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Conference Paper · July 2016

DOI: 10.13140/RG.2.2.11875.14883

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Abstract
Climate change is impacting wine production in all parts of the world in highly variable ways that may change the expression of *terroir*, from rapid loss of viability right through to highly beneficial aspects that increase suitability. The ability of the wine sector to adapt to climate change is largely constrained in a relatively consistent manner across the world, with very similar barriers being identified in several countries (Aus, USA, Por, Ita, Esp). The most important of these include accessibility to meaningful predictive climate data projections, the capacity and ability to use the predictive data, and the identification of relevant and practical adaptation response actions. The authors are proposing the development of a simple guide to possible response actions based on a hazard risk analysis and a control point approach that will incorporate a wide range of viti-vinicultural climate types and *terroirs*. The guide will constitute a framework that can be upgraded as new adaptation options become uncovered through research and practical experience relevant to each region, thereby allowing individual regions to better define their own relevant adaptation strategies. A preliminary framework covering a sample section of the value chain will be presented for discussion.

Keywords: climate change, impacts, terroir, adaptation, global framework

INTRODUCTION

Climate is arguably the most important determining factor of ‘terroir’ of wine for a given varietal. Climate change is impacting wine production in all parts of the world in highly variable ways that may change the expression of *terroir*, from rapid loss of viability right through to highly beneficial aspects that increase suitability. An example at one end of such impact is the recent expansions in wine production in the United Kingdom and Denmark, where previously the climate was relatively inhospitable for wine grape growing.

The impacts of climate change on the wine industry that are already being reported include advancing harvest dates (Daux et al., 2011; Webb et al., 2011), shifts in vineyard production areas (e.g. removal in some and planting in others, Fraga et al., 2016), compressed vintages (Fraga et al., 2013; Dunn et al., 2015), increased hang time (due to decoupling of flavour and sugar ripening, Sadras et al., 2012; Bonada et al., 2015), increased bushfire risk (Head et al., 2014; Marangon et al., 2016), more heatwaves (Christidis et al., 2014; Webb et al., 2010), changed vineyard management techniques (Salomé et al., 2016; Webb et al., 2007), and increased refrigeration need in wineries (Barbaresi et al., 2016; Estrada-Flores and Platt, 2007).

If the wine industry in any part of the world wishes to survive and thrive in the future, it will need to adapt to the challenges of climate change. Under a changing or changed climate it will be important for individual producers to decide whether ‘business as usual’ remains a viable and sustainable option, or if changing their style of wine will allow for improved value through maintaining and enhancing consumer perception of the new ‘terroir’.

Whilst the range and extent of impacts will be highly variable for each wine growing region across the globe, it is clear that the ability of the wine sector to adapt to climate change is largely constrained in a relatively consistent manner across the world. This is because very similar hurdles have been identified in several countries including Australia[1], the United States of America[2], Portugal[3], Italy[4] and Spain[5]. Underpinning most of those hurdles is a general lack of easily accessible, understandable and usable climate change forecasts in a relevant timescale at locally specific resolution, and a clear outline of how they can be used to decide the most appropriate practical adaptation options that are best suited to the region.

In meeting this challenge, we propose that there is a need for a generalised framework that will be a resource providing a systematic method for wine producers to know where to find relevant and practical information about climate change forecasts, evaluate their reliability and use them to assess potential adaptation options. The framework will aid decision-making through a risk assessment based model that examines both the probability of occurrence with seriousness of impacts, thus providing an objective basis for decisions within a chosen strategic mindset (i.e. optimistic, balanced, pessimistic etc.). The framework will also allow for evaluation of the impact of business decisions (e.g. outsourcing equipment access such as harvesters can lead to loss of control when rapid need is required) as well as provide for process integration and higher level evaluation or for drill-down of process activities to understand how they affect overall outcome and simulate different options.

By investing in the development of a globally relevant framework, a range of benefits will be realised for the wine industry, including:

- Avoiding replication in planning efforts as well as R&D across countries, tapping into the publicly available information at the global level
- Reducing the risk (and cost) of mistakes for regions when implementing adaptation options, through the collation of regionally-relevant adaptation responses
- Increasing the capacity and capability of industry to adapt to climate change
- Creating a standardized approach that allows for comparison between scenarios, locations and technological options in different regions

MATERIALS AND METHODS

A preliminary framework was prepared that has at its heart a flow chart that elicits responses to a standardised set of aspects to help guide the user towards decisions that can then be developed into a practical action plan. The framework is based on the HACCP (hazard analysis and critical control point) approach (Pierson and Corlett, 1992). HACCP systems define process control as a function of critical control points (CCPs), which are critical to control and monitoring of the process to minimise risks. Being preventive, HACCP is seen as the most cost-effective approach to process control and, because it focuses on CCPs, it improves the scientific basis for safety and control processes. The framework we propose is a simple staged system, which can be tailored by the individual to meet their own perceptions of degree of risk and for their choice of timeframe of consideration. The stages are described below:

Stage 1 - Identification of key impacts

The first stage guides the user to identify the impacts from climate change that are of relevance to their own particular region and within the timeframe of their interest. A preliminary generic list (Table 1) was prepared that allows the user to select the impacts, however this needs to be further expanded along the full production chain in the full development of the framework that we propose. In this example list, for each process and impact, a range of needed weather / climate forecast lead-times are proposed to allow for meaningful adaptation decision-making.

In some process impacts, forecasts are required that have different timeframes, as illustrated by the shaded cells in Table 1. For example, a successful assessment of water needs requires short-term weather forecasts to calculate water allocation during a given year’s growth cycle, medium-term weather outlooks to prepare logistics to counter years of drought or increased pest pressure and long-term climate forecasts to set up adequate irrigation networks (e.g. pumping, flow, distribution, control, etc.).

[1] http://research.wineaustralia.com/research-development/applying-for-funding/

[2] http://www.academicwino.com/2015/10/climate-change-california-wine-somm-journal.html/

[3] http://www.advid.pt/imagens/artigos/13492774081061.pdf

[4] http://tinyurl.com/h7wngeg

[5] http://www.mdpi.com/2071-1050/7/5/5094/htm

Table 1. Preliminary sample of some of the climate change impact factors for various processes in the production chain and their respectively decision-making relevant weather / climate forecast lead-times.

PROCESS Impacts	Short-term (1-30 days)	Medium-term (1-12 months)	Long-term (1-50 years)
PLANTING VINEYARD			
Siting			
Choice of scion variety			
Choice of rootstock			
Assessment of water needs			
Choice of trellis			
GROWING GRAPES			
Growth cycle duration			
Pathogen pressure			
Abiotic stress			
Productivity			
Quality			
Identity			
MAKING WINE			
Wine style			
Harvest date			
Harvest duration			
Building design			
Energy consumption			
Emissions			
LOGISTICS			
Destination constraints			
Choice of itinerary and transportation			
Fuel and energy consumption			
Emissions			
DRINKING WINE			
Style suitability			
Trends, fads and fashion			
Seasonality			

<u>Stage 2 - Risk assessment for significance</u>

In this stage, the relative risk of an impact is assessed and then assigned a 'significance' rating that provides a ready means of prioritising actions.

A risk assessment matrix (Figure 1) was adapted from Weiss (2003), that takes account of varying levels of belief in respect of climate change, ranging from 'Scientific absolutist' to 'Environmental absolutist'. For greater simplicity, in our adaptation of Weiss' work, we retained three levels of belief: balanced, optimistic and pessimistic. The risk assessment considers the confidence of the impact as well as the degree of intervention required in adapting in order to arrive at a 'risk score'. The risk score is then considered according to the belief values of the user to determine the significance of each step. The high significance risks can then be considered as a CCP for further analysis, however, the user can then proceed to address all the various risks if they wish.

Intervention / Confidence		Impossible	Hunch	Suspicion	Belief	Clear indications	Preponderance	Credible	Clearly showing	Clearly convincing	Doubtless
		1	2	3	4	5	6	7	8	9	10
Whatever it takes	1	1	2	3	4	5	6	7	8	9	10
Comprehensive measures	2	2	4	6	8	10	12	14	16	18	20
Expensive & politically(financially?) difficult measures	3	3	6	9	12	15	18	21	24	27	30
Measures against more serious aspects	4	4	8	12	16	20	24	28	32	36	40
Formal plans for strong measures	5	5	10	15	20	25	30	35	40	45	50
"No regrets" measures	6	6	12	18	24	30	36	42	48	54	60
Ban low-benefit, high damage actions	7	7	14	21	28	35	42	49	56	63	70
Research & monitoring	8	8	16	24	32	40	48	56	64	72	80
Research only if public opinion demands it	9	9	18	27	36	45	54	63	72	81	90
Reassure public & decision makers	10	10	20	30	40	50	60	70	80	90	100
		Score range (balanced decision-maker)				Score range (optimistic decision-maker)			Score range (pessimistic decision-maker)		
Low risk significance - no intervention		1	to	21		1	to	41	1	to	11
Moderate risk significance - consider intervention		22	to	59		42	to	89	12	to	39
High risk significance - execute intervention		60	to	100		90	to	100	40	to	100

Figure 1. Risk assessment matrix for CCP identification (adapted from Weiss, 2003)

Using this matrix, a balanced decision-maker would only consider intervention (i.e. identify as CCP) using formal plans for strong measures for a risk for which there are clear indicators that it may occur (risk score > 22). For the same risk, an optimistic decision-maker (one that will invest or move resources only when convinced that risk is inevitably threatening to business) would do the same only when available information is clearly convincing of the inevitability and seriousness of the risk (risk score > 42). A pessimistic decision-maker (one that is ready to spend resources on preventing materialization of even low-probability threats to business), on the other hand, would intervene at the same level as soon as a suspicion on the risk arises (risk score > 12).

<u>Stage 3-Identification of key factors</u>

This stage of the framework allows for the identification of the factors that need to be considered in understanding what the impacts of climate change will be at each CCP identified in Stage 2. A fully developed framework will have more factors than were identified for the purposes of this study.

<u>Stage 4 - Assess critical points</u>

This stage continues further to develop responses for each of the key factors identified in Stage 3 for each CCP. A standardised set of activities has been developed for this part of the analysis as illustrated in Figure 2. For each step, the status of knowledge and range of impacts and opportunities relevant to the region are listed and considered.

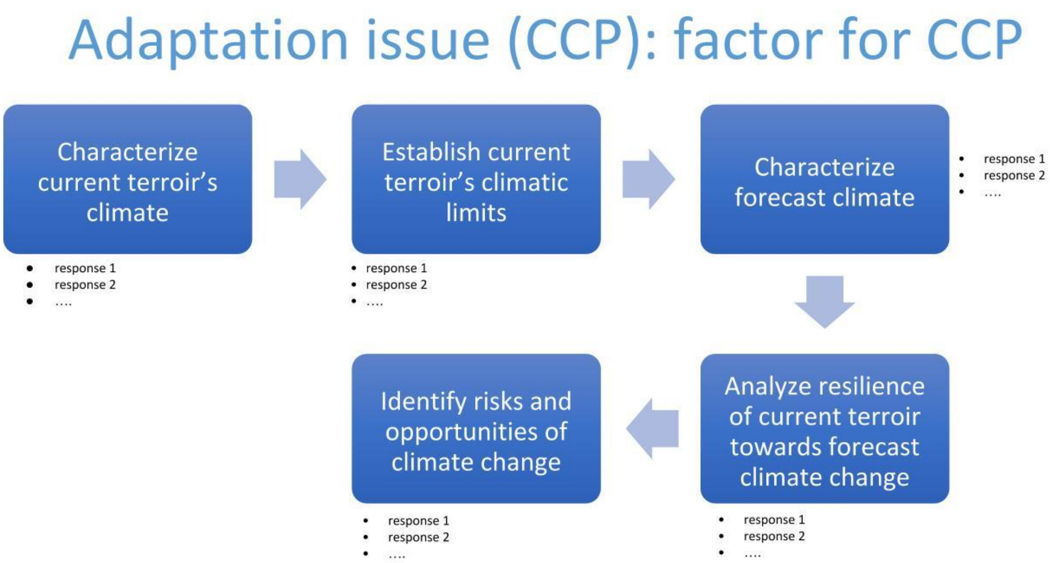

Figure 2. Standardised set of activities for assessing each impact factor of a 'critical control point'

The framework aims to answer the following questions in respect of each critical control point:

- Which sources of climate information exist (both historical and forecast) that allow for better planning of climate impacts for:
    - getting grapes that allow the best expression of the vineyard's terroir and,

- maximizing operational profitability
- How accessible and easily usable are those sources by the wine industry?
- Which geographical areas in those regions are already covered, which are currently being studied and which are not yet considered?

Stage 5 - Develop an action plan

Following completion of the first four stages, an action plan for adaptation can be developed, which will include consideration of the business case for change, as well as identify any missing knowledge and consequently R&D needs. Developing an action plan was outside the scope of this study, which was intended to demonstrate the feasibility of the framework approach. The fully developed framework could include a template action plan for users.

RESULTS AND DISCUSSION

In undertaking the analysis it was necessary to limit the scope to a reasonable boundary. Therefore, the work described here was limited to two critical processes, directly influenced by climate, on two different time-frames; one long-term (i.e. creation of a new vineyard) and the other mid- to short-term (i.e. setting the harvest date), in three world wine-growing regions, being (a) Australia and New Zealand (AUS/NZ), (b) European Union (EU), and (c) North America (USA/CAN). These two "critical control points" were identified by applying the first two stages of the framework to a generalised process flow of wine production, and then using the risk matrix for each of the regions within the scope of the study and for an intermediate degree of belief in climate change.

An important underlying step was to identify the various sources of climate change prediction data and conduct a preliminary assessment for the three wine-growing regions covered within the scope of the work. This assessment appears as Appendix 1.

Creation of new vineyard

The results of the application of the first two stages of the framework leading to identification of this as a critical control point is given in Table 2.

Table 2. Climate-driven CCPs in the process of creating a vineyard and their respective relevant lead-time assessment for successful adaptation

PROCESS Impacts	Short-term (1-30 days)	Medium-term (1-12 months)	Long-term (1-50 years)
PLANTING VINEYARD			
Wines to be made			
Siting & terrain preparation			
Choice of scion variety			
Choice of rootstock			
Assessment of water needs			
Choice of trellis			
Planting density			

The process of planting a vineyard is identified as a CCP. According to the level of significance a grower confers onto this process, the intervention should be reasoned according to the confidence of the perceived risk. For example, a balanced decision-maker could easily accept that the vineyard's success will be highly dependent on the choice of scion variety. In this case, if that choice is perceived as clearly showing risk towards return on the investment of planting the vineyard, the balanced decision-maker would be open to execute interventions such as research and monitoring but wary of moving into actual actions before the perception becomes clearly convincing. A pessimistic decision-maker, however, might go for formal planning for strong measures, while an optimistic one would only consider action but not execute any at this stage. The risk assessment matrix, thus provides an objective tool for decision as a function of perceived risk.

Assuming a balanced stance for decision-making, stages three and four of the framework were then applied giving rise to the complete information required (Table 3) for creation of an action plan.

Setting the harvest date

The results of the application of the first two stages of the framework leading to identification of this as a critical control point is given in Table 4.

Table 4. Climate-driven CCPs in the process of making wine and their respective relevant lead-time assessment for successful adaptation

PROCESS Impacts	Short-term (1-30 days	Medium-term (1-12 months)	Long-term (1-50 years)
MAKING WINE			
Wine style			
Harvest date			
Harvest duration			
Building design			
Energy consumption			
Emissions			

Stages three and four of the framework were then applied giving rise to the complete information required (Table 5) for creation of an action plan.

Table 3. Control point assessment for: Creation of new vineyard

Impact factor	Characterize current terroir's climate	Establish current terroir's climatic limits	Characterize forecast climate	Analyze resilience of current terroir towards forecast climate change	Identify risks and opportunities of climate change
Wines to be made	Define relevant climatic indices	Establish historical range of variation for climatic indices	Calculate new climatic indices from forecast climate variables	Compare new climatic indices with historical ones	List probable impacts on changes of wine style and production indicators (yield, date of harvest, etc.)
	Define wine style indicators	Propose acceptable range of variation for wine style conservation		Evaluate trend and magnitude of change	Propose new wine styles made possible and plan for production
				Evaluate probable effect on variation of wine style indicators	
Terrain preparation	Define relevant climatic indices	Establish historical range of variation for climatic indices	Calculate new climatic indices from forecast climate variables	Compare new climatic indices with historical ones	List probable impacts on changes of fertility, water balance and erosion risk
	Establish fertility issues	Propose acceptable range of variation for conservation of current terroir terrain characteristics		Evaluate trend and magnitude of change	Identify new needs for irrigation, drainage, deep fertilization and erosion control.
	Establish current water balance			Evaluate probable effect on terrain characteristics	Plan for adaptation.
	Establish current erosion risk				
	Identify needs for irrigation, drainage, deep fertilization and erosion control				
Variety + rootstock	Define relevant climatic indices	Establish historical range of variation for climatic indices	Calculate new climatic indices from forecast climate variables	Compare new climatic indices with historical ones	List varieties and rootstocks that will be out of their climatic range
	List currently adapted varieties	Propose acceptable range of variation for conservation of current varieties and rootstocks, considering their climatic ranges		Evaluate trend and magnitude of change	Identify new varieties and rootstocks that fit the new climatic situation
	List currently adapted rootstocks			Evaluate suitability for current varieties and rootstocks	
Water needs	Define relevant climatic indices	Establish historical range of variation for climatic indices	Calculate new climatic indices from forecast climate variables	Compare new climatic indices with historical ones	Estimate level of risk for keeping «business as usual»
	Establish historical yield series	Propose acceptable range of variation for water availability to conserve wine style and historical level of yield		Evaluate trend and magnitude of change for water availability	Identify new production chains more in line with forecast new water availability situation and how to adapt vineyard to them
	Evaluate historical water requirements			Assess terroir resilience under new climate	

Impact factor	Characterize current terroir's climate	Establish current terroir's climatic limits	Characterize forecast climate	Analyze resilience of current terroir towards forecast climate change	Identify risks and opportunities of climate change
	Establish historical terroir's water availability				
Training system	Define relevant climatic indices	Establish historical range of variation for climatic indices	Calculate new climatic indices from forecast climate variables	Compare new climatic indices with historical ones	Estimate level of risk for keeping «business as usual»
	List training systems in use for terroir and compare their adequacy	Propose acceptable range of variation for currently used training systems		Evaluate trend and magnitude of change	Identify new training systems more in line with forecast new water availability situation and possibilities to evolve from current to those
				Assess adequacy of current training system under new climate	
Density of planting	Define relevant climatic indices	Establish historical range of variation for climatic indices	Calculate new climatic indices from forecast climate variables	Compare new climatic indices with historical ones	Estimate level of risk for keeping current density
	Evaluate current density of plantation	Propose acceptable range of variation for current density of plantation		Evaluate trend and magnitude of change	Identify new density more in line with forecast new water availability situation
				Assess adequacy of current density under new climate	Plan for density change

Table 5. Control point assessment for: Setting of harvest date

Impact factor	Characterize current terroir's climate	Establish current terroir's climatic limits	Characterize forecast climate	Analyze resilience of current terroir towards forecast climate change	Identify risks and opportunities of climate change
Wines to be made	Define relevant climatic indices	Establish historical range of variation for ripening rates	Calculate new ripening rates from forecast climate variables	Compare new ripening rates with historical ones	List probable impacts on changes of wine style and production indicators (yield, date of harvest, etc.)
	Define wine style indicators	Propose acceptable range of variation for wine style conservation or innovation		Evaluate trend and magnitude of change	List possible actions to conserve wine style
				Evaluate probable effect on variation of wine style indicators	Propose new wine styles made possible and plan for production
Ripening control	Define relevant climate indicators that are drivers of ripening rates and characteristics	Establish historical range of variation for ripening rates and characteristics	Calculate new ripening rates from forecast climate variables	Compare new ripening rates with historical ones	List probable impacts on ripening characteristics
	Define indicators of ripening characteristics for current terroir	Propose acceptable range of variation for conservation of current terroir ripening characteristics		Evaluate trend and magnitude of change for significance	Identify response options for control of ripening to achieve preserved wine style.

Impact factor	Characterize current terroir's climate	Establish current terroir's climatic limits	Characterize forecast climate	Analyze resilience of current terroir towards forecast climate change	Identify risks and opportunities of climate change
	Establish acceptable models for ripening rate prediction			Evaluate probable effect on ripening characteristics	Plan for implementation of preferred adaptation options
	Establish compositional indicators relevant to and influenced by ripening				
Logistics	Define relevant climatic indices and logistics indicators (KPIs)	Establish historical range of variation for climatic indices and logistics KPIs	Calculate new climatic indices from forecast climate variables	Compare new climatic indices with historical ones	List risks in logistics chain equipment and planning methods
	List current logistics needs (e.g. harvester, transport fleet, labour, winery load charts, etc.)	Propose acceptable range of variation for conservation of current logistics (i.e. variance of planned vs actual)		Evaluate trend and magnitude of change for significance of impact on logistic KPIs	List response options for logistics and winery (e.g. extend/shorten hang time, fleet expansion, sub-contract infrastructure)
	List current planning principles (e.g. method of scheduling intake at winery, method for contingencies and changes, reuse number per vat, etc.)			Evaluate suitability of current styles with changed logistics	

A proposal for full development of the framework

The framework used in this study shows promise as a globally-applicable tool, but it would require further development and refinement to validate the approach beyond the limitations of the scope of this preliminary study. A large proportion of the background work has been undertaken in this study, and complete expansion of the framework would be achievable in a relatively short period of time. Such development would need to involve expert practitioners from the global wine sector in order to ensure complete relevance. There will also be a need for collation of a large amount of information about climate change data and forecasts from around the world, and it will be important that collaborators are in a position to ensure that knowledge and information gaps identified will be addressed in a timely fashion.

Given the need for international collaboration, there will be a requirement for some overall management of the project at the global industry level, for example the OIV. The authors consider that if sufficient interest exists from the wine sector to further develop this framework, that they would be prepared to lead a collaborative proposal to suitable funding and coordinating wine industry organisations. Expressions of interest and support of industry are sought by the authors.

CONCLUSION

A paradox exists today in the wine industry: being dubbed the «canary in the coal mine» of climate change for several years (Goode, 2012). There is a large corpus of research that has been growing exponentially to address expected outcomes of climate change, the impacts at different scales and points of the value chain and mitigation and adaptation strategies together with an increasingly comprehensive set of base data from remote or more recent times (Ashenfelter & Storchmann, 2016) that focus specifically the grape and wine industry. Yet, very little is still understood by the wine industry in terms of what climate change is, how it can be forecast, what uncertainties exist, if and how currently existing forecasts can be used for assessing risks and to support decision-making. This apparent paradox has been highlighted in a recent paper (Sacchelli et al., 2016) and seems to stem from inefficient uptake of scientific findings by the socio-economic community.

At the same time, the climatology science community is busy developing ways of communicating climate change to farmers and the creation of successful climate services tailor-made for end-users and developed with them is a major aspect of current ongoing research projects (Brasseur & Gallardo, 2016).

In this work, a preliminary proposed 5-stage framework for developing climate change adaptation plans has been developed and tested.

The framework uses an HACCP-based approach utilising a novel risk assessment matrix to identify key control points in wine production process chain which can then be evaluated and addressed for adaptation.

The framework was shown to have promise as a globally-relevant method for developing practical climate change adaptation plans in the context of conserving terroir or developing new paradigms for the consumer market. Its global applicability allows for researchers and practitioners to collaborate to locally assess their own adaptation challenges and opportunities. At a later stage, because of the common framework, local assessments may be combined in a joint global assessment for the benefit of the wine industry. This global assessment will be useful to create specific policies upholding wine industry sustainability and to objectively evaluate the effects of other policies that bear impact on it (water, emissions, biodiversity, trade, etc.).

If sufficient interest from industry exists, then the authors propose a full development of the framework to be conducted under the auspices of a global wine industry organisation or a consortium of similar peak bodies in wine producing countries.

LITERATURE CITED

Ashenfelter, O., & Storchmann, K. (2016). The Economics of Wine, Weather, and Climate Change. Review of Environmental Economics and Policy, rev018.

Barbaresi, A., Dallacasa, F., Torreggiani, D., & Tassinari, P. (2016). Retrofit interventions in non-conditioned rooms: calibration of an assessment method on a farm winery. Journal of Building Performance Simulation, 1-14.

Bonada, M., Jeffery, D.W., Petrie, P.R., Moran, M.A. & Sadras, V.O. (2015), Impact of elevated temperature and water deficit on the chemical and sensory profiles of Barossa Shiraz grapes and wines. Australian Journal of Grape and Wine Research, 21: 240–253.

Brasseur, G. P., & Gallardo, L. (2016). Climate services: Lessons learned and future prospects. Earth's Future, 4(3), 79-89.

Christidis, N., Jones, G. S., & Stott, P. A. (2015). Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. Nature Climate Change, 5(1), 46-50.

Daux, V., de Cortazar-Atauri, I. G., Yiou, P., Chuine, I., Garnier, E., Le Roy Ladurie, E., ... & Tardaguila, J. (2011). An open-database of Grape Harvest dates for climate research: data description and quality assessment. Climate of the Past Discussions, 7(6).

Dunn, M.R., Lindesay, J.A. & Howden, M. (2015), Spatial and temporal scales of future climate information for climate change adaptation in viticulture: a case study of User needs in the Australian winegrape sector. Australian Journal of Grape and Wine Research, 21: 226–239.

Estrada-Flores, S; & Platt, G (2007). Electricity usage in the Australian cold chain, Food Australia, 59: 8; 382-390.

Fraga, H., Malheiro, A. C., Moutinho‐Pereira, J., & Santos, J. A. (2012). An overview of climate change impacts on European viticulture. Food and Energy Security, 1(2), 94-110.

Fraga, H., Santos, J. A., Malheiro, A. C., Oliveira, A. A., Moutinho‐Pereira, J., & Jones, G. V. (2016). Climatic suitability of Portuguese grapevine varieties and climate change adaptation. International Journal of Climatology, 36(1), 1-12.

Goode, J. (2012). Viticulture: Fruity with a hint of drought. Nature, 492(7429), 351-353.

Head, L., Adams, M., McGregor, H. V. & Toole, S. (2014), Climate change and Australia. WIREs Clim Change, 5: 175–197. doi: 10.1002/wcc.255

Marangon, M., Nesbitt, A., & Milanowski, T. (2016). Global Climate Change and Wine Safety. In Wine Safety, Consumer Preference, and Human Health (pp. 97-116). Springer International Publishing.

Sacchelli, S., Fabbrizzi, S., & Menghini, S. (2016). Climate change, wine and sustainability: a quantitative discourse analysis of the international scientific literature. Agriculture and Agricultural Science Procedia, 8, 167-175.

Sadras, V. O., & Moran, M. A. (2012). Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc. Australian Journal of Grape and Wine Research, 18(2), 115-122.

Salomé, C., Coll, P., Lardo, E., Metay, A., Villenave, C., Marsden, C., & Le Cadre, E. (2016). The soil quality concept as a framework to assess management practices in vulnerable agroecosystems: A case study in Mediterranean vineyards. Ecological Indicators, 61, 456-465.

Webb, L. B., Whetton, P. H. & Barlow E. W. R. (2007), Modelled impact of future climate change on the phenology of winegrapes in Australia. Australian Journal of Grape and Wine Research, 13: 165–175.

Webb , L., Whiting, J., Watt, A., Hill, T., Wigg, F., Dunn, G., Needs, S., & Barlow, E.W.R. (2010). Managing Grapevines through Severe Heat: A Survey of Growers after the 2009 Summer Heatwave in South-eastern Australia, Journal of Wine Research, 21 (2-3), 147-165.

Webb, L. B., Whetton, P. H. & Barlow E. W. R. (2011), Observed trends in winegrape maturity in Australia. Global Change Biology, 17: 2707–2719

Weiss, C. 2003. Scientific Uncertainty and Science-Based Precaution. International Environmental Agreements: Politics, Law and Economics 3:137-166.

Appendix 1 – Inventory and assessment of currently available open-source climate change data sources for the regions studied.

Name	Institution	Country	World region	Spatial coverage	Historical data	Forecasts	Summary
CLIMATE-ADAPT	European Commission	Belgium	EU	Europe	No	Impacts	The Climate-ADAPT Map Viewer provides observations and projections of climate change impacts, vulnerability and risks from the following projects and organisations: ClimWatAdapt, ESPON Climate,JRC-IES and ENSEMBLES.
Climate Change Scenarios	MeteoSwiss	CH	EU	Switzerland	Since 1864	Until 2101	The climate change scenarios have been developed by Swiss researchers for the "Swiss Climate Change Scenarios CH2011" initiative, led by the ETH Zurich and MeteoSwiss. The results, published in 2011, pull together the latest knowledge on climate change in Switzerland, as all relevant studies that were available at the time were fed into the model simulations. The changes that can be expected to occur in temperatures and precipitation were given for three Swiss regions: north eastern, western and southern Switzerland.
IMPACT2C WebAtlas	EC	EU	EU	EU	NA	+2°C, +3°C	The IMPACT2C web-atlas depicts the climate change impacts of a +2°C global warming for the key sectors – energy, water, tourism, health, agriculture, ecosystems and forestry, as well as coastal and low-lying areas, – at both the pan-European level, and for some of the most vulnerable regions of the world. By using a multi-model ensemble of both climate and impact projections it is possible to define ranges of impacts and therefore quantify some of the uncertainty around future climate and climate impact projections.
Climate change initiative	ESA	France	EU	Global	Since early 1990s	No	The objective of the Climate Change Initiative is to realize the full potential of the long-term global Earth Observation archives that ESA together with its Member states have established over the last thirty years, as a significant and timely contribution to the ECV databases required by UNFCCC. It ensures that full capital is derived from ongoing and planned ESA missions, including ERS, Envisat, the Earth Explorer missions, relevant ESA-managed archives of Third-Party Mission data and the Sentinel constellation.
ClimatHD	Meteo France	France	EU	France	Since 1900	Until 2100	ClimatHD propose une visualisation simple, accessible à tous, de l'état des connaissances sur le changement climatique en France, aux échelles nationale et régionale, basée sur les derniers travaux des climatologues. L'application offre une vision intégrée de l'évolution passée du climat et des projections simulées pour le futur. Elle permet de visualiser, à l'échelle nationale et pour chaque région de France métropolitaine, l'évolution depuis 1900 et à l'horizon 2100 de différents paramètres et phénomènes : températures, précipitations, jours de gel, vagues de chaleur, vagues de froid, pluies intenses, tempêtes...
Futures of Climate	DRIAS	France	EU	France	Since 1976	Until 2100	In this space you may interactively explore the information made available in DRIAS Futures of climate, visualization, using maps, various simulated climate change scenarios for the next century over France. Two levels of exploration are proposed: a «beginner course» quick and easy and an « expert course » more complete.

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German Climate Atlas	Deutscher Wetterdienst	Germany	EU	Germany	Since 1881	Until 2100	The General section of the German Climate Atlas provides selected weather elements (air temperature, precipitation, etc.) as well as other parameters which suggest some of the possible anticipated effects of climate change.
Klimaateffectatlas Nederland	Climate Adaptation Services	Netherlands	EU	Netherlands	No	2050	This interactive tool sets (future) threats of flooding, flooding, drought and heat stress on the map. You can fill your parish name and see what is happening in your area. Using the search option makes it possible to zoom directly to a municipality or waterway.
Climate explorer	KNMI	Netherlands	EU	Global	Some series go as far back as the year 500 AD	No	The KNMI Climate Explorer is a web application to analysis climate data statistically. It started in late 1999 as a simple web page to analyse ENSO teleconnections and has grown over the years to more than 1TB of climate data and dozens of analysis tools. The KNMI Climate Explorer is not operational: if it breaks down it will be fixed during Dutch office hours. Over the last few years the availability has been pretty good, although sometimes a few users slow down the system by doing large computations simultaneously. The seasonal forecast verification page was supported by the EU project ENSEMBLES, the rest is an informal KNMI project. Much of the observational data is updated monthly. Other data is updated when needed. More and more data is pulled from external sites on request, see the link external data.
E-OBS Climate Indices	ECA&D - KNMI	Netherlands	EU	Europe	Since 1950	No	For every ECA&D station, a total of 75 indices have been calculated. Indices data are freely available for non-commercial research and education: see our data policy for more details. Each index describes a particular characteristic of climate change (both changes in the mean and the extremes). A core set of 26 indices follows the definitions recommended by the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI). These indices are calculated in a similar way for other regions of the world. An additional set of 49 indices highlights particular characteristics of climate change in Europe (including snow depth, sunshine duration, etc.).
Serviços de clima	IPMA	Portugal	EU	Portugal	Since 1865	Until 2100	Apresentam-se agora os primeiros resultados gráficos deste projeto para a temperatura e precipitação, correspondentes ao clima dos últimos 150 anos e ao clima previsto até ao final do século, identificando as anomalias em relação à normal de referência 1961-90 e utilizando dois cenários socioeconómicos contrastantes.
ENSEMBLES Downscaling Portal	Universidad de Cantabria	Spain	EU	Global	Several decades	Regional and local	The downscaling portal allows end-users to calibrate/downscale the coarse model outputs in the region of interest using historical observed records. The portal includes public observation datasets (e.g. GSOD) and allows uploading new historical data (including private datasets, not available for other users).

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							This Statistical Downscaling portal provides user-friendly web access to different statistical downscaling techniques and works transparently with the observations, reanalysis and global climate simulations (see the common list of variables available for all models in the portal), obtaining the resulting outputs in simple formats (e.g., text files).
Servicios climaticos	AEMET	Spain	EU	Spain	Since 1850	From 3 months to 2100	En este apartado se incluye información climatológica general sobre valores medios y extremos de las series de datos climatológicos, productos de vigilancia del clima, predicciones de rango estacional, y proyecciones de cambio climático para el siglo XXI para España bajo diferentes escenarios de emisión.
Decadal forecast	MetOffice	UK	EU	Global	Validation with observed values	5 years	Decadal forecasts, also called 'near-term' climate predictions, range up to a decade ahead. Predictions account for natural variability and climate change as these are expected to be of similar size in many parts of the world over this forecast period. Forecasts are experimental, so at this early stage of development expert advice is needed to assess the reliability of regional predictions.
Climate impact indicator toolkit	CLIPC: Climate Information Portal for Copernicus	UK	EU	Europe	From climatic series	Impacts according to some climate change scenarios (i.e. RCP85)	The toolkit allows you to access climate change indicators. The toolkit presents tools allowing you to explore the available data and to switch between different indicators and different climate change and socio-economic scenarios. The available impact indicators can be selected through the overarching themes CLIPC focuses on; urban, water and rural available at the top of the toolkit. The left side of the toolkit allows you to zoom in and out, select layers, add additional layers, open a help function, go back to the homepage, download and save your selection and share you selection.
Forecasts	ECMWF	UK	EU	Global	No	Medium, extended and long-range	All ECMWF's operational forecasts aim to assess the most likely forecast and also the degree of confidence one can have in that forecast. To do this the Centre carries out an ensemble of predictions which individually are full descriptions of the evolution of the weather, but collectively they assess the likelihood or probability of a range of possible future weather.
GPC Outlooks	MetOffice	UK	EU	Global	Validation with observed values	2 to 6 months	Model probabilistic guidance for temperature and rainfall up to six months ahead. Updated monthly.
Multi-model decadal forecast exchange	MetOffice	UK	EU	Global	Validation with observed values	1 to 5 years	International multi-model decadal forecast exchange. Currently three variables are included: surface air temperature, sea-level pressure and precipitation. These are shown as differences from the 1971-2000 baseline
Forecasts	ECMWF	UK	EU	Global	Since 1950s	10 days to 13 months	Our Integrated Forecasting System (IFS) provides forecasts for multiple time ranges.

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							We provide a range of forecast products to address different user requirements. These present key aspects of the forecast evolution and the associated uncertainty. Specific products designed to highlight potential severe weather events include the Extreme Forecast Index and tropical cyclone activity.
CPC Three-month outlooks	NOAA-NWS	USA	North America	USA	Since 1981	0.5 to 12.5 months	The Climate Prediction Center's (CPC) products are operational predictions of climate variability, real-time monitoring of climate and the required data bases, and assessments of the origins of major climate anomalies. The products cover time scales from a week to seasons, extending into the future as far as technically feasible, and cover the land, the ocean, and the atmosphere, extending into the stratosphere.
Flexible forecasts	IRI	USA	North America	Global	Since 1950	1 to 6 months	Probabilistic seasonal forecasts from multi-model ensembles through the use of statistical recalibration, based on the historical performance of those models, provide reliable information to a wide range of climate risk and decision making communities, as well as the forecast community. The flexibility of the full probability distributions allows to deliver interactive maps and pointwise distributions that become relevant to user-determined needs.
Global Climate Dashboard	NOAA-NWS	USA	North America	USA	Mostly since the 1950s	Until 2020	NOAA portal for climate change, climate variability and climate projection data for the USA. Is integrated with long-term data sources from NOAA and short- to long-term forecast data from the Climate Prediction Center.
NW Climate Toolbox	CIRC	USA	North America	USA	Short-term	70-90 days	The Pacific Northwest Climate Impacts Research Consortium (CIRC) is a research organization funded by NOAA to provide policy makers, resource managers, and fellow researchers with the best available science covering the changing climate of Oregon, Washington, Idaho, and western Montana.
Tableau Climate Projection Tool	CIG	USA	North America	Pacific Northwest	Varies	2050s to 2080s	The Climate Impacts Group at the University of Washington provides regional tools for helping to reduce climate risks by providing robust and reliable information that people can use when making decisions. CIG provides the fundamental scientific understanding, data, tools, and guidance decision makers need to identify and reduce climate risks. This tool allows users to graphically visualize projected changes in temperature and precipitation for two future time periods in three regions in the Pacific Northwest.
Pacific Northwest Climate Maps	CIG	USA	North America	Pacific Northwest	Since 1915	2020s to 2040s	Additional tool available from the CIG that provides an examination of how climate varies from time to time and place to place across the Pacific Northwest. The tool creates maps that show climate anomalies – the changes in climate – associated with different patterns of climate variability compared to average conditions during 1915-2003.
Cal-Adapt	Cal-Adapt	USA	North America	California	1961-1990	Mix of short-term to 2070-2099	The California Energy Commission developed the Cal-Adapt Web site to synthesize existing California climate change scenarios and climate impact research and to encourage its use in a way that is beneficial for local decision-makers.
ClimateWise	ClimateWise	USA	North America	USA	Varies	Varies	Private organization that has produced a tool and framework to help local leaders develop “Whole Community” adaptation strategies to address the impacts of climate change.

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Weather and Climate Summary and Forecast	OWB	USA	North America	Western USA, focus in wine areas	Since Spring 2014	6 to 90 days	Dr. Greg Jones has produced a weather and climate forecast update for almost six years. These updates are sent almost every month, usually around the 5-10th, during the active growing season and then less frequent in the middle of winter.
Climate Information Platform	CSAG - UCT	ZAF	Africa	Africa	Since 1894	Until 2100	CIP is a web interface that integrates two important information sources into one easy to use interface. The first important source is a climate database that stores and manages queries to a large suite of observational climate data as well as projections of future climate. The second important source of information is an extensive collection of guidance documentation that facilitates the best use of the climate data, its interpretation and, importantly, resultant actions. The philosophy guiding CIP is that data is not information and as such only has value when well interpreted and correctly used or applied to appropriate problems.
Climate change in Australia	CSIRO & DoE	Australia	Australia	Australia	Since 1950s	Yes	Provides observations and (do)decadal projections at a fairly broad scale (NRM regions) covering the four main climate 'superclusters' and the 15 'sub-clusters'. Projections in the Explorer module are given for Humidity, Rainfall, Solar radiation, Wind speed, T-mean, T-max, T-min, ET
Climate Watch	BOM	Australia	Australia	Australia	Since early 1900s	Yes	Has a range of historical data as well as projections for the next 3 months. It is possible to drill down to a reasonably high resolution for local predictions of rainfall and temperature. Outlook videos are also useful at the coarser resolution