Atmospheric Influence on Grapevine Development

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In many European regions, viticulture and winemaking play a major socioeconomic role in local economies, with climate being a central component of the terroirs, governing vineyard microclimate, vine development and growth, phenology, yield, and grape berry composition, which ultimately control attributes and typicity of the produced wines. Nonetheless, climate change is already affecting the viticultural suitability of many wine regions throughout the continent and is expected to continue along this same path in the upcoming decades. These climate-driven shifts may lead to a redesign of the geographical distribution of wine regions, while wine typicity may also be threatened in most cases. Climate change does require the implementation of well-timed, appropriate, and economically efficient adaptation strategies, while respecting local specificities for an effective reduction of the risks to which this vulnerable sector is exposed. However, knowledge on the adaptation potential of a range of measures is still incipient and will need more research in the near future.

Keywords: viticulture ; wine production ; climate change ; adaptation ; risk reduction

1. Grapevine Cycles Versus Weather and Climate

Grapevine development is associated with several stages of its vegetative and reproductive cycles. Under the conditions of many traditional viticultural regions (i.e., extratropical viticulture), the grapevine vegetative cycle extends over one full year, whereas its reproductive cycle lasts for two years. The reproductive cycle governs several important qualitative and quantitative properties, such as the number of grape clusters in the following year. The vegetative cycle encompasses two main sequential periods: dormancy period and growing season. The grapevine phenological development comprises several stages or phenophases (Figure 1). These stages of grapevine vegetative and reproductive cycles are largely controlled by atmospheric conditions [1].

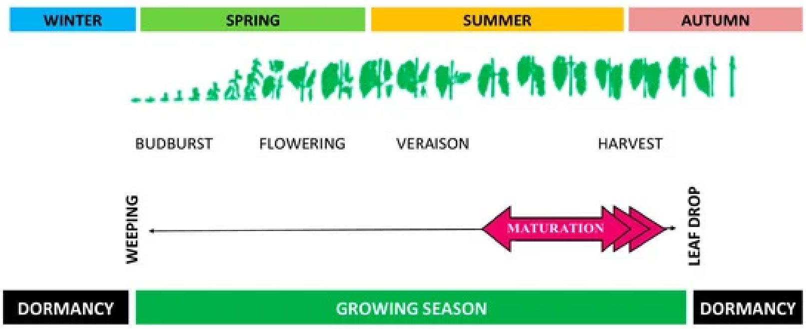

Figure 1. Vegetative cycle and main vine phenological stages.

The impact of atmospheric forcing on grapevine can be divided into two different time scales. On the long-term, climate, which corresponds to the statistical distribution of the different atmospheric variables over long-term periods (decades) at a given location [2], determines the bioclimatic envelope of that location and its viticultural suitability [3][4]. Macroclimates are determinant of the wine geography and the distribution of grapevine varieties, whereas mesoclimates and microclimates promote different terroir units, with diverse wine identity and diversity [5]. The wide range of climate-driven scales, as well as the spatial complexity and temporal dynamics in viticulture, have already been documented [6]. On the short-term, weather considerably governs the whole grapevine development process, as it requires suitable temperatures, radiation intensities, and duration, as well as specific levels of water availability throughout its growth cycle, ultimately influencing yield, biomass production, berry attributes, and wine structure and flavour [7][8]. Effectively, the evolution of weather conditions in a given location can be used to predict local/regional grapevine parameters, such as yield [9] or phenology [10].

2. The Role of Temperature

Among all atmospheric elements, air temperature is considered the most important in driving the growth and development of grapevines [11], in cases where water, radiation, and nutrient requirements of the plant are fulfilled [12][13]. From the climatological viewpoint, the distribution of traditional viticultural regions worldwide is mainly confined within a belt defined by the isotherms of average growing season temperatures (April–October, NH; October–April, SH) of 12–13 °C and 22–24 °C [4], underlining the key role played by temperature on viticultural suitability. Growing season temperatures below 12–13 °C commonly occur in regions with growing seasons too short for proper vine development, with typically low solar radiation levels and insufficient heat accumulation. On the other hand, growing season temperatures above 22–24 °C often lead to excessive heat stress on vines, which is also frequently associated with either severe water stress, in dry climates, or strong pest and disease pressures, in humid climates. These areas may also have difficulty in meeting the chilling requirements for the dormancy period, with resulting erratic bud break [4].

For the meteorological timescales, temperature conditions strongly control both grapevine physiology and berry composition during the preceding and the current growing season [14][15]. The inflorescence primordia differentiation starts around the bloom stage of the preceding year [16][17]. Warm and sunny conditions during this period promote the formation of inflorescence primordia, whereas cool and cloudy weather promotes the formation of tendrils [18][19]. Hence, the environmental conditions in the preceding year have a direct influence on the yield of the following season [20].

From leaf fall to the beginning of spring, grapevines are dormant and consist entirely of woody tissue, with little physiological activity [3]. This period encompasses two sub-periods that are controlled by endogenous and exogenous thermal factors needed for dormancy release. The first sub-period (endo-dormancy) is triggered by chilling accumulation (chill units) during autumn/winter, whereas the second sub-period (eco-dormancy) is driven by heat accumulation until bud break. Therefore, the winter chill is an important condition for grapevine growth development, as cold promotes bud dormancy [21][22], besides other processes such as day length shortening and ageing of the photosynthetic active parts of the plants. From late winter to early spring, the accumulation of daily mean temperatures above 7 to 10 °C generally promote dormancy break and the onset of the grapevine growing cycle [23].

During the growing season, grapevines undergo constant changes in terms of morphology and physiology. The length of the growing season for each variety is directly related to the growing season mean air temperature [24], though it may be additionally linked to soil moisture and crop management practices [25]. The length of the different phenological stages significantly differs not only according to each variety, but also to the thermal conditions in a given region for each specific year [26][27]. Despite relatively high resilience to abiotic stresses, extremely low temperatures during winter [28], negative temperatures (Celsius scale) around/after budburst [29][30][31][32], and hail events may severely damage the developing buds, leaves, and inflorescences [33][34]. Cool conditions [30] or extreme heat [20][35][36] may also affect vine physiology and yield, though some grapevine varieties are more tolerant to extreme temperatures than others. Grapevines under severe heat stress may undergo a significant decrease in photosynthetic productivity, as well as suffer injures in other biochemical processes [37]. Extreme events during the veraison–maturity period, such as heatwaves, can significantly influence sugar accumulation [38] and may lead to a decrease in anthocyanin biosynthesis and content [39]. Secondary metabolites, more specifically phenolics, due to their contribution to colour, flavour, aroma, texture, astringency, and stabilization of wine, as well as antioxidant properties [40], are extremely important for fruit quality and wine production [41]. High temperatures may also lead to important losses, as they also influence the synthesis of volatile compounds, which strongly contribute to the sensory character of wines [42]. In autumn, the gradual shortening of the day length and decreasing of temperatures promote acclimation to freezing temperatures in winter. During this phase, the translocation of carbohydrates, amino acids, organic acids, and some minerals from leaves to perennial organs (trunk and roots) reaches its maximum [43]. This period, considered as a survival strategy, ordinarily coincides with the generalized leaf senescence, followed by leaf fall and the subsequent dormancy period.

3. The Role of Water

Precipitation is another key atmospheric variable in viticulture, as it has a large footprint on soil water balance, determining soil water availability for the plant and its corresponding water status. Water stress leads to a wide range of effects that are also dependent on the grapevine development stage [44]. For instance, moderate-to-high soil moisture during budburst and shoot/inflorescence development is critical for vine growth [45]. Water stress at this stage may lead to stunted shoot growth, as well as poor flower-clustering development and berry set [46]. However, excessive humidity during early development stages may also overstimulate growth, which may lead to excessively vigorous and dense canopies, thereby potentiating the risks of diseases. From flowering to berry ripening, severe water stress may lead to reduced leaf area, thus limiting photosynthesis, as well as promoting flower abortion and cluster abscission [47].

Nevertheless, dry weather during ripening is generally favourable to high-quality wine production [48][49][50]. Slower leaf development also promotes higher water use efficiency [51] Conversely, excessive precipitation is commonly unfavourable to maturation [52], for instance due to sugar dilution [53] or to bunch rot [54]. Recent studies indicated that water deficit affects grape and wine composition [55][56]. Regulated deficit irrigation has been used to improve berry and wine quality [57], increasing the concentration of terpenes by modulating structural and regulatory genes involved in volatile organic compounds biosynthesis [55]. Water deficit early in the season, before veraison, also stimulated increased anthocyanins and phenolic concentrations [58]. Furthermore, the timing and intensity of water deficits influence the extent of changes in berry metabolism and in wine colour, aroma, and flavour by modifying berry size and/or the synthesis of berry compounds, with a positive contribution to the fruit and wine organoleptic properties. Indeed, a water-deficit treatment typically increases the skin to pulp ratio in the berries, when compared with well-watered grapevines [59], increasing the amount of skin tannins and anthocyanins. Colour differences may result from increased anthocyanin synthesis caused by water deficit during the fruit development [60].

4. The Role of Radiation

Solar radiation is also a crucial factor in viticulture. The synthesis and accumulation of sugar, phenolic, and many aromatic compounds during maturation are indeed favoured by high solar radiation levels [61]. Regions with relatively low solar radiation normally adjust the training systems and canopy density to maximize the sun-exposed leaf area. Although more exposed leaves generally favour photosynthesis and stomatal conductance, water demand also increases [62], and other problems may also arise, such as leaf and cluster sunburn. On the contrary, less exposed clusters result in lower berry temperatures, generally leading to lower sugar contents and lower anthocyanin concentrations [63]. Additionally, shading due to high canopy density may significantly decrease bud fertility [64], thus negatively affecting the yield potential in the subsequent season.

In the Mediterranean-type climatic regions, such as in Southern Europe, vineyards are already typically exposed to high radiation levels, high air temperatures, and soil water deficits, which can impact grapevine productivity. Under these circumstances, grapevine leaves often show temporary photoinhibition, chlorosis, and necrosis, thus leading to low intrinsic water use efficiency and excessive exposure of grape clusters [65]. Hence, low vigour tends to be connected to reduced berry weight, sugar content, and yields. Still, other organoleptic properties of berries, such as flavour and aroma attributes, are frequently inhibited by excessive solar radiance and severe dryness or, as in the case of tannins, may be exacerbated in concentration and/or altered in molecular structure. These conditions may lead to unbalanced wines, with undesirable high alcoholic content and low acidity [66], with low commercial value. However, other studies [67][68][69] showed that vineyards exposed to relatively high levels of sunlight, including UV-B radiation, produce berries of high quality for winemaking by inducing synthesis of polyphenols and monoterpenes as photo-protectors.

5. Agro-Climatic Indices and Viticultural Zoning

The aforementioned effects of climate and weather on grapevines have been described by several agro-climatic indices. They commonly provide closer relationships between the grapevine development and atmospheric conditions than individual atmospheric variables, such as monthly mean temperatures, radiation, or precipitation. These indices were developed to integrate the plant–atmosphere interactions, thus following the plant physiological development more closely. Further, they can be used to assess the suitability of a given region or site for viticulture, in general, or a specific variety in particular. Due to the strong link between temperature and grapevine development, the agro-climatic indices are frequently based on temperature, such as indices using simple growing degree-day concepts (temperature integration). As a classical example, Amerine and Winkler [23] developed the Winkler growing degree-day scale for a base temperature of 10 °C. Following a similar concept, after some modifications in the temperature summation during the growing season and including a coefficient for day length, the Huglin index [70] was later developed. Molitor et al. [71] applied a trapezoidal model approach to simulate grapevine phenology (UniPhen), on the basis of cumulative degree-days, using three threshold temperatures (10 °C—lower threshold; 20 °C—upper threshold; 30 °C—heat threshold). Other indices based on hourly temperature accumulation were more recently applied [22]. To put more emphasis on the temperature conditions during the ripening period, which may ultimately influence the wine style, the cool night index [52][72], based on the mean minimum temperature in September (NH), was proposed. The dryness index is another very common index in viticultural zoning [61][72], which is based on an estimation of the potential soil water balance. Hence, viticultural zoning using agro-climatic indices is common to assess the suitability of a given region for viticulture and wine production for specific grapevine varieties.

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