KEYNOTE LECTURE

Climate change is here to stay: adapting vineyards to a warming world

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INTRODUCTION

As an industry that thrives more on, but may also be more affected by, vintage variation and regionality than any other agricultural enterprise, grape and wine production is ever more being impacted challenged by climate change. Though the gradual increase of CO_2 in the atmosphere lies at the root of our changing climate, the associated changes in temperature and humidity arguably pose the greatest challenges to grape growers. In many regions, soil moisture is decreasing while rising temperatures are increasing both the plant water demand and the heat stress during the growing season (Green, 2024). Though winter temperatures are on an upward trend as well, the risk of winter freeze and spring frost damage persists. Therefore, grape growers face climate-related production challenges and threats throughout the year. One consequence of the global warming trend is the exploration of grape production in previously unsuitable, or marginally suitable, areas further from the equator and at higher elevations (Fraga et al., 2016; van Leeuwen et al., 2024). This trend is taking advantage of the overall lengthening of the growing season (defined as the frost-free period) and the increase in seasonal heat summation (measured as growing degree days), weighed against the availability of suitable land and other resources and the risks imposed by unseasonable temperature fluctuations. In established grape-growing regions, growers might also consider planting on sites with different slope aspects to exploit mesoclimates with less direct solar exposure. Of course, moving to a new location is not an option for growers in existing vineyards, who instead must adapt by using alternative means to mitigate the perceived adverse effects of climate change.

Successful adaptation and mitigation requires decisions to choose from and implement a set of alternative or complementary choices either when replanting a vineyard or when extending the lifespan of an established vineyard. Replanting choices may include changes in scion or rootstock cultivars, planting density, row direction, trellis design, training system, or potential irrigation need (Naulleau et al., 2021). Once a vineyard has been established, cultivars may be grafted over, the trellis design and training system can be somewhat retrofitted, irrigation can be added (provided water is available) or altered, and additional choices concern vineyard floor or soil management, pruning strategy and seasonal canopy management, crop load management, harvest timing, and how to control emerging or changing pests and diseases. In any case, vineyards are costly to establish and take years to reach a positive return on investment, and then growers must ensure continued vineyard profitability for decades. Such economic considerations paired with market uncertainties and growing labor constraints mean that the aforementioned choices cannot be made by considering climate change in isolation, but must also integrate decisions regarding mechanization and automation (Kurtural and Fidelibus, 2021). This presentation builds on our current knowledge of grapevine biology and recent advances in viticultural practices to discuss possible adaptation strategies that growers may use to mitigate climate change effects.

A WORLD VINE WEB

Following their initial cultivation and domestication perhaps as early as 11,000 years ago in the Caucasus and Levant regions of southwestern Asia, grapevines of the species *Vitis vinifera* L. have been spread, locally selected, and bred around the Mediterranean basin and Black Sea and from there gradually to other parts of Europe and Asia and eventually to suitable areas across the world (Dong et al., 2023). Consequently, the thousands of cultivars available today vary extensively in many relevant traits. When grown under similar conditions of summer drought, *V. vinifera* cultivars differ noticeably in growth and potential canopy size (Fig. 1), suggesting that underlying genetic differences in shoot vigor could be explored for choices of both planting and breeding material. While differences in phenology, yield and fruit composition, or winter hardiness are well established, at least for some cultivars (Morales-Castilla et al., 2020; Suter et al., 2021; Keller, 2025), the potential variation in heat and drought tolerance among cultivars (as well as rootstocks) remains poorly understood and somewhat controversial. Apart from a few widely dispersed "global" cultivars, moreover, most others are grown regionally or even locally, and it is often unknown if or how well those cultivars are suited to diverse climates and soils. This knowledge gap could be gradually closed with a "world vine web" consisting of a network of cooperating sites to conduct replicated field trials that include some common keystone cultivars among many unique ones for testing in common garden experiments. Trials need not be planted in the same year, nor do they need to be managed identically, but some commonalities (to the extent that local conditions permit) and a minimum of three years of overlap of mature vines (at least four years old) would facilitate comparison of the collected data across sites. Ensuring that essential data, such as phenology, canopy size, yield components, and fruit composition, along with weather and soil variables and cultivation practices are collected in a reasonably standardized way and deposited in a common database would lay a foundation for future meta-analyses, modeling efforts, and breeding material selection. Such a coordinated approach would empower growers to make informed choices regarding planting material for vineyard establishment, replanting, or topworking.

MITIGATING HEAT STRESS

Temperatures below about 15°C and above about 35°C during the growing season limit grapevine photosynthesis and may reduce vegetative growth and yield formation, while also adversely impacting fruit composition (Hewitt et al., 2023; Keller, 2025). However, although little, if any, development occurs below approximately 10°C, a robust upper threshold for phenology and shoot growth has yet to be established. Again, observations in common garden experiments in disparate climates, in addition to well-designed growth chamber experiments, would be helpful to determine if a universal threshold exists for *V. vinifera* or if the threshold varies by cultivar or other environmental factors. There is also a need to determine optimum temperature windows for fruit quality-impact components, which will certainly be different for different cultivars or different uses (e.g. wine styles) of grapes from the same cultivar. Moreover, because solar radiation heats tissues, future experiments should clearly distinguish between ambient temperature and the temperature of the tissue or organ being investigated (Spayd et al., 2002; Keller et al., 2022).

Considering that many cultural practices in new and established vineyards aim to constrain shoot growth, our main target for heat stress mitigation is likely the flower or fruit clusters. When a vineyard is established or replanted, rows could be offset somewhat from true north–south to reduce the heat load on the warmer afternoon side of the canopy (Hunter et al., 2021). In established vineyards, delayed winter pruning may delay budbreak with the dual effect of reducing the risk from spring frost damage and also potentially delaying grape development such that ripening occurs under cooler conditions (Poni et al., 2022). Alternative practices to delay ripening include reductions in source size (e.g. shoot trimming or defoliation) or source activity (e.g. application of antitranspirants) near veraison (Gutiérrez-Gamboa et al., 2021; Previtali et al., 2022). Conversely, increasing the sink size by retaining more buds during winter pruning remains a poorly investigated subject (Keller, 2023). For example, machine pruning could be paired with mechanization or automation of canopy or crop load management integrated with remote sensing and machine learning (i.e., applying principles of artificial intelligence) to achieve desired yield and quality targets. Canopy management practices such as shoot positioning or leaf removal need to be adapted to prevent grape berries from overheating in direct sunlight. The warmer the climate, the more growers should question whether positioning shoots vertically and stripping leaves, especially on the west side of the canopy, are desirable. More direct mitigation practices include the installation of shade nets to shield the fruit zone from midday or afternoon sun, or of evaporative cooling systems to cool the fruit zone. Assuming we could define cultivar- or target-use-specific berry temperature thresholds (e.g. 25°C or 35°C) above which key fruit composition traits (e.g. acidity, anthocyanins, monoterpenes) are adversely impacted, and provided pressurized water is available, misting could be controlled using feedback loops to operate only intermittently above a threshold temperature. By using much less water compared with overhead sprinkler cooling, or even extra drip irrigation applied before or during a heatwave, such misting may also be more compatible with deficit irrigation strategies.

MITIGATING DROUGHT STRESS

Grapevines under water stress reduce shoot and berry growth, as well as leaf photosynthesis. Their smaller and more open canopy leads to greater sun exposure of the clusters, which increases berry temperature and changes fruit composition (Keller, 2023). Depending on the intended use of the grapes (e.g. wine style, fresh consumption, juice), mild to moderate water stress is desirable. Even heavily cropped juice and table grapes can be grown with minimal yield penalties under mild water deficit (Keller et al., 2023). For most winegrapes, water deficit before veraison is more beneficial than water deficit during ripening, and even small differences in plant water status can alter the wine flavor profile (Palai et al., 2023; Diverres et al., 2024). More severe water stress, however, may lead to berry shriveling and yield and quality loss, and under prolonged, extreme drought stress, grapevines may shed their leaves to avoid plant death.

In dry climates, the use of (drip) irrigation gives growers precise control over the timing and extent of water deficit. Irrigation, where and when available, is obviously also the solution to mitigating drought stress (Naulleau et al., 2021). Even small doses of applied water can often maintain soil moisture at levels that prevent excessive vine water stress. However, where irrigation is not possible, water deficit often develops gradually during a dry summer, becoming more severe as the grapes begin to ripen. Such uncontrolled water stress can severely curtail photosynthesis and berry growth and even lead to berry shriveling. It may also reduce bud fruitfulness, compromising next year's crop and, if it extends over multiple seasons, result in vine decline. Options to mitigate drought stress without irrigation are limited; they may include application of in-row ground covers (i.e., organic or synthetic mulch), soil tilling, or reducing the size of the canopy (e.g. shoot trimming or defoliation) or its transpiration rate (e.g. application of antitranspirants) to limit water evaporation from the vineyard. Tilling, however, is often undesirable and has the added drawback of increasing the temperature of the vineyard floor. Moreover, any reduction in plant transpiration tends to increase the canopy temperature. Removing clusters, while slightly improving the plant water status, has not been found to alleviate the adverse and long-term impacts of severe drought stress.

Although drought-tolerant and presumably deep-rooting rootstocks are often touted as an ideal tool to mitigate drought stress effects, it remains debatable whether genetic differences in rooting patterns are practically meaningful (Smart et al. 2006). Moreover, roots exploring deeper soil horizons usually grow in nutrient-poor and relatively hypoxic environments while their continued access to water favors shoot vigor, which undermines our ability to manage canopy size and density (Fig. 2), and may have unpredictable consequences for yield and fruit quality. Therefore, the "deeper roots are better" approach is not desirable in irrigated vineyards, where growers aim to control vigor using deficit irrigation.

WILDFIRES, PESTS, AND DISEASES

One aspect of drought stress, especially in combination with heat stress, that is outside the control of most growers is the increasing prevalence of wildfires. Apart from the direct threat of fires to vineyards and wineries, their major impact is on wine aroma via smoke-derived compounds that are absorbed by grapes. Because adaptation to such erratic events is challenging, most research has focused on mitigation either in the vineyard or in the winery. A review of smoke taint and mitigation practices is beyond the scope of this overview, and readers are referred to online resources (e.g. https://www.awri.com.au/industry_support/winemaking_resources/smoke-taint; https://www.wcsetf.org).

Possible effects of climate change on pest and disease pressure in vineyards were discussed in a recent review, which found the available data to be insufficient to make clear predictions (van Leeuwen et al., 2024). With few exceptions of truly successful biocontrol strategies (e.g. rootstocks to control phylloxera and nematodes), mitigation practices to alleviate possible increases in pest or disease pressure typically include the use of organic or synthetic control agents (e.g. within the framework of integrated pest management). In response to public and political pressure, however, grapevine breeding efforts are increasingly targeting disease resistance as a key goal of cultivar adaptation to lower the use of pesticides (Trapp and Töpfer, 2023). Because most resistant or tolerant cultivars have various proportions of North American *Vitis* species in their genetic background, phenological observations will be crucial to ensure that they do not undergo budbreak too early in spring.

CONCLUSION

Rising temperatures and changes in humidity associated with global climate change are increasingly challenging grape production. Higher temperatures accelerate grapevine phenology, but temperature thresholds and cultivar suitability to different climates (both summer and winter) remain relatively poorly understood. Both heat stress and drought stress reduce yield and fruit quality, and they may have other adverse consequences for the sustainability of grape production. This presentation argues that the genetic diversity within *Vitis* combined with suitable mitigation practices before and after vineyard planting can be used to effectively adapt to climate change in existing and new grape production regions.

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FIGURES

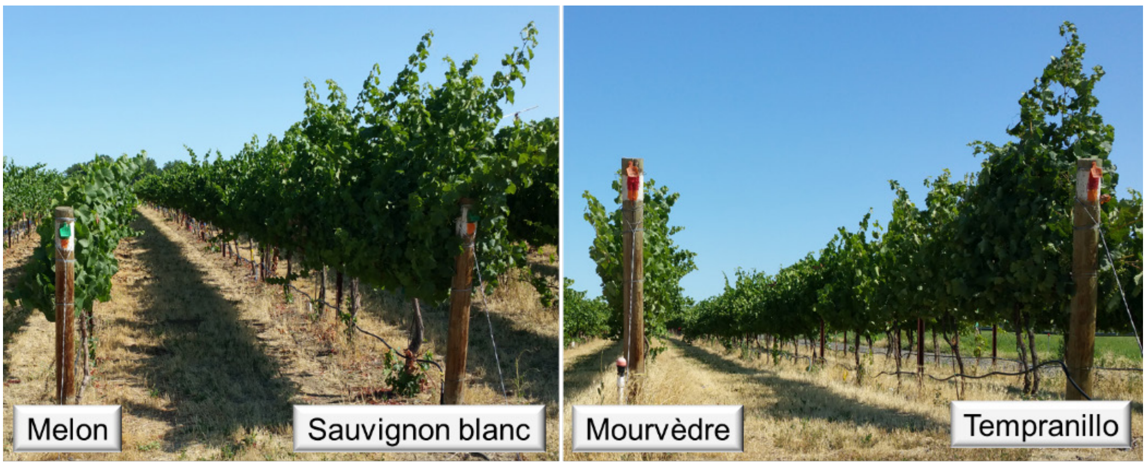

Figure 1. Under the same soil water availability, own-rooted *Vitis vinifera* winegrape cultivars differ markedly in shoot growth and canopy size. All vines shown were grown in the same vineyard in southeastern Washington, USA, with irrigation water applied from budbreak through fruit set.

Figure 2. Aerial view of own-rooted Riesling winegrapes growing on a southwest-facing slope near an irrigation pond in southeastern Washington, USA. Despite the arid climate (<200 mm annual precipitation), the vines grow extremely vigorously where the roots have access to subsurface water, while vigor of the vines higher up on the slope is easily controlled by deficit irrigation.