepare for climate change. We then explore responses to variability and extremes through the lens of two 'extreme events': a respondent-defined 'good year' and 'bad year' in UK viticulture. Building on a conception of private sector adaptation as an iterative process of organisational learning, we then outline the updates to business activities and practices that respondents reported undertaking following their experience during 'a good year' and 'a bad year'. This allows us to reflect on how variability and extreme events act to influence adaptation to longer-term trends. We close with a discussion of the results and of the contribution of the study to adaptation literature.

2. Climate change and the UK wine sector

Wine grapes are highly sensitive to climate. Quality wine production is limited to areas with average growing season (circa April-October in the 'cooler' wine grape growing regions of the Northern Hemisphere) temperatures of around 13–21° Celsius. For individual grape varieties, the GST temperature range is typically just a few degrees (Jones and Webb, 2010). Climate change means that many of the world's most celebrated wine regions are increasingly exceeding the known climate-maturity temperature envelopes for the varieties that they are known for (Jones et al., 2005; Schultz and Jones, 2010). This is likely to have significant and increasing effects on grape development and regional wine quality and style and to produce geographical shifts in suitable production areas over time (Schultz, 2016; Tóth and Végvári, 2016; Webb et al., 2012).

Subtle differences in inter- and intra-annual climatic conditions produce significant vintage variation in production needs and the resulting wine's expression. Alongside instabilities in the broader socio-economic factors that shape complex climate risk, this variability means flexible management strategies and development of organisational 'routines' (Berkhout et al., 2006: 137), which can be dynamically applied in the context of variable conditions, has always been a necessary feature of viticulture and winemaking (Metzger and Rounsevell, 2011). Since one of the anticipated characteristics of future climate change is enhanced inter-annual climate variability (Seneviratne et al., 2021), anthropogenic climate change is deepening uncertainties in established viticultural regions. This will likely require additional efforts to adjust viticultural systems to manage or harness the opportunities of climate variability, beyond what would be expected due to normal vintage variability.

Early research is highlighting potential limits and barriers to adaptation in established viticultural regions (e.g. Battaglini et al., 2009; Fraga et al., 2018; Lereboullet et al., 2013; Neethling et al., 2017). Of particular note, in some established wine regions, producers face barriers to adapting to climate change linked to inflexibilities in the way in which the sector has developed; a situation characteristic of adaptation 'lock-in'[1] (Siebenhüner et al., 2021; Watkiss and Betts, 2021). The commercially productive lifespan of vines commonly exceeds 50 years, meaning that like infrastructure, vines have a long-lived investment horizon. Meanwhile, many Old World wine regions have established their commercial profile through designated variety, climate, soil and topography assemblages, which have been concretised in production standards linked to appellation-based regulations and Protected Designation of Origin (PDO) certifications (Candiago et al., 2022). Such contexts may not be easily reconciled with a shift to varieties, or viticultural systems, with characteristics more suited to a changing climate (see Morales-Castilla et al., 2020), or with relocating vineyards (e.g. to higher altitudes or latitudes) as climatic conditions shift.

At the same time as research suggests that many long-established wine grape producing regions will decline in the following decades (e.g. Jones et al., 2005), in the UK, GST increases have allowed producers to ripen different and more marketable grape varieties (than those grown in the 1990s and earlier) and to produce high-quality wines, including at higher latitudes (Nesbitt et al., 2016). Near-term future climate projections suggest climate change may afford England and Wales[2] ongoing increasing viticultural opportunity, including growing other new varieties or clones thereof for still wine production (Nesbitt et al., 2022). Meanwhile,

[1] The UK Climate Change Risk Assessment defines adaptation lock-in as emerging from "early actions or decisions that involve long lifetimes or path dependency, which will potentially increase future risk or vulnerability and that are difficult or costly to reverse later" (Watkiss and Betts, 2021: 10).

[2] See Dunn et al. (2019) for analysis of the viticultural limitations projected in Scotland.

increasing yields – including during 'bumper years' such as the 2018 record hot summer and warm autumn – and a growing national and international profile of sparkling wines (WineGB, 2022b), have enhanced investor confidence and the sector has undergone recent rapid expansion (see Fig. 1). This expansion has been concentrated particularly in south-eastern and southern England, but commercial vineyards have been established as far north as Yorkshire.

In this landscape, UK viticulture has been touted as a rare sector – and viticultural region – that stands to benefit from climate change. Yet, despite these opportunities, wine production in the UK is likely to remain subject to high levels of ongoing climate risk. Averages of bioclimatic indices, such as GST and Growing Degree Days (GDD), mask the range of other climatic processes that shape vine productivity and winemaking outcomes, including shorter-term temperature and precipitation events that can be critical for wine producers at monthly, daily or even hourly timescales (Jackson and Lombard, 1993; Mosedale et al., 2015; Tonietto and Carbonneau, 2004). Climate change is likely to alter the timing, duration and characteristics of recurrent seasonal and lifecycle events (Fraga et al., 2013; Jones and Webb, 2010) and it presents potential for more extremes and greater variability in temperature and precipitation at both intra-annual and inter-annual scales (Beniston et al., 2007; Seneviratne et al., 2021; UKCCC, 2021). Projected climatic threats include ongoing frost risk (arising from earlier budburst, in response to warming spring temperatures that leave vines vulnerable to spring frosts), heavy rainfall at key phenological stages, disrupted growing seasons and the threat of novel disease and pest burden (Mosedale et al., 2015; Mozell and Thach, 2014; Nesbitt et al., 2022). Such factors are likely to result in ongoing erratic production and frequent high losses, alongside bumper years, with varying volumes of wine going to market, and into reserve wine storage, year-on-year. They are also likely to lead to challenges producing wine of a consistent typicity and quality, beyond the 'norms' of vintage variability.

Temperatures may also exceed optimums for the grape varieties and types of wine currently being produced. Strikingly, projections suggest that, within the next 20 years, conditions that defined high-quality sparkling wine producing years in Champagne between 1996 and 2015 will only occur in cooler years in large parts of south-eastern England (Nesbitt et al., 2022). Meanwhile, these regions could become reliable still Pinot noir production areas, with GST profiles closer to those experienced in Burgundy during this period (ibid). Focus on production of sparkling wine in the sector to date has arisen, in part, as a response to pressures to maintain a high price point for English and Welsh wines, amidst low relative yields (e.g. as compared to Champagne) (Nesbitt et al., 2018). Transitioning to alternative styles – and still wines – may therefore prove challenging for producers. Research also suggests many vineyards in the UK are sub-optimally located for resilience to climate risk (ibid).

3. Temporal and relational dimensions of adaptation

Literature on private sector adaptation to date – including within viticultural studies (e.g. Neethling et al., 2017; Nicholas and Durham, 2012) – has focused on adaptation and factors shaping adaptive capacity at individual firm- or farm-levels, at specific stages of production and at specific moments in time. However, research increasingly recognises: (1) the social, interconnected and complex nature of climate risks and adaptation responses (e.g. Challinor et al., 2018; Simpson et al., 2021); (2) the potential – indeed the likelihood – for adaptation action to redistribute vulnerability to climate impacts over time and from one place to another (e.g. Atteridge and Remling, 2018; Schipper, 2020); and (3) the role of relational ties in conditioning adaptive capacity (e.g. Canevari-Luzardo et al., 2019). From these interconnected ideas, a broader, more integrated, relational and dynamic, view of adaptation is needed, that considers how climate risk and adaptation interact within food and production systems, at different scales and times and through different responses. This research embeds such an approach through a value chain lens and through considering adaptation to both climate variability and longer-term change.

A value chain lens allows us to consider climate impacts and adaptation across the whole wine sector. Value chains refer to the full range of activities carried out by firms, farmers, workers and other actors, to bring a product or service from conception, through different phases of production, to delivery to final customers (Kaplinsky and Morris, 2001; Ponte et al., 2019). Businesses in value chains are necessarily interconnected through flows of goods, services and knowledge. Interdependencies often emerge where individual actors do not have control over all of the resources that they need to maintain their business activities – including in the face of climate variability and extreme events – and access these externally to the firm through business networks. These interdependences between enterprises can mean the exposure and adaptive capacity of firms is not shaped by just the firm itself, but also by other firms to which they are connected (Canevari-Luzardo, 2019b; Canevari-Luzardo et al., 2019; Fleming et al., 2014; Lim-Camacho et al., 2017; Rahman et al., 2022).

We incorporate a focus on different temporal dimensions of adaptation, meanwhile, by considering adaptation to both climate variability and longer-term climate change. Adaptation literatures treat variability cautiously, perhaps driven by a desire to avoid conflating longer-term 'adaptation' strategies, that aim to reduce adverse impacts and maximise opportunities of climate change, with short-term 'coping' efforts to mitigate the immediate adverse impacts of climatic shocks and stresses, including those which may not be directly attributable to climate change (Fischer, 2019; IPCC, 2014). Yet variability is central to producer experience of climate risk in UK viticulture (Nesbitt et al., 2016) and may increase due to climate change.

Considering adaptation to both climate variability and change is also important for understanding the ways in which experience of climate variability and extreme events may stimulate adaptation learning and support or limit longer-term – even 'transformational' (Fedele et al., 2019) – adaptation, that reduces the overall vulnerability of the sector to future changes. Key knowledge gaps remain about how variability and one-off extreme events act to influence decision making and adaptation to longer-term trends. It is clear that adapting to climate variability alone is unlikely to be sufficient to support adaptation to longer-term climate change and adaptation to variability may lead to path dependencies that structure adaptation lock-ins, which constrain adaptation options at a later point in time (Dilling et al., 2015). Yet literature also suggests gradual exposure to climatic changes and experience of extreme events can increase the incentive for, and probability of, adaptation (Lee and Zhao, 2021; Travis, 2014) and that incremental adaptation can lead to transformational adaptation over time (Kates et al., 2012; Mapfumo et al., 2017).

A theoretical basis for considering the relationship between adaptation to variability and longer-term change in businesses is developed in the organisational adaptation literature, which draws inspiration from extensive bodies of work in evolutionary economics and innovation studies. This literature employs the concept of 'routines' to describe a process of organisations fitting activities and procedures to recognised circumstances that they encounter (Orsato et al., 2017). Routines take many forms in organisations and can include repeated patterns of behaviour, that can reflect organisational culture and norms, and may be dynamically enacted in response to a recognised set of circumstances (Pentland and Hærem, 2015; Uittenbroek, 2016). In viticulture, pruning strategies within annual growing cycles, are clear examples of organisational routines. In the climate change literature such a model of organisational adaptation is most explicitly articulated in Berkhout et al. (2006), where the authors suggest that business encounters with (climate change) 'signals' can lead to innovation and adaptation of routines, as advantages of alternative modes of practice are discovered. The approach, which has parallels with other loop learning models applied to climate change adaptation (e.g. Tschakert and Dietrich, 2010), denotes a model of adaptation learning that occurs as firms engage in a dynamic process of signal interpretation, routine experimentation, evaluation and iteration (Berkhout, 2012; Berkhout et al., 2006).

Organisational learning literatures have often given particular attention to the role of direct encounters with novel circumstances in innovation of business activities. This focus broadly aligns with adaptation literatures which suggest that experience of variability and extremes may serve as 'focusing events' (Demski et al., 2017) or 'pacemakers of adaptation' (Travis, 2014). However climate change signals can also be indirect and socially derived (Maslach et al., 2018), taking such forms as regulations, demonstrations, training or guidance from social networks or industry bodies. A distinction can also be drawn from the literature between learning and innovation that is more passive and that which is more active. A more passive form of learning can occur in organisations through the tacit accumulation of experience acquired from routine repetition and exposure to new signals over time. Organisations may also engage in more active investments in optimising or identifying alternative operating routines; what Berkhout et al. (2006) call 'search'.

In the wine sector, characterised by high-levels of interannual variability in growing conditions and production, Berkhout et al.'s (2006) model of organisational adaptation suggests that businesses may innovate organisational routines in response to vintage variation, extreme events and other indirect climate signals. However, there can be no assumption that any of these processes of learning will necessarily lead to more inherently adaptive outcomes. A complex landscape of interacting factors shapes how businesses make decisions and climate signals won't be interpreted and translated into adaptive action in any straightforward way (Berkhout, 2012; Orsato et al., 2017). Incremental adaptation to address short-term climate variability may also fall short in preparing for longer-term change due to the uncertainty, unprecedented magnitude and threshold effects of such change and its complex interactions with interconnected social systems (Dilling et al., 2015).

Organisational adaptation also requires 'dynamic capabilities' (Berkhout et al., 2006) that enable a business to iterate and adapt their operational activities.[3] The dynamic capabilities that exist within a business at any one time are defined through decisions taken at earlier points in time, that either enable or restrict future adaptation decision-making (Astigarraga and Ingrand, 2011). Owing to the non-stationarity of climate risk (Haasnoot et al., 2020), dynamic capabilities are not determined by static factors. As a result, actions undertaken in response to climate variability and short-term shocks and stresses may create path dependencies, 'sunk cost' effects and a range of other barriers to future adaptation decision making that characterise adaptation lock-in (Dilling et al., 2015; Schipper, 2020; Siebenhüner et al., 2021).

Through events such as the exceptionally grape-friendly growing conditions experienced during 2018 and the resulting bumper harvest, in this study we consider how adaptation to vintage variation shapes or limits longer-term adaptation to climate change in the UK wine sector. In doing so, we are able to build on calls from theoretical literatures (e.g. Thornton et al., 2014; Tschakert and Dietrich, 2010) – with limited existing empirical application – to treat adaptation not as a discrete event, but as a process over time.

4. Methods

Our analysis began with value chain mapping; to identify high-level groupings of actors, activities and business linkages and capture the overall nature of the value chain (c.f. Canevari-Luzardo et al., 2019; Carabine and Simonet, 2018). This was undertaken through literature review and initial engagement with sector actors. Annex 1 in Supplementary Materials (SM) provides additional details on this and other methodological aspects of the research.

Semi-structured researcher-administered interview protocols (provided in Annex 2 of SM) were used to ask respondents about proactive (anticipatory) activities, undertaken to manage climate change within their business. Respondents were then asked to provide a narrative account of the challenges and opportunities that they experienced within their business during 'a good year' and 'a bad year' and of how they responded to these. Respondents were also asked to identify key business linkages and relationships, and to consider how these relationships shape their exposure to climate risk and enabled or restricted their adaptation responses. The protocols additionally collected data on business histories, perceptions of climate risk and business identifying information.

Questions on adaptation behaviours and impacts were primarily open-ended, to allow respondents to highlight the issues and activities most salient to their experiences. We paid careful attention to the influence that question order or presentation might have on responses. The protocols also replicated questionnaire items on a previous survey of UK producers conducted in early 2014 (Nesbitt

[3] Such dynamism aligns with ideas of (operational) flexibility that have defined resilience and robustness in adaptation pathways approaches (Metzger et al., 2021; Ranger et al., 2013; Walker et al., 2013) and in business literatures (Busch, 2011; Shekarian et al., 2022).

et al., 2016), which provided the opportunity to indicate change in perspectives over time. By replicating a question on belief in climate change, employed in a nationally representative survey conducted at approximately the same time (Steentjes, 2020), we were also able to compare attitudes to climate change among individuals in the viticulture sector with national populations.

30 respondents from 27 unique businesses and organisations were interviewed. Initial respondents were recruited through producer association WineGB's 2019 members conference, with snowball sampling used by asking respondents to identify other actors to whom they were connected through business ties. We also adapted the researcher-administered interview protocol into an online survey tool, to enable additional quantification of some questions. This survey tool was distributed by WineGB and led to a further 44 responses, bringing our total participants to 74. At times in this paper, we provide statistics on the number of respondents to highlight a given idea (e.g. the number of respondents to report undertaking an adaptation behaviour, or to identify a given risk). These counts refer to ideas raised autonomously by respondents in response to *open-ended* questions during the interview phase of the research (n = 30), unless otherwise stated.

Respondents were drawn from businesses including: (1) 'independent grape growers' that sell all, or most, of their grapes for transformation by other winemakers; (2) 'independent winemakers' that buy-in grapes for winemaking; (3) 'integrated grower-winemakers' that make wine from grapes that they grow themselves, or from a combination of grapes that they grow and buy; (4) input and service providers; (5) independent wine sellers; and (6) sector support bodies. Given the diverse range of actors along the value chain and the in-depth nature of the interviews, sample sizes of individual actor types were necessarily small. However, within this limitation, we tried to sample a diverse range of actors, from businesses of varying size and scope. Annex 3 in SM provides a list of respondents and provides details on the numbers of each value chain actor type in the sample. 68% of respondents were from grape growing or winemaking businesses (collectively called 'producers' in this study). While sample sizes prevent generalisation to wider populations, the value of such detailed case study methods for theory-building is widely established within the social sciences.

During analysis, codes were developed and iterated both deductively and inductively, structured initially around our research questions. It wasn't possible to cleanly differentiate actions that respondents described taking to address the additional risks (and opportunities) associated with climate change, from those related to managing expected (baseline) variability in climate parameters. We also didn't have scope to evaluate the adaptation potential of respondents' activities within this study. We therefore followed the approach of wider literatures (e.g. Berrang-Ford et al., 2021) and coded actions described as proactive (anticipatory) adaptation to climate change by respondents as 'adaptation', regardless of their actual potential to reduce risk. Through the 'good/bad year' lens we realised that a distinction could be made between the responses that participants described undertaking during or immediately following the experience of a climate event, and the longer-term updates made to business activities following experience of that event. We see this as the difference between (1) enacting business routines and updating them in the course of their performance and (2) updates which shape the enactment or performance of routines in subsequent performance cycles. We label this 'coping' and 'learning' respectively.

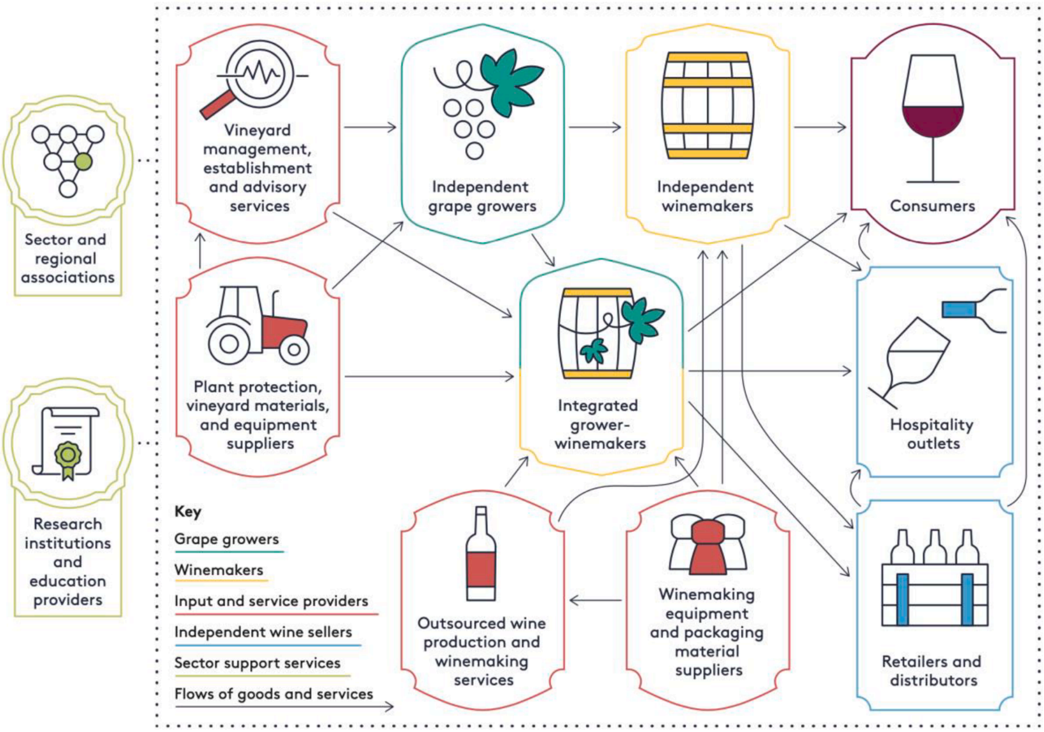

Fig. 2. The UK wine sector value chain network.

5. Results

5.1. The UK wine sector value chain

Fig. 2 identifies core groups of actors within the UK wine sector based on the value chain activities that they are involved in: Grape growers; winemakers; input and service providers; independent wine sellers; and sector support services. These categories of value chain actor are not discreet. Rather there are varying levels of vertical integration (combination of two or more stages of production within a single business) among businesses within the sector and businesses often crosscut more than one category of actor (see Annex 3 of SM). Some producers offer inputs and services to other producers (e.g., grape processing; contract winemaking; or bottling, labelling, disgorging or storage services) as part of business diversification strategies. Others outsource these activities to other businesses. Some 'input and service providers', (e.g., vineyard establishment and management agencies, viticulture and agronomy consultancies and crop protection and agricultural input producers), are also involved in their own grape or wine production activities, which they may use to test new production methods and technologies for dissemination among clients. There are even large retailers (e.g., supermarkets) which undertake their own English and Welsh wine production. The main flows of goods and services identified between these actors are shown in Fig. 2.

5.2. Perceptions of climate risk and opportunity

Our results indicate a very high awareness of climate change among respondents from across the UK wine sector, as well as a new sense of optimism about the opportunity of climate change for UK viticulture. The sector has moved towards viewing climate change as not just a threat for wine production, but as both a threat and an opportunity. This trend, captured in Fig. 3, represents a significant shift in perceptions in the sector, within a short window of time. Respondents linked the exceptionally strong 2018 harvest, and other recent hot summers, to this optimism and, correspondingly, to the rapid growth and investment seen within the sector. "*Without a shadow of a doubt, we wouldn't be planting in the volume and the bulk we are, had we not got the confidence that we can now consistently ripen [these grapes] and produce… world class wines which can compete on the global stage*", Respondent 14 described.

Perceptions of the opportunities and threats of climate change for the UK wine sector, reported by respondents, closely echoed those found in the scientific literature (section 2) and those reported in Nesbitt et al. (2016); Nesbitt et al. (2022). Alongside warmer

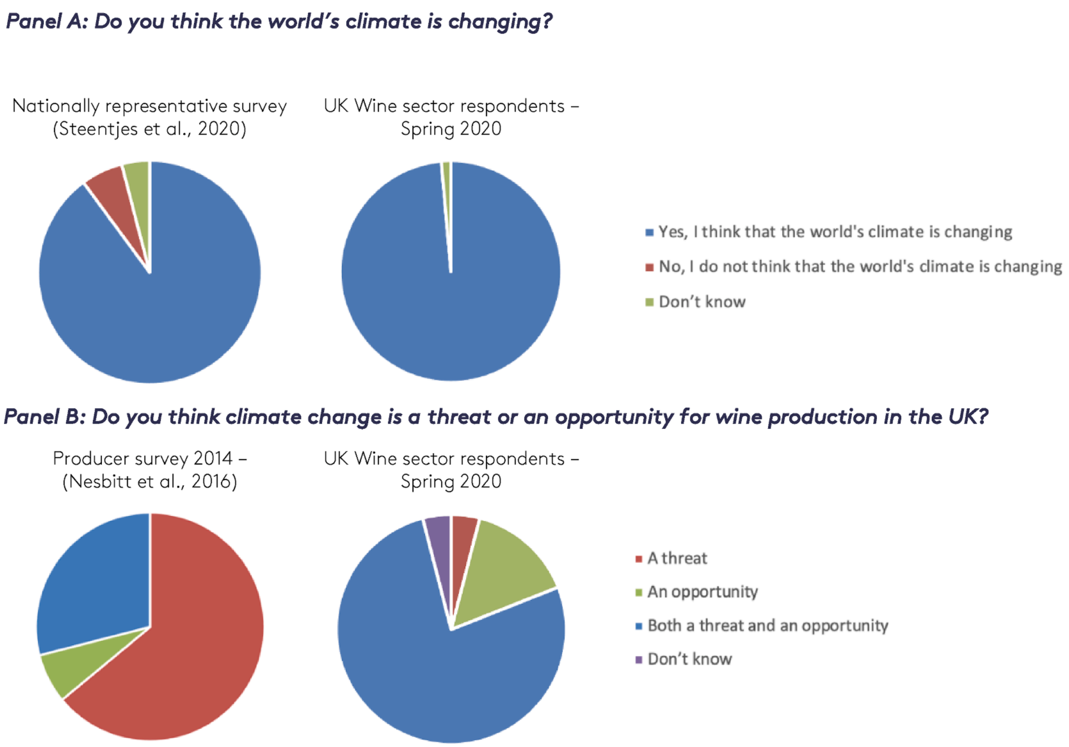

Fig. 3. Perceptions of climate change in the UK wine sector recorded in interview and survey responses in this research (n = 74) in spring 2020, compared to: Panel A – A nationally representative survey in autumn 2019 (Steentjes et al, 2020); and Panel B – A 2014 survey of UK grape growers and wine producers (Nesbitt et al., 2016). Questions asked were: Panel A – "As far as you know, do you think the world's climate is changing or not?"; and Panel B – "Do you think climate change is a threat or an opportunity for wine production in the UK?". Respondents surveyed in Nesbitt et al. (2016) only include producers of grapes or wine, while respondents in our 2020 sample also include other value chain actors. However similar trends can be observed within the 2020 sample, even if other value chain actor respondents are excluded.

temperatures and additional growing degree days, allowing production of higher quality wines, 26 (of 30) interview respondents described climate change as an opportunity to ripen new types of grapes and/or produce new types of commercially popular wine. The potential to produce quality wines in the UK was contrasted by six interview respondents to the climate change-related heat and drought challenges being experienced in many of the world's major traditional wine regions. Nine input and service providers described opportunities to access new markets for new or existing products and services – including for technologies and services that support adaptation – as climate change and growth within the sector increases demand. Retailers and distributors saw opportunities to expand their UK wine offerings.

Optimism was accompanied by widespread concern about the risks of climate change. Ongoing, or increasing, interannual variability in the climatic suitability of growing conditions – as well as the impact of this on yields, production, wine quality and typicity, availability of wine for sale and demand for inputs and services – was almost universally considered the greatest risk of climate change for the sector by respondents. 29 interview respondents highlighted concerns that climate change would result in more extreme events and variable production and 11 highlighted concerns about heightened or novel pests and diseases. Four interview respondents suggested that, even in the UK, temperatures may increase beyond the climatic suitability window for the dominant varieties and wine styles currently being produced. Five expressed concern that, for a sector dependent on 'luxury' prices, rapid growth in the sector, in response to climate trends, could lead to market saturation and drive down the price of grapes and wine. Four suggested that raw materials used to make wine sector inputs, and their corresponding value chains, could also face disruption, as a result of climate risk. One interview respondent highlighted a concern that wider societal, political, environmental and economic disruption, as a result of climate change, could impact their business.

A fuller summary of respondent perceptions of the opportunities and challenges of climate change for the sector is provided in Annex 4 of SM.

5.3. *Preparing for climate change: Proactive 'adaptation'*

Respondents along the value chain reported undertaking extensive and wide-ranging actions to prepare their businesses for climate change. These actions are embedded across diverse dimensions of business design and operations and target a range of perceived direct and indirect climate risks and opportunities, within businesses at all stages of the value chain. We group the most notable of these actions below, as we identify six, interrelated, dimensions of business operations, in which respondents described seeking to proactively integrate 'adaptation'.

5.3.1. *Business design, size and core products and services*

One group of climate change preparedness responses identifiable within the dataset relates to business design choices and core activities. Respondents described efforts to incorporate climate change and its effects into business design and development, often right from vineyard or initial business establishment. Rapid expansion of the sector (Fig. 1) – i.e. investment in the sector itself – was characterised as adaptation to climate change by interview respondents, as they described entering the sector, investing in business development and expanding their activities in response to the perceived opportunities of climate trends. Respondents described climate change influencing choices of production regimes, such as the types of wine produced and growers' choice of soil management regime (e.g. organic production regimes, chosen to support vineyard drainage and resilience). The dataset also provides examples of respondents linking strategic business decisions, such as the level of vertical integration within their business, to climate change. Winemakers described investing in in-house bottling facilities, in response to perceived opportunities for business expansion. Input and services providers also reported investing in developing new products and services to respond to new (anticipated) demand linked to climate trends within the sector. These include climate-focused agronomy services, new crop protection technologies, to guard against new pests and diseases, and developing contract-winemaking capacity for still wine production.

5.3.2. *Infrastructure, premises, equipment and inputs*

The dataset also provides evidence of adaptation objectives informing decisions about infrastructure, equipment and premises. Growers emphasised the importance of 'getting the site right' and eight grape-growers highlighted having made use of consultancy services to support site selection, often including the use of highly downscaled climate information to assess site suitability. Eleven grape-growers highlighted having selected grape varieties, clones and rootstock in similar ways; making use of consultancy services and sourcing other forms of expertise, often from within the business network, to inform decisions about which varieties and clones to plant. This decision support is commonly underpinned by historic climate data to inform current suitability, but is also sometimes informed by future climate change data, to determine future reliability of any given variety. Some of these efforts may be explainable by the large up-front long-term (25-year +) investment horizons associated with vine lifetimes. Respondents gave other examples of climate change informing investment decision making in regard to business premises and equipment. For example, one winemaker reported investing in underground wine storage tanks, to protect their wine from anticipated higher temperatures.

5.3.3. *Marketing strategies*

In the context of concerns that climate change-driven, rapid expansion of grape-growing in the UK could lead to market saturation and drive down the prices of grapes and wine, respondents described undertaking a range of marketing and certification strategies focused on differentiating products to consumers, to gain competitive advantage and develop their value proposition. Ten interview respondents, for example, outlined actions intended to integrate adaptation and other sustainability objectives, by enabling them to market their products as 'green' and 'environmentally-friendly'. These include employing new energy and water saving production strategies, adopting organic production methods, procuring environmentally-friendly packaging materials and securing sustainability accreditations. Producers interviewed also commonly reported adopting production models that conform with the use of protected wine names with PDO labels such as English Quality Sparkling Wine (DEFRA, 2011), or – in the case of one Sussex-based producer – the more recently available 'Sussex' wine designation (DEFRA, 2021).

5.3.4. *Operational flexibility*

Respondents described a range of actions undertaken to embed 'operational flexibility' (Kamalahmadi et al., 2022; Shekarian et al., 2022) into their operations and activities, to allow them to adjust business activities in the face of variable and changing climate conditions. Many of these strategies are conventional historical practices for reducing risk to standard climate variability in viticulture and winemaking in Europe. However, recall that there are widespread concerns within the sector that climate change will result in more extreme events and variable production (Section 5.2). Thus, respondents considered a range of strategies undertaken to retain or enhance their operational flexibility, to manage interannual variability in growing conditions and in grape and wine quality and quantity, as also being key to future adaptation to climate change. Eleven growers interviewed described prioritising grape varieties and clones that can be used for different types of winemaking, depending on the climate conditions experienced within a given year. Thirteen winemakers highlighted a specific commitment to non-vintage production models, in order to enable storage and blending of reserve wines across years. Five producers highlighted having recently diversified their vineyard sites, or suppliers, to limit exposure to climate shocks; for example, planting grapes in, or sourcing grapes from, different counties that are less likely to experience concurrent frost risk. Business diversification was also widely reported by respondents across the value chain as a strategy undertaken to buffer firms from the financial impacts of shocks and stresses created by climate variability and change.

5.3.5. *Business relationships and value chain networks*

Another group of anticipatory climate change preparedness strategies identifiable within the dataset relates to actions respondents described undertaking to manage business relationships and value chain networks in the face of climate risk. These strategies aim to buffer climate impacts on demand and supply for grapes, wine, inputs and services across the sector. Input and service providers, for example, outlined strategies such as stockholding and diversifying their own supplier networks to cope with varying availability in and demand for (climate-sensitive) inputs (e.g. cork). Reflecting literatures which suggest that business relationships along value chains can unlock resources for adaptation (Gannon et al., 2021) and enable joint problem-solving (Canevari-Luzardo, 2019b), respondents also provided examples of actions undertaken with the goal of building adaptive capacity within their own business through direct investments in the adaptive capacity of other businesses within their supply chain. These included knowledge sharing activities (e.g. winemakers providing climate resilience training to their grape suppliers), as well as approaches to contracting and payments (e.g. input and service providers offering products on credit, to allow growers and winemakers to cope with variable production costs).

5.3.6. *Experimentation and monitoring*

Aligning with Berkhout et al.'s (2006) concept of 'search', respondents described embedding active exploration of alternative ways of responding to climate pressures within their business activities, through structuring and monitoring experimentation strategies, and seeking out relevant external experience and knowledge. Almost all grape-growers interviewed, for example, described employing and experimenting with new grape varieties or viticultural regimes, (such as pruning and training strategies), with the goal of identifying strategies that may be more suited to changing climates. Winemakers similarly trialled different production techniques, to test and

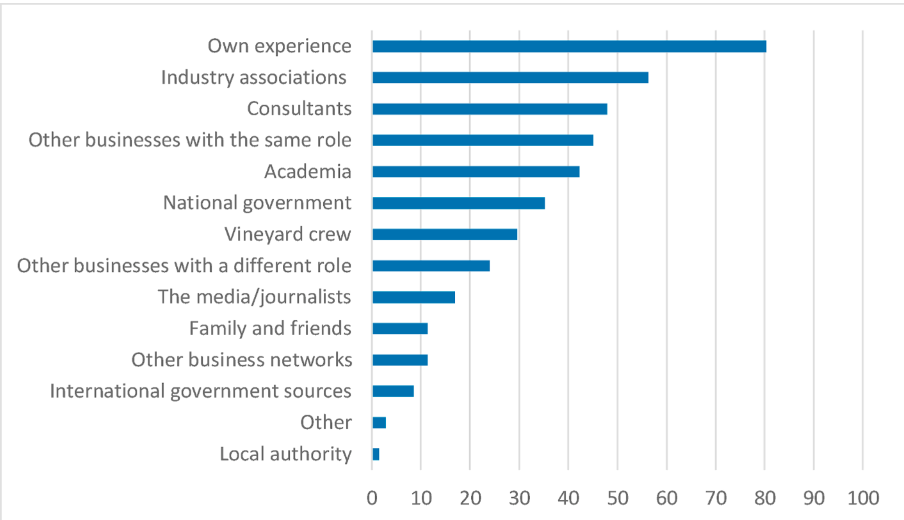

Fig. 4. Percentage of respondents to report relying on each source of information when deciding what action to take to manage climate change within their business (n = 74).

observe outcomes year on year. These activities were often supported through detailed record keeping, to monitor and evaluate interactions and outcomes across climate conditions, vine phenology, management responses and the resulting fruit and wine. Respondent 3 explained: "*One of the main things we focus on a lot is collecting data on weather, but also vine physiology. [We identify] bigger yields and the timing of when things happen in the vineyard, you know key stages in the vineyard, and [we] record [these] year on year. Then, when faced with a situation, we can look at previous years and see if it's panning out to be fairly similar to year X or Y and [observe] what happened because of how we reacted. So, in a similar year, we can decide to react in a different or similar way*". This explanation from Respondent 3 mirrors the learning cycle in Berkhout et al., (2006): Through signal interpretation, in the context of variation generated through experience, experimentation and search, routines are enacted and innovated, which informs future cycles of innovation as new stimuli are encountered. Respondents place overwhelming emphasis on their own experience in adaptation decision-making (Fig. 4). However, respondents also described seeking out other forms of knowledge, including about future climate change, to incorporate into adaptation decision making and the innovation of organisational routines. This includes information from social and business networks, industry associations, academia and national government.

5.4. Learning through 'a good year' and 'a bad year' in the UK wine sector

To further understand how variability influences adaptation to longer-term climate trends, we explored respondents' experience of 'a good year' and 'a bad year' in UK viticulture. The respondent-defined 'good year' under focus is the year 2018, when exceptionally grape-friendly growing conditions led the UK wine sector to report record yields (Fig. 1). Data on this year is drawn from 29 of the 30 interview respondents, who all reported 2018 to be the year they considered the UK to have experienced the most favourable weather conditions for grape growing since they started working in the sector.

The 'bad year' considered in this research is 2012, when the wine sector reported the lowest wine yields on record. For purposes of brevity, and since the opportunity lens has received less attention in literature on agricultural adaptation, within this paper we only summarise participant accounts of 'a good year' in UK viticulture, including graphically in Fig. 5. However, Annex 5 in SM provides an accompanying synthesis and graphical summary of key impacts and responses during 2012, described in relation to 'a bad year'.

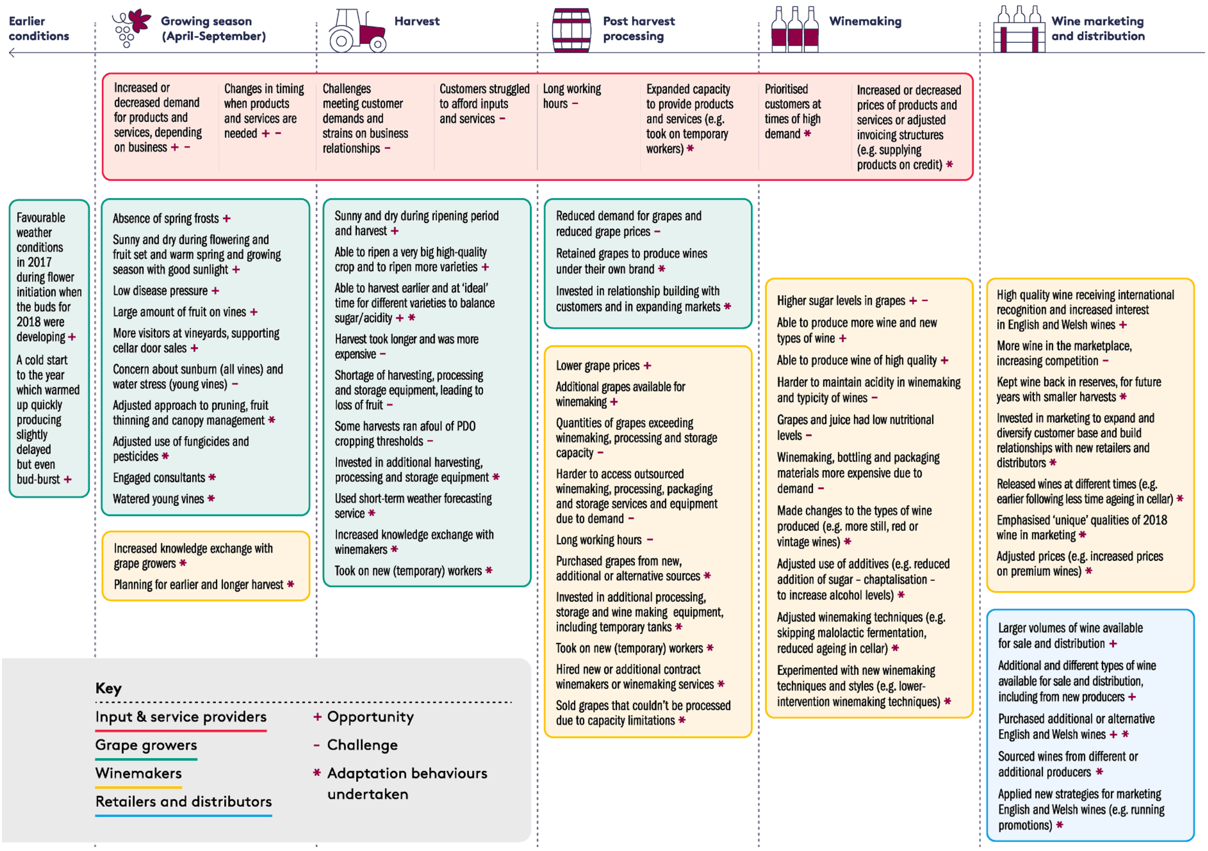

Fig. 5. 2018 – A good year in UK viticulture.

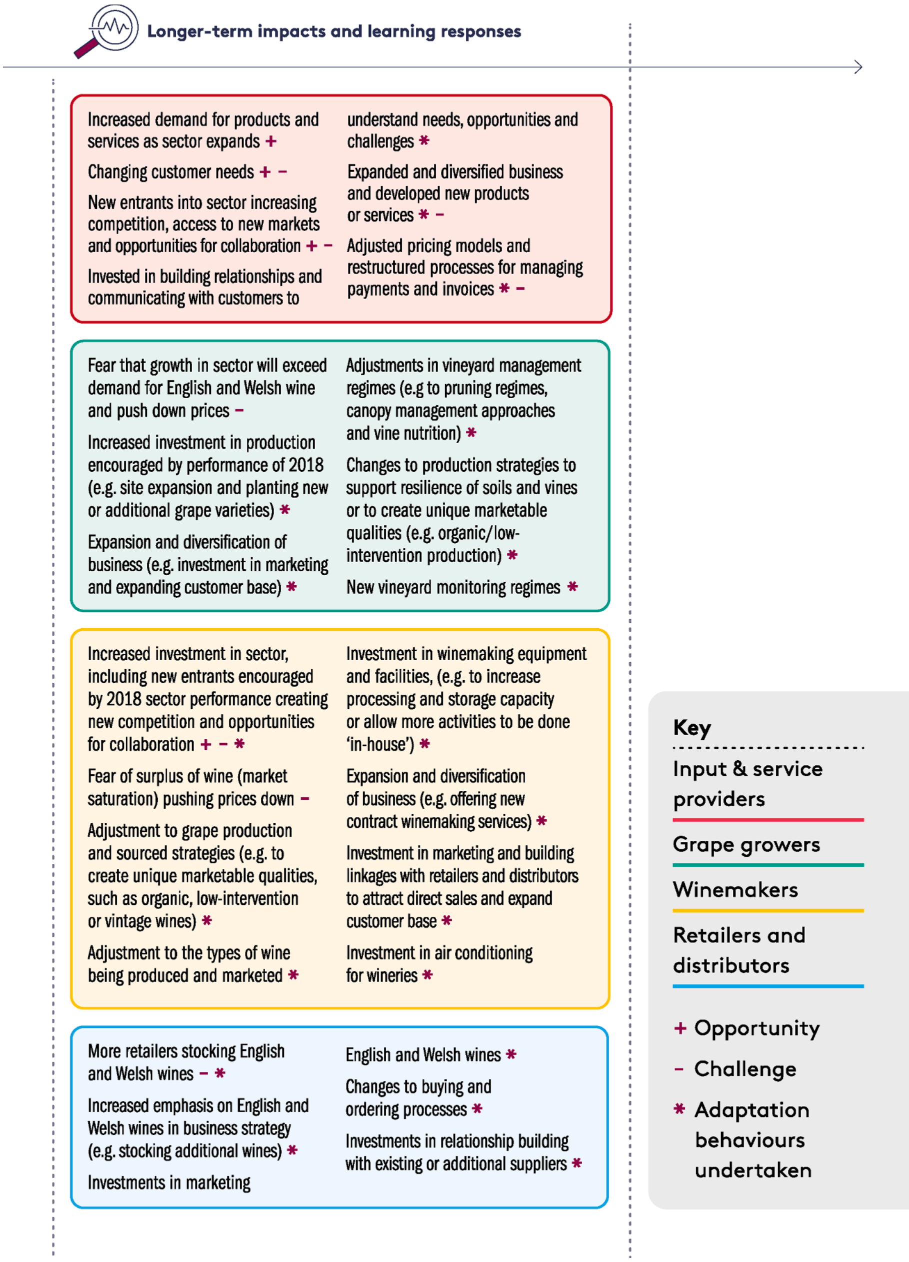

Fig. 5. (*continued*).

5.4.1. Opportunities during 'a good year' in UK viticulture

Respondents characterised 2018 as "*an almost perfect year*" (Respondent 5). They described "*a relatively cold start to the year, which warmed up very quickly*" (Respondent 2). This generally led to slightly delayed, but even, budburst, that avoided frost damage. From this point "*it just stayed warm and dry*" (Respondent 3), meaning there was "*really abundant flowering, [with] good quality flowers; off the back of which the fruit set was really good*" (Respondent 5). The warmth and dryness in 2018 led to a generally lower disease and pest burden and continued "*into the autumn, when we were trying to ripen the crop*" (Respondent 24). As a result, growers were able to ripen "*a very big crop [of] exceptional quality*" (Respondent 1). Because it stayed dry throughout the harvest season, it was possible to pick grapes at their ideal harvest time and "*when the fruit came in, they were in really good condition, [with] the fruit acids nice and low [and] the sugars really high*" (Respondent 16). Many of the resulting wines were very well received. "*There was a lot of publicity, a lot of articles in the press*" around the 2018 harvest Respondent 10 explained, which drove sales. With the market flush with additional grapes, winemakers with sufficient processing capacity were able to produce additional wine at bargain prices. Greater volumes of wine offered retailers the opportunity to run promotions and increase sales. Input and service providers, meanwhile, often reported increased demand for their products and services: "*If [clients] can see a useful crop developing, [their] willingness to invest in it… is greater*" Respondent 24 explained.

5.4.2. Challenges during 'a good year' in UK viticulture

In 2018 producers faced immediate capacity challenges in harvesting, processing and storing additional grapes and wine, shaped particularly by limitations in equipment and labour. Some growers struggled to harvest grapes quickly enough to maintain their quality, or lacked capacity to process and store them. And as "*literally every UK vineyard was wanting more and more tank space because of yield*" (Respondent 16), producers and input and service providers struggled to access and supply additional processing equipment, contract winemaking and storage facilities. Grape growers encountered new vineyard conditions in 2018, that they were sometimes unprepared for and highlighted challenges that they faced maintaining the acidity or typicity of the wines they produced. "*In some of the vineyards [the grapes] got a bit too ripe*" Respondent 18 explained. "*If you weren't exactly tuned in, you could have made sparkling wines that did not match your style*" Respondent 15 added.

Some producers – particularly those who did not fruit-thin during the summer – also produced harvests that ran afoul of cropping thresholds set by PDO wine schemes for England and Wales. Use of the PDO 'English Quality Sparkling Wine', limits producers to maximum yields of 80 hectolitres/hectare (DEFRA, 2011). Some producers pursuing a bumper crop, "*got caught out when they didn't realise that there was a restriction on the amount of crop load they could have*" (Respondent 22). The extra cost of processing, bottling and storing wine was also significant, especially in an industry dominated by sparkling wine production, which may not be sold for several years and thus where outgoings may not be recouped for a long period of time. Respondents also found markets were not prepared for the high volumes of grapes and wines that were produced in 2018. Independent winemakers didn't all have the processing capacity to benefit from the additional grapes available on the market. And as grape prices dropped, some producers without existing or robust contracts were not able to find buyers for their grapes, or had to sell grapes at low prices, relative to the cost of production.

5.4.3. Coping responses

Grape growers made adjustments to viticultural techniques throughout the 2018 growing season, such as to fruit thinning, pruning regimes and pest and disease management protocols, responding to changing conditions as they arose. Respondent 2 explained of their business: "*Normally… we would… drop some of the fruit, to reduce the yield to try and ensure that the remaining crop would ripen. But because the… weather was so good… we made the decision to leave the entire crop on the vine and it actually ripened*". Producers also made changes to the way they harvested and sold their grapes, for example selling excess grapes that they could not process themselves.

Winemakers, meanwhile, adjusted the way in which the wine was made; reducing, for example, chapitalisation (sugar addition), used to control acidity and alcohol levels. Others made vintage wines and still wines, to maximise the qualities within the harvest, or blended wines, when grapes "*were too ripe to be used in sparkling wine production*" (Respondent 6) or didn't have a characteristic typicity. Producers also described storing wine in reserves, in anticipation of future years with lower production levels, to allow them to smooth peaks and troughs in supply.

Producers also acquired additional processing and production equipment and sourced additional inputs, labour and services to cope with the additional grapes, for example buying additional tanks and investing in storage capacity. Sellers increased their investments in marketing and adapted their marketing approach *"[to] communicate to [consumers] why 2018 was quite special compared to any other year*" (Respondent 5). Respondents also described working closely with other businesses across the value chain, to manage the unprecedented volumes and conditions; exchanging knowledge, sequencing processes where possible and renegotiating contracts to maximise opportunities.

5.4.4. Learning

Respondents also outlined a range of updates made to business activities and operations, following 2018, that they linked to their experiences during this year (see Fig. 5). Growers described updates to viticultural regimes that they introduced, such as renewed commitments to fruit thinning activities during the growing season to "*iron out troughs and peaks [in annual production]… [and] combat inconsistencies*" (Respondent 1). For some, 2018 prompted the introduction of new monitoring systems: "*For the first time [in 2018], we had some problems with… fermentations… because of the nutritional level… As the result of that, we… put a new regime in place [to] monitor [nitrogen levels in the grapes] every year… going forward*" (Respondent 1). Respondent 2 suggested 2018 offered a "*new benchmark*" for monitoring and comparing crop development across annual cycles: "*Any changes in the weather in future years, you can kind of look back and say, 'well, those conditions in 2018 were like that, which meant we were able to do this. But this year we're already a week behind what we were then*'", they explained. This account parallels 'knowledge articulation and codification' within Berkhout et al.'s (2006) conceptualisation of learning cycles.

Respondents also described investing in new equipment and business expansion, for example to increase processing capacity. Others described diversifying business activities (e.g. expanding still wine production capacity) or adjusting production processes. Respondents also described innovation in products and services offered by their business and adjustments to pricing and payment models; for example, to accommodate additional stockholding or lines of credit, for customers facing unprecedented and fluctuating production expenses. Selling techniques were also updated, with sellers investing additional resources in marketing English wines and building relationships with English winemakers. Some producers transitioned, for example, to "*wholesale as well as retail*" (Respondent 11) and some input and service providers described refocusing their business on particular sections of the market, or on particular activities.

2018 was seen by some as emblematic of the opportunities of climate change for viticulture and prompted additional investment in the sector. For others, this bumper harvest was viewed with concern, amidst fears that surplus wine and additional investment into the sector driven by climate trends could drive down wine prices and returns. This latter perspective aligned with increased commitment among some producers to invest in developing unique marketable qualities within their grapes and wine (e.g. to align with 'Organic' or protected wine name designations).

6. Discussion

Awareness of climate change is very high within the UK wine sector and respondents in this study often showed high awareness of the risks and opportunities of climate change; wherein, collectively, respondent perceptions of the direct risks of climate change show broad alignment with climate science projections for the sector. Results in Sections 5.3 and 5.4.4 show that businesses channel this awareness into extensive proactive action designed to incorporate adaptation to climate change into their business design and activities, often right from vineyard or business establishment. Box 1 summarises the diverse business decisions in which adaptation responses are embedded in the sector. Many of these were observed at multiple stages of the value chain.

Adaptation-related responses in the UK wine sector aim to address a range of anticipated direct and indirect business risks and opportunities of climate change, which impact on and interact through multiple stages of the value chain. Respondents at different stages of the value chain are taking actions designed to support adaptation to the direct effects of climate change, such as increased temperatures and climate variability (e.g. installing cooling systems in vineyards). But many adaptation responses target climate impacts that ripple through value chains as they impact on demand and supply. The 'good/bad' year analytical lens made climate impacts on demand and supply particularly visible. However, respondents are also preparing for these impacts over longer-term timescales; anticipating increased climate variability and ways in which longer-term climate trends may introduce new risks and opportunities into the sector.

Our study also begins to illustrate the complex and social nature of climate risk transmission pathways, through which business risks and opportunities emerge (c.f. Canevari-Luzardo et al., 2019; Challinor et al., 2018). Adaptation responses undertaken within one business can redistribute risks and opportunities elsewhere in the value chain. Many of the adaptation decisions identified in Box 1 depend on resources (inputs, services, markets and knowledge) that are accessed through other value chain actors and that may themselves be subject to direct or indirect climate risks. Business relationships therefore determine access to key resources for adaptation, which may be opened-up or closed-down through those business relationships and through the adaptation responses of those businesses. Research and development efforts among input providers, for example, may open-up access to new adaptation technologies for businesses elsewhere in the value chain. Fluctuations in demand and supply, meanwhile, produce complex and uneven effects along value chains that lead to both 'winners' and 'losers' across good years and bad years. This is also seen in responses to longer-term change: For example, as vineyards and wineries become "*more confident [they] can produce a good grape*" (Respondent 13)

Box 1
Business decisions shaped by adaptation objectives in the UK wine sector.

Business size, growth strategy and scale of investment.

Choice of business premises and site.

Equipment and technology selection and investment decisions.

Choice of product and service offerings.

Choice of production techniques and regimes.

Outsourcing strategies and vertical integration.

Use of storage and holding of stock and product reserves.

Choice of suppliers.

Choice of inputs and services.

Contracting decisions.

Management of and investments in business relationships.

Design of pricing and payment structures.

Workforce size and structure.

Sustainability strategy and investment decisions.

Marketing strategy and investments.

Information use and knowledge procurement.

Investments in experimentation, monitoring, research and development.

Knowledge sharing activities.

and expand, in turn input and service producers are preparing for increasing – and different – demands for their products and services. Fearing market saturation, other respondents considered such increased investment within the sector to be a threat to their own business viability.

These examples highlight that businesses not only have to adapt to a changing climate, but also have to adjust to the adaptation responses of other businesses and to the dynamic and complex outcomes that emerge as climate impacts are amplified or attenuated through social responses. Our data also provides examples of businesses actively engaging in activities designed to enhance their own adaptative capacity by conditioning the adaptive capacity of businesses elsewhere within the value chain (e.g. through knowledge exchange and the design of contracting and payment structures).

Business decision-making sits in a landscape of diverse and complex climate and non-climate risks, opportunities and uncertainties. Thus, adaptation responses outlined by respondents sit along what has been described-elsewhere as the adaptation-development spectrum (Gannon et al., 2021; Singh et al., 2015). They are made up of climate-specific adaptation responses (e.g. subscribing to early-warning climate information services to monitor frost risk), as well as actions designed to support broader business resilience, in the face of multiple social, environmental and market risks (e.g. business diversification activities such as contract winemaking, tourism and production of other goods and services). Adaptation responses also often seek to address current climate variability and longer-term change in parallel.

There is still work to do to define a universally valid typology of private sector adaptation actions, with existing efforts mostly focused at individual sector levels (Goldstein et al., 2019). However, the business decisions in which adaptation is embedded in the UK wine sector (Box 1) have parallels to adaptation responses observed among other businesses in other sectors and geographies (e.g. Crick et al., 2018; Gannon et al., 2018) and generally align with the broad categories of 'soft', 'hard' and 'ecosystem-based' approaches to private sector adaptation outlined in Goldstein et al. (2019). They may therefore represent a suitable preliminary typology that could be employed and elaborated in future private sector adaptation research.

Results in this study also demonstrate empirically the need to conceptualise adaptation, not as a discrete and static event, but as an ongoing iterative and creative process of adjustment and learning. Rather than just comprising discrete actions undertaken at a given moment in time, adaptation tends to be integrated into business processes and activities iteratively, with many adaptation decisions constantly and creatively updated. Indeed, even adaptation actions that initially appear defined through singular actions (e.g. site selection, or investment in frost protection) may be reviewed and updated over time (e.g. through site diversification).

The way we understand this iteration of adaptation action through our data has a lot of salience with Berkhout et al.'s (2006) conceptualisation of organisational adaptation learning. Characteristic of 'routines' (ibid), many business activities and practices – such as pruning or the selection of additives introduced in winemaking processes – are repeated, but implemented dynamically, within and across (annual) phenological, production and business cycles. Through the coping responses described during a good year (Section 5.4.3) and a bad year (Annex 5), respondents described matching procedures to the circumstances that they faced: For example, grape growers reduced crop thinning and winemakers reduced chapitalisation (sugar addition) in 2018.

We propose that this process of enacting routines is shaped by decision-making *models*, informed by learning cycles and previous experiences. These models are constituted through interpretations of events and outcomes. In our dataset they are partially codified in simple heuristics, taking the form of 'rules of thumb' involving prescribed responses to recurrent events, such as 'if X occurs, we do Y' (see an example of such a heuristic and related accounts of record keeping in Section 5.3). We intend to further conceptualise such models in future work. However, we suggest that the models that underpin such heuristics often involve detailed and nuanced interpretation of complex causal processes, often expressed through narratives of what has happened in previous business cycles. We suggest that these models are dynamically and creatively enacted in decision-making within different material and temporal contexts and ambitions.

Respondent accounts of learning following 'a good year' (section 5.4.4) and 'a bad year' suggest that extreme events play an important role in updating these decision-making models. Through different but repeated events, models take on new meanings, as respondents gain new understandings of the risks and opportunities of different responses and their potential outcomes. From new meanings, new proactive adaptation responses are borne. Again, the lens of extremes during the 'good/bad' year made this development and iteration of adaptation strategies especially visible. But we propose that, through ongoing experience of recurrent but different events, this is likely to occur to varying extents in all years.

We also see evidence that adaptation learning is not just tacit (c.f. Berkhout et al., 2006). Respondents actively embed processes of experimentation within their business activities and observe outcomes, across both regular business cycles and irregular and extreme events (for example, through experimental approaches to managing and monitoring small numbers of vines, separate from a main crop). This reflects the value that actors within the sector place on their own localised experience in deciding on adaptation action (Fig. 4) and also how they actively seek to learn and enhance this experience through experimentation. Respondents also encounter and actively seek out other forms of knowledge, or indirect signals, (e.g. from social and business networks, from national government and industry associations and academia). Our data suggest that these indirect signals shape how respondents interpret direct experience and the actions that they undertake. Thus, despite the ambiguity of direct signals of climate change (Berkhout et al., 2006), climate change has become a kind of master-narrative in the sector, through which respondents often interpret their experiences[4] (c.f. Hulme, 2023).

[4] "*In [the last] 10 years, we've seen some of the warmest summers ever recorded, we've seen some of the biggest harvests we've ever had. And those are all driven by temperature [and climate change]. So I think it has enabled us to change the varieties that we've been planting and growing*" Respondent 14 explained.

The updates made to business operations and strategy following experiences during a good year (Section 5.4.4) and a bad year, highlight that often irregular and extreme events constitute a focal or tipping point, from which new investment or innovation in adaptation emerges (e.g. investment in storage). Our data suggest that dynamic, localised experiences of climate extremes and variability over short and medium timescales, can contribute to incremental and even transformative adaptation action, that allows actors to move from responding to acute shocks and pressures, to adapting their activities to prepare for longer-term climate trends. Following experience of severe frosts, Respondent 11, for example, described a desire to invest in expensive frost equipment to protect their production from ongoing spring frost risk, which represents a key ongoing climate risk for the sector. "*We would like to spend a lot more money on frost protection, so we know that we will [reliably] have a crop. Because one year we lost 75 percent of our grape production in one night*" they explained. In the wine sector, this finding highlights that annual vintage variation can drive longer-term strategic planning.

Nevertheless, literatures highlight the risks of using climate variability and previous events and experiences to guide adaptation to climate change (e.g. Dilling et al., 2015). Moreover, within complex and constantly evolving risk environments, it is clear that adaptation actions in the UK wine sector are undertaken in response to multiple interacting climatic and non-climatic stressors (c.f. Feola et al., 2015; Nicholas and Durham, 2012). Adaptation actions undertaken in such contexts can create conditions, contingencies and entanglements that shape adaptation pathways and the desirability and feasibility of future adaptation actions.

We have not evaluated the potential of the different adaptation responses that we've identified to reduce climate risk. However, we see signs of potential adaptation lock-in emerging, where future adaptation actions are likely to be limited by path dependencies arising from previous decision making. This is particularly apparent in our dataset in areas where – amidst fears of market saturation in a rapidly growing sector – businesses are seeking to set themselves apart from their competitors through adoption of unique marketable characteristics in their products and services. In doing this, they are locking-in to specific production systems, which may be incompatible with, or reduce flexibility towards, adaptation opportunities (Clark and Kerr, 2017). Subscription to the 'Sussex' PDO label, for example, requires wine to be made entirely from grapes grown in Sussex, where producers may otherwise source grapes from multiple counties, to buffer losses experienced in a given region, in a given year (e.g. due to frost). The 'English Quality Sparkling Wine' PDO, meanwhile, limits choices about which grape varieties producers can plant and is associated with maximum yield thresholds, that were exceeded by some producers during the hot summer of 2018. This example clearly shows that regulation and other factors in the business environment also play an important role in enabling resilient adaptation. It also suggests that business decisions that may appear maladaptive in the context of climate change, may be made deliberately, resulting from a complex balance of business trade-offs. As explained by Respondent 18, for example, "*we are not going to start looking at new disease resistant varieties… While growing them might be easier, selling them would not be*".

7. Contributions

This case study of the UK wine sector stands in contrast to earlier literatures which suggest that businesses consider climate change to be too uncertain or long-term to engage in proactive adaptation. This study highlights extensive ways in which businesses in the UK wine sector integrate proactive action, intended to support adaptation, into their business design and activities. In doing so, it makes a number of notable contributions to existing adaptation literatures. Findings reflect and extend suggestions that experience of extreme events and exposure to climate risk (and opportunity) is likely to influence the salience of climate change (Demski et al., 2017; Reser et al., 2014) and the mode and extent of adaptation (Berkhout et al., 2006; Blennow et al., 2012); and that farmers are likely to be especially attuned to climatic changes due to their close and dependent relationship with the weather (Geoghegan and Leyson, 2012).

Through our analysis of the wine sector, we have proposed a typology of business decisions that may be shaped by adaptation objectives, which may have transferability to other sectors and could be adopted and developed in future research. The potential for any of these adaptation responses to reduce climate risk cannot be assumed. However, this typology may serve as a useful pathway for identifying and investigating adaptive responses in other business contexts; particularly since adaptation actions often sit along 'the adaptation-development spectrum', meaning they are not always immediately recognisable as adaptation behaviours.

The research also demonstrates that amidst climate change 'opportunities', climate risk remains present. Real world adaptation produces winners and losers, highlighting that adaptation opportunities and challenges interact and need to be jointly incorporated into adaptation planning. Business relationships have been an under-considered dimension in literatures on business enabling environments for private sector adaptation. Yet, as we move beyond thinking about the direct impacts of climate risk, this study shows that value chains are important sites through which climate impacts are amplified or attenuated through social responses and thus require greater attention within adaptation theory and practice. Collaboration and sector-wide systems perspectives will be essential to enable joint problem solving. It is notable that none of our interview respondents mentioned undertaking structured climate risk assessments within their business; a finding which wider literatures suggest is not unique to this sector. New climate risk assessment and adaptation planning methods, that account for business interactions across spatial and temporal scales, are likely going to be needed to maximise opportunities and avoid maladaptation within the private sector.

Results in this study also empirically demonstrate the need to conceptualise adaptation, not as a discrete and static event, but as an ongoing iterative process of adjustment and learning. Our data suggest that businesses creatively and dynamically iterate their practices and activities through both their repeated performance within business cycles and in response to encounters with novel circumstances. We suggest actors in the UK wine sector draw on their own localised understandings in deciding on adaptation action, continually iterating models which link experience to projections of the future. They also actively seek to learn and enhance their understandings through experimentation and through the integration of these experiential forms of knowledge, with other forms of knowledge (e.g. from business networks and industry associations). Extreme events are key moments in the iteration and innovation of adaptation strategies, including for longer-term climate change. Our work adheres to Berkhout et al.'s (2006) theory of organisational adaptation wherein organisations update routines through learning and experience. But it also recognises the decision-making models of actors within organisations, suggesting that these models may serve as a fruitful avenue for future enquiry towards more nuanced understandings of adaptation learning.

This case study also highlights that even a sector with high awareness of the opportunities and challenges of climate change can be in danger of creating adaptation lock-in. Businesses within the nascent UK wine sector are arguably freer to define wine tastes, styles and production and marketing strategies, that maximise the opportunities of warmer climates and account for changing climate risks, than many longer-established wine regions globally. Yet our case study shows that adaptation is undertaken in complex and constantly evolving risk environments, in response to multiple interacting climatic and non-climatic stressors and adaptation measures are often adopted with the goal of simultaneously addressing both short-term variability and longer-term change. There is emerging evidence in this study that some adaptation actions being adopted may be sub-optimal to cope with future climate change. Indeed, without ongoing innovation in their application, we suggest that some adaptation strategies within the UK sector may risk recreating inflexibilities seen in other more established viticultural regions, that will limit the ability businesses have to adapt to future climate pressures at inter-annual and longer-term scales. Timely identification of adaptation lock-in risks is likely to be an essential component of ensuring long-term resilience to climate change across a wide range of production systems and economic sectors.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr Alistair Nesbitt is CEO of Vinescapes Ltd. Vinescapes provides both strategic consultancy and operational services to the UK wine production sector. Professor Steve Dorling is Professor of Meteorology at the University of East Anglia and CEO of Weatherquest Ltd. Weatherquest support viticulture clients with weather and climate services through Vinescapes Ltd. The other authors declare no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2023.100572.

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