RECENT ADVANCES IN OUR UNDERSTANDING OF THE IMPACT OF CLIMATE CHANGE ON WINE GRAPE PRODUCTION

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Abstract:

Context and purpose of the study - According to the last IPCC report, the scale of recent climate changes are unprecedented over many centuries. Each of the last four decades has been successively warmer than any decade since 1850. Projections for the future foresee that temperature could reach +3.3°C to +5.7°C under the most pessimistic scenario. It is also projected that every region will face more concurrent and multiple changes in climatic impact-drivers. The frequency of extreme climate events is also likely to increase, as well as the occurrence of indirect constraints. These evolving climatic conditions are alrealdy affecting and will continue to affect the suitability of traditional wine grape production areas, but also create opportunities in new locations.

To assess the impact of climate change on grape production, higher atmospheric CO_2 content and temperatures, as well as modified water regimes are the most considered environmental parameters, although some other features such as light quality can play a significant role. These parameters affect directly the basic physiological activities of the grapevine plant such as photosynthetic activity, mineral and water uptake, with consequences on vegetative and reproductive development as well as metabolic activities. These responses are also under the control of genotypes (both scions and rootstocks) and cultural practices. More and more studies are released, improving deeply our understanding of the mechanisms involved. At whole plant level, impacts are assessed in terms of phenology, yield, vegetative development and fruit composition. Considering the current situation, it is well known that the growing season has on average lengthened by up to 2 days per decade since the 1950s in the Northern Hemisphere and recent millesimes have experienced the most early harvests for several centuries. Berry composition has also evolved with an increasing sugar content and pH, and modified polyphenolic and aromatic compound concentrations. Crop levels have also been affected in some Mediterranean regions where water is limiting. Other living organisms interacting positively or negatively with grapevine such as microorganisms or insects are also impacted by climatic conditions, and this may affect the health status of the plant. Evaluating the impacts under future climatic conditions is a challenge by itself. While experiments are enable to test the basic physiological responses, integrating the global and long term impacts at plant or vineyard level is more complex. Combining climate and plant models is almost mandatory to simulate how grapevine could perform in the future.

From recent data collected in our research groups, we will illustrate the advances in terms of understanding the responses of grapevine from molecular to whole plant level and how modeling is a powerful tool to integrate these responses over spatial and time scales and enable to project ourselves in the future.

Keywords: Vitis, Climate change, Abiotic stresses, Biotic interactions, Complexity, Modelling

Introduction

Last IPCC report (2023) is not controversial. The increase in temperature since the pre-industrial period (1850-1900) to the last decade (2011-2020) is in average 1,1°C with 97% of this increase related to human activities. The rate of temperature rise is unprecented since 1970, in comparison to any other 50 year period over the last 2 millenars. This temperature increase is mainly due to GHG emissions which 58% occurred before 1990 et 42% over the last 30 years. The greenhouse (GHG) gas concentrations have now reached 410 ppm of CO_2, 1866 ppb for CH_4 and 332 ppb for N_20 in 2019 (IPCC, 2021). In 2019, 22% of GHGs were produced by activities related to agriculture, forestry and other land uses with high heterogeneity across regions in the world. Human activities have likely enhanced the probability of extreme event occurrence since 1950s, especially heat waves and drought. Human and ecosystems are equally impacted with several effects approaching irreversibility. One major impact is related to water availability, with 50% of the world population currently experiencing severe water scarcity for at least one part of the year. For the future, atmospheric CO_2 concentrations may reach 600 to 1000 ppm at the end of the XXIth century, depending on the most probable emission scenario (Cheng et al., 2022). Global warming will continue with almost no chance to limit it to +1.5°C, even +2°C, until the end of the XXIth century (from 1850-1900 period). The most probable temperature increase will be between +2.7°C for the intermediate GHG emission scenario and +4.4°C for high GHG emission scenario. Every additional increment in temperature will enhance changes in extreme events (Figure 1). Among others, an intensification of the global water cycle should be expected with very wet and very dry weather and climatic events and seasons. In addition, every region is projected to experience more and more multiple changes in climatic and non climatic impact-drivers and risks in climate driven food insecurity is likely to increase. Natural variability will continue to modulate general effects of climate change and this variability is important to take into account in adaptation planning. Regarding adaptation, any action that focus on sectors and risks in isolation, and on short term gains, will often lead to maladaptation over the long term.

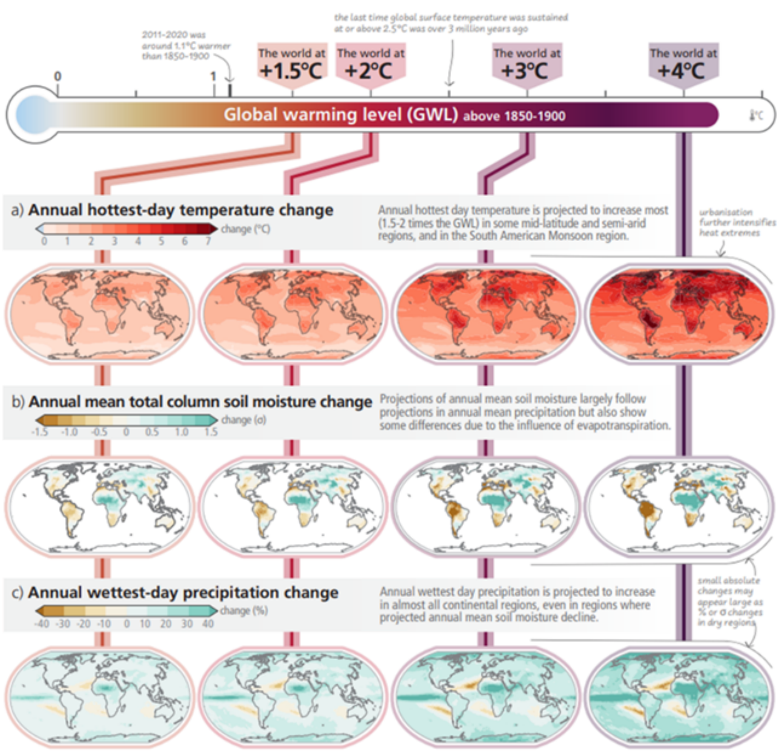


Figure 1: Projected changes of annual maximum daily maximum temperature, annual mean total column soil moisture and annual maximum 1-day precipitation at global warming levels of 1.5°C, 2°C, 3°C, and 4°C relative to 1850–1900 (IPCC, 2023).

Considering these general features and with the objectives to evaluate the risks and the opportunities for the wine sector in each producing area, it is of crucial interests to downscale climatic simulations at regional or local scales

(Quénol et al., 2017, Santos et al., 2022). A large number of studies have been published over the past five years for different vineyard areas around the world (for example, Zito et al., 2022; Blanco-Ward et al., 2019; Cardell et al., 2020; Moral et al., 2022 etc…). They differ by the GCM (Global Circulation Model) groups they consider (CMIP5 or CMIP6), the number of GCM models considered, the downscaling methods and the spatial scales taken into account (Quénol et al., 2017). Most of these studies include the calculation of bioclimatic indices such as Growing Degree Days, Winkler indice, Huglin indice, Growing season rainfall, Water balance etc…, in order to evaluate the future suitability of specific vineyard areas, calculated at a spatial scale between 5 to 25 km^2 (Cardell et al., 2019, Hoffman et al., 2019; Quénol et al., 2021). Few of them aims at delivering data for every vineyard area in a specific country or wine region, such as Australia (Australian Wine Atlas) and France (Zito, 2021; Quénol and Neetling for Loire Valley : https://atlasagroclimatique.techniloire.com/), in order to drive adaptation strategies for the industry. Finally there are few attemps to deliver simulations at a higher spatial resolution (below 1 km spatial resolution) in order to support decision making at vineyard scale (Le Roux et al., 2018; Resseguier et al., 2021), as shown on Figure 2.

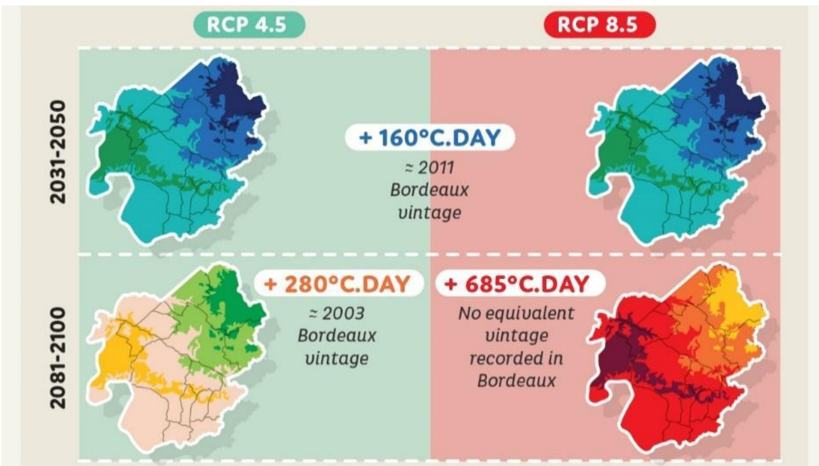


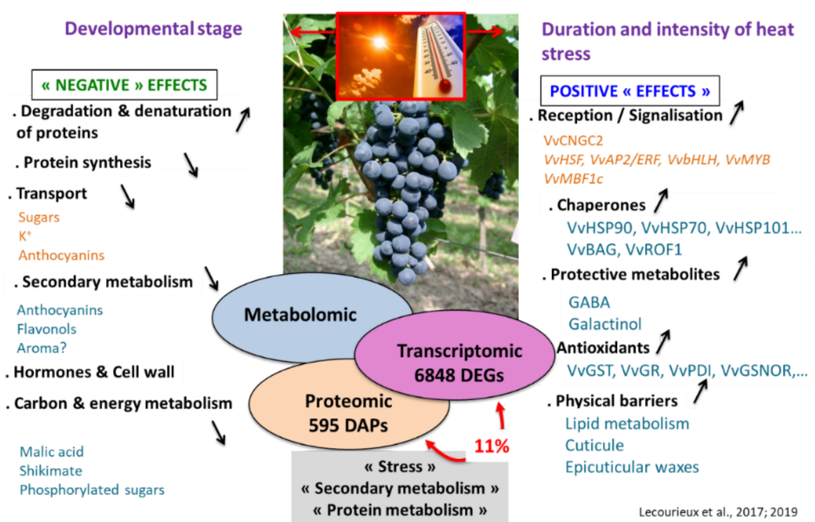
Figure 2 : Maps of the Huglin Index expected changes in the Huglin Index (B) over the Saint-Emilion/Pomerol vineyard area for the period 2031 to 2050 and 2081 to 2100 according to the climate scenarios RCP 4.5 and RCP 8.5. in comparison to the period 1986 to 2005 (Resseguier et al., 2021)

Impacts at the physiological level

As reported by many authors, the evolution of the environmental conditions are impacting grapevine functioning. It is likely that in the future cultivated grapevines will have to face more and more abiotic constraints occurring concomitantly or successively over one or several growing cycles affecting their physiology and metabolism. The effects of some of the major abiotic drivers of grapevine development and functioning have been recently reviewed by several authors (Torregrossa et al., 2017; Bernardo et al., 2018; Delrot et al., 2020; Lecourieux et al., 2020; Gambetta et al., 2020; Clemens et al., 2022).

The effects of high CO_2 concentration in the atmosphere has received less attention than the other factors, mainly because of experimental difficulties. High CO_2 is usually supposed to enhance growth and yield, although some authors consider it could also be considred as a stress factor through its effects on redox status and as the driver of increased temperatures (Foyer and Noctor, 2020). A recent review of literature (Clemens et al., 2020) reports that high CO_2 usually induces an increase of photosynthetic activity as well as a transient increase of Water Use Efficiency, an advanced phenogical timing and some modifications of the host-pest interactions. From the main long term FACE (Free Atmospheric CO_2 Enrichment) experiment in a german vineyard (Hoschule Geisenheim University), positive effects of elevated CO_2 on photosynthetic activity, vegetative growth and yield have been consistently reported over 5 years for Riesling and Cabernet-Sauvignon, while the modifications of berry composition are not consistent (Wohlfart et al., 2018; Kahn et al., 2022, Kahn, 2023). Recent results show also that eCO_2 concentrations changed the active soil bacterial composition (Rosado-Porto et al., 2023).

Water scarcity is considered to be a major consequence of climate change because needs for water will increase due to higher temperature and a decrease of rainfall in some geographical zones in the world. Because vineyards are mainly located in areas with Mediterranean climate types, drought may be a major threat for viticulture although grapevine may be considered as adapted (Chaves et al., 2010; Gambetta et al., 2020). From a physiological point of view, drought is known to decrease transpiration and stomatal conductance and increase temporarly WUEi (Water Use Efficiency) and photorespiration. Photosynthesis is less sensitive and starts to decrease when water potential reach more negative values. Leaf osmotic adjustement occurs but this mechanism is not well described in grapevine. Grapevine is also characterized by hydraulic vulnerability segmentation with more sensitive leaves and petioles which drop in order to protect canes and perennial parts from embolism (Charrier et al. 2016). Xylem resistance to embolism is also increasing over the season as the water stress increases (Charrier et al. 2018; Lamarque et al. 2023). Severe drought can eventually lead to irreversible embolism formation depending on the specific susceptibility of the cultivar (Charrier et al. 2018; Lamarque et al. 2023). Taken all this into account, Gambetta et al. (2020) defined 4 criteria which could contribute to the definition of drought tolerance in grapevine : maximal transpiration, response of stomatal closure to water potential, turgor loss point and root volume. Using traits related to these properties, Dayer et al. (2022) designed in silico elite genotypes for their tolerance. However a major difficulty remains to compare the outcomes of these studies to field data. Drought has also a major effect on fruit size and yield with more pronounced pre-veraison impacts. A reduction of 10% in yield for every 0.2 MPa of water potential is reported (Gambetta et al., 2020), but it probably does not take into account interannual effects of water scarcity on bud fertility (Guilpart et al., 2014) and cumulative effects on reserves. Increase in berry sugar content and decrease in acidity are not consistently reported. Accumulation of amino-acids seems to be general while the positive effects on secondary metabolites appear to be highly variety-dependant. Despite a large number of studies, understanding drought effects and drought tolerance at the level of the whole vine (from roots to fruit)



remain challenging to evaluate accuratly the risks for grapevine growing in the context of climate change.

Average temperature increase and related extreme events where maximal temperatures could reach critical values largely above 40°C for several days are the most generalized features of climate change. Their effects on grapevine have been largely reviewed from molecular to berry composition aspects (Torregrosa et al., 2017; Lecourieux et al., 2017; 2020; Ollat et al., 2019; Venios et al., 2020; Petenuzzo et al., 2022), although the underground aspects have been much less considered (da Costa et al., 2023). The consequence of temperature increase on advancing the grapevine phenology and shortening the growth cycle, with consequences on berry ripening conditions, is well described. However the impacts of winter temperature and pre-veraison extreme events in delaying bud-burst and veraison respectively are probably not enough taken into account. Photosynthesis appears to be one of the most critical physiological processes to extreme temperature related to sensitivity of Photosystem II. Studies performed at whole plant level show differences in sensitivity among organs, with a preferential allocation of biomass to vegetative growth in comparison to fruits and perennial parts (Torregrosa et al., 2017; Ollat et al., 2019). Lecourieux et al. (2017, 2019) performed a very comprehensible work at fruit level to assess the specific effects on berry composition and consequences on wine quality.). They were able to identify key heat stress-sensitive molecular players, including transcription factors and genes involved in ROS metabolism which could regulate berry response to heat stress (Figure 3). Other heat stress-deregulated genes potentially involved in important aspects of fruit development and berry quality were also pinpointed. Some of these genes are currently under functional validation and their contribution to varietal differences in thermotolerance are investigated (Lecourieux et al., 2022).

However it is clear that the most probablematic issue is not the effect of individual abiotic factors, but the combination of them. In an attempt to briefly review the studies already performed on grapevines, Ollat et al. (2022) reports mainly synergenitic effects between high CO_2 and not stressful high temperature (Martinez-Luscher et al., 2015) and an antagonist and surpassing effect of drought in any combined conditions (Tzortzakis et al. 2020; Arrizabalaga-Arriazu et al., 2021). Combining drought and heat stress (> 35°C), Lehr et al. (2023) reported also a stronger effect of drought at leaf level but in the same conditions Hewitt et al. (2023) observed a more pronounced impact of heat on metabolome and transciptome of berries. They identified proline concentration and the expression of *P5CS* (pyrroline-5-carboxylate synthase, from the proline biosynthesis pathway) gene in leaves as potential markers of combined stresses. The combined effects are most of the time not additive and plants should prioritize responses. In addition combined effects could be highly specific with the expression of unique genes increasing with the number of combined stresses as reported by Ollat et al. (2022). Recent results confirm these observations on grapevine and that epigenetic modifications may be central in grapevine responses to combined drought and heat stresses (Tan et al., 2023). There is no doubt that combined abiotic factors analyses deserve much more investigation.

Impacts at the whole plant level

Phenology is considered as the first biological and the less controversial indicator of climate change. Many reports of earlier bud-burst, flowering, veraison and ripening dates, as well as shorter developmental cycles, mainly since the end of the 1980th, have been released (Garcia de Cortazar-Atauri et al., 2017). Among other impacts of earlier developmental stages, ripening under warmer summer conditions is probably the most important for viticulture and wine making, with consequences on the suitability of specific varieties to provide good quality grapes in a given location (Van Leeuwen and Seguin, 2006). Indeed an increase of more than 2°C for average temperature during the ripening period has been reported for France since 1980. Of course, the effect of warming on phenology is expected to go on. Modelling phenology for the future show that depending on the varieties, the GHG emission scenario and the phenological models, advances can reach in France 6 to 13 days for veraison and between 23 and 40 days for theoretical maturity at the mid XXIst century in comparison to the last decades of the XXth century (Pieri and Lebon, 2014; Garcia de Cortazar-Atauri et al., 2017; de Resseguier et al., 2021; Zito et al., 2022; Bécart et al., 2022). The development of accurate phenological models taking into account winter temperature and extreme heat events is currently a challenge in order to properly evaluate spring frost risks or other impacts in relation with their stage of occurrence (eco-climatic indices, Caubel et al., 2015).

Table 1 : impacts of climate change on grapevine phenology in France since 1989 (Observed data and simulation from BRIN and WANG models, for Chardonnay in Colmar, Cabernet-Sauvignon in Bordeaux, Syrah in Avignon). (Ollat and Touzard, 2018).

Number of days per decade	Colmar (Alsace region, North-East of France	Bordeaux (South-West of France)	Avignon (South-East of France)
Bud-burst	-3	-0.6	-3.5
Flowering	-5.6	-2.4	-4.2
Veraison	-6.1	-3	-4.5

Although it is one of the main parameter to ensure vineyard sustainability, the observed or expected effects of climate change on yield are much less reported. It is quite difficult to link historical records of yield (when they exist) to climatic data, because many other parameters such as viticultural practices have an effect on crop level. Consequently it oftern uncertain to conclude if climate change, with combined effects of higher CO_2 and temperature and more pronounced drought, has already been the driver for observed yield losses in viticulture. Nevertheless a 50-year record of the weight of 200g berry samples at harvest for Grenache in the Southern Rhône Valley shows a decrease of 20% over half a century with a significant positive correlation with wet day frequency over the Véraison-Harvest period and a negative correlation with mean temperature during the Fruit Set-Lag phase (Bécart et al., 2022). Although temperature effects could be explained by the shortening of the developmental cycle and destructive extreme temperatures, yield appears to be mainly highly sensitive to water availability during the period between flowering and veraison (Yang et al., 2022). Several studies relay on this relationship to analyse yield evolution in the context of climate change. Using historical data from 1986 to 2015 in various European vineyards, Yang et al. (2022) characterized several risk intensity for yield losses at regional level based on CWSI (Crop Water Stress Indicator). In a predictive approach, Naulleau et al. (2022) developed a yield model (GraY) based on water balance and were able to simulate a potential decrease of yield from 10 to 30% for a Mediterranean vineyard at the end of the XXIst century depending on the climatic scenario. In a more general approach, based on the use of the crop model STICS, Fraga et al. (2016) reported that yield maybe strongly affected in the South of Europe, with septentrional and eastern regions benefiting from increace in CO_2 content and temperature. Finally, extreme events such as spring frost and ail storm might be the most impacting hazards for yield, but their occurrence in the future is highly difficult to evaluate (Bois et al., 2023).

Berry composition and related wine quality relay on the content of many primary and secondary metabolites, and minerals, and on the equilibrium between them. Our hypotheses on the impacts of climate change are mainly based on experimental data mainly recorded for a specific compound or a class of compounds submitted to a single climatic parameter. Interactions with yield are also rarely taken into account. Historical records from temperate regions such as France show a continuous increase in sugar content and decrease in acidity since the end of the 1980^{th} (Ollat and Touzard, 2018, Bécard et al., 2022). Potassium concentration, a key component of pH, is also increasing with sugar content (Duchêne et al., 2020). The decrease in acidity is a serious concern regarding its role in wine balance and preservation. A delay between sugar and anthocyanin accumulation is reported under high temperature (Sadras et al., 2012), but the global impact of climate change on secondary metabolites is highly difficult to predict considering the varietal sensitivity and many antagonist effects of high temperature and drought on anthocyanins and on some aroma compounds (van Leeuwen et al., 2022). Specific and complex aging aromas seem to be enhanced by both constraints (Le Menn et al., 2019). In addition elevated CO_2 was shown to limit the decoupling effect of high temperature between anthocyanin and sugar accumulation (Martinez-Lüscher et al., 2016; Arrizabalaga-Arriazu et al., 2020). UVB radiation has a similar antagonist effect (Martinez-Lüscher et al., 2016).

Considering climate change impacts, biotic interactions are often not taken into account, most probably because they are very difficult to predict. In addition to the direct effects of climatic parameters on the biology of the pathogen/pest, changes in phenology of both parterns of the interactions have to be considered (Castex et al., 2023). Based on an international survey (Bois et al., 2017), it was reported that mildews (both downy and powdery) are the primarily sanitary concerns all over the world, followed by grey mold and trunk diseases. However because of their international distribution, it is highly difficult to link them to any specific climatic indice, and then to simulate their incidence in the future. Targeting Burgundy vineyards, Zito (2021) confirmed this difficulty. A meta-analysis of literature (Delmas, personal communication) reveals also the necessity to increase investigation efforts on these topics. A major issue is to consider complex interactions between biotic and abiotic factors such as in Bortolami et al. (2021) for esca symptoms and drought, or in Becker et al. (2023) for *Lobesia botrana* and elevated CO_2.

Considering the variability among genotypes

While evaluating the impacts of climate change on grapevine and assessing the risks for the future, varietal sensitivity should be a key point. Indeed for all the impacts summarized previously, varietal differences both at scion and rootstock levels have been reported (for example Carvalho et al., 2017; Dayer et al., 2020; Suter et al., 2021; Lamarque et al. 2023; Ollat et al., under press). Clonal variability has also been considered in some studies (such as Arrizabalaga-Arriazu et al., 2020). The large variability of phenology is, of course, a major aspect (Parker et al., 2013) which interfers with the occurrence of abiotic and biotic stresses. If controlled conditions are the most convenient way to analyse the genetic variability, long term common garden and genotype x environment field experiments over large climatic gradients are the most valuable ways to address these complex interactions and provide data which could be used to assess impacts and adaptation options (Destrac and Van Leeuwen, 2016; Marguerit et al., 2019). Nevertheless, the issue of elevated CO_2 remains to be addressed on large panel of diversity, which is more than a difficult task.

Modelling is the cornerstone of the evaluation of future impacts and risks

Considering the current knowledge, modelling remains the most efficient way to evaluate the possible impacts and risks associated to climate change for the future through the intregation of climatic predictions (outputs of climatic models) with biological models (either statistical or process-based) at the level of plant, crop or interacting biological agent (pest or pathogens). Modelling helps to integrate the complexity of the processes and in some cases reveals unexpected global properties, named emergent properties (Bertin et al., 2009) interactions. It is also a great tool to check hypotheses, design ideotypes and evaluate adaptation strategies. It would be a hard task to summarize the numerous studies already published for grapevine. Some examples could be cited which consider impacts at continental scales (Fraga et al., 2016, Yang et al., 2022, Castex et al., 2023), national levels (Garcia de Cortazar-Atauri, 2006; Pieri and Lebon, 2014; Sgubin et al., 2018; Zito et al., 2022), regional or local levels (de Resseguier et al., 2020). Other modelling exercices attempt to integrate the genetic variability into predictions (as described in Vivin et al., 2017, Dayer et al., 2022). The last examples are related to the evaluation of adaptation strategies (Morales-Castilla et al., 2020 for varieties, Naulleau et al., 2022 for systemic approaches). In any case, we should keep in mind that "*all models are false*", and remain aware of uncertainties, complexity and limits of use.

Conclusions

Climate change is a huge challenge for the wine sector and it raises many new scientific and applied questions. Although the impacts of the major abiotic factors such as heat and drought has been investigated for decades by the grapevine communitys, as shown above, there is an urgent need to consider the combination of factors as well as future and unknown situations. We are facing the issue of complexity. Only pluridisciplinary studies, able to analyse the responses of grapevine at different levels (from gene to vineyards) and approaches such as modelling which enable to account for this complexity arecapable of tackling these questions. .

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