# Chapter 22
# Climatic Challenge for Global Viticulture and Adaptation Strategies

**Rizwan Rafique, Touqeer Ahmad, Tahira Kalsoom, Muhammad Azam Khan, and Mukhtar Ahmed**

**Abstract** Climate change has posed mammoth challenges for the global viticulture, and almost all the growing regions are facing the mounting pressure exerted owing to this unchecked climatic challenge. Pedo-climatic and topographic features largely affect the production and quality of table and wine. Climatic variability in the form of rising $CO_2$ and elevated global temperature with increased intensity of water scarcity during the growing season has contributed to the unsustainability of global viticulture. Early phenological development, shortening of phenophases, poor berry development, early maturity with lower yield and inferior quality are the consequences of these challenges. Moreover, the physiological activities of vines, e.g. photosynthetic activity, transpiration and stomatal conductance, are negatively affected along lower water use efficiency (WUE), hence higher irrigation demands.

**Keywords** Viticulture · Climate change · Temperature · $CO_2$ · Water deficit · Phenology · Physiology · Berry quality

## 22.1 Introduction

Grapevines of *Vitis vinifera* are a distinct crop belonging to family Vitaceae. They are a non-climacteric fruit species, commonly used as table grapes and dried raisins and in vinification (wine production) and distillation to produce liquors (Kuhn et al. 2013; Ruel and Walker 2006). Grapes contribute about 16 percent of global fruit production (Bhat et al. 2017). Grapevines are cultivated on an area of 7.4 million hectares with an annual production of 77.8 million tons globally in 2018 with five countries, Spain (13%), China (12%), France (11%), Italy (9%) and Turkey (6%),

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contributing about 51% of the viticulture industry. The major share of viticulture industry is occupied by the wine industry (246 mhl consumption) with 57% production of wine grapes (OIV 2019). Bordeaux, Burgundy, California, Champagne, La Mancha, Cape/South Africa, Porto/Douro, La Rioja, Mendoza, South Australia, Mosel and Tuscany are home to major wineries globally (Fraga et al. 2012). Table and dried grapes contribute 36% and 7% (Fig. 22.1), respectively, in the total grape production, and now there is a rising popularity of table grapes with fresh grape's juice and dried grapes or raisins with 1.3 million tons production (OIV 2019).

Grape cultivation originated in Armenia near the Caspian Sea region, and gradually, it spread westwards to Europe and eastwards particularly in Iran and Afghanistan (Creasy and Creasy 2018). Viticulture regions are widespread, but usually concentrated in temperate climatic zones. Europe consists of the largest viticulture zones in the world (about 40%), although many areas in Asia, such as India, China, Turkey, Afghanistan, Iran and Pakistan, are emerging as the new high-quality table grape-producing regions. China, in Asia, has recorded major increase in grape production over the last few years. Similarly, viticulture has made inroads in US regions, e.g. California, Georgia, Washington and Florida, with good fruit quality for wine and fresh consumption. In the southern hemisphere, Argentina, Australia, New Zealand, Chile, Brazil and South Africa are among the rapidly flourishing viticulture regions. The major grape producers and global viticulture distribution in different regions are given in Figs. 22.2 and 22.3.

**Fig. 22.1** Global viticulture with respect to usage as wine, table and dried grapes

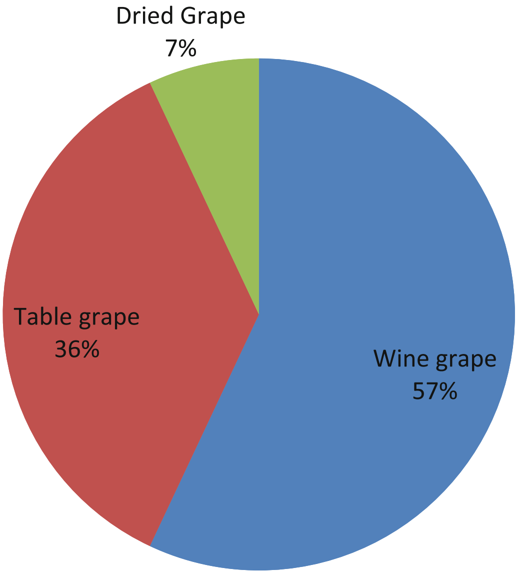
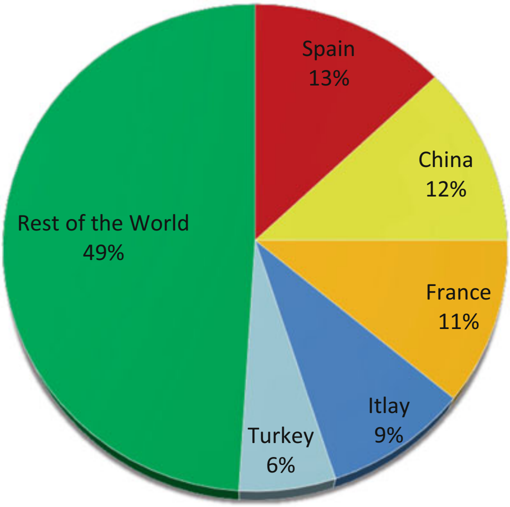
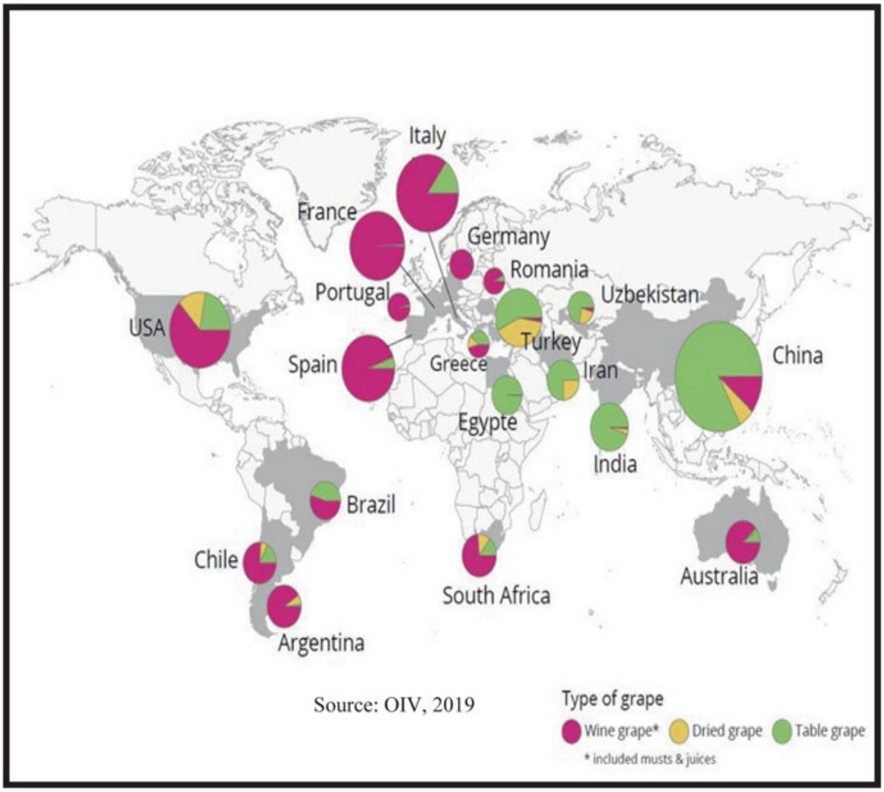


**Fig. 22.2** Global grapevine production trends and share of five leading producers





Source: OIV, 2019

**Fig. 22.3** Global distribution of grapevine in different climatic zones of the world

## 22.2 Botanical and Anatomical Characteristics

Like all other members of Dicotyledoneae, grapevines start their life cycle with two cotyledons. Family Vitaceae's members are termed grapevines, and it contains about 1000 species with 17 genera. Although most members of this family belong to in the tropics or subtropics, even then a species (*Vitis vinifera*) from the temperate zones has become the world's chief fruit producer in about 90 countries. Cultivated grapes belong to either genus *Vitis* (2n 38 chromosomes) or genus *Muscadinia* (2n 40 chromosomes) and have distinct floral morphology (Fig. 22.4). Roots of this family are generally fibrous and well branched and can grow to several metres in length. Vines climb through tendrils which act to provide support, and leaves grow alternatively on branches (Creasy and Creasy 2018; Mullins et al. 1992). There are about 24,000 named cultivars, but there is often more than 1 name for the same cultivar; the number of different and distinguishable cultivars is about 4000 (OIV 2013).

## 22.3 Factors Influencing Viticulture

Grapevine development is affected by a highly intricate system, consisting of soil characteristics, climate features and vineyard management (Magalhaes 2015). The concept of terroir emerged in this system of interacting factors such as physical, biological and environmental components along with viti-vinicultural techniques which give distinctive characteristics to the products (OIV 2010; Van Leeuwen et al. 2004; Fraga et al. 2013). All the elements in the terroir strongly affect the growth and development of grapevine cultivars. Moreover, these factors also influence the wine type, fruit yield and berry quality. A brief description of these factors is given in Sects. 22.3.1 and 22.3.2.

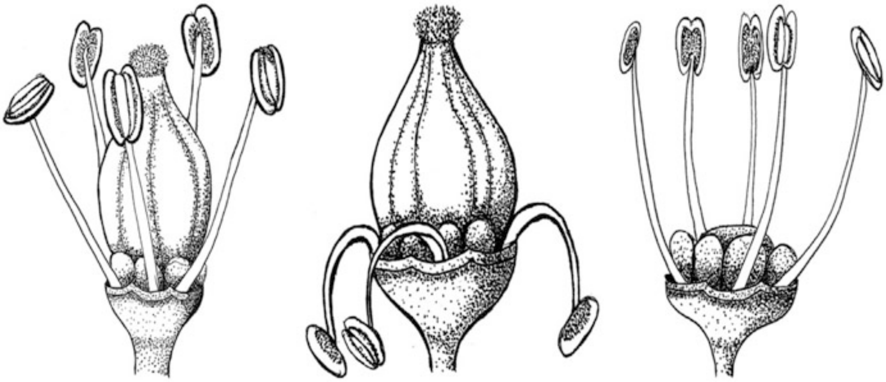


**Fig. 22.4** Flower types in the genus *Vitis*: perfect (left), female (centre) and male flower (right). (Keller 2010)

### 22.3.1 Climate

Grapes are cultivated between 50°N and S, where suitable areas lie in small limits. Vines need cool winter and warm to hot and dry summer for good quality of fruit. Subtropics with winter rains are the most suitable areas for viticulture. Rains and cloudy weather at flowering adversely affect the fruit set, while excessive rains during berry ripening lead to berry and bunch rot. Raisins are produced by sun-drying between the vine rows in areas with at least 1 warm, sunny month without rain after harvest is essential (FAOSTAT 2016). Regional climate is the key element of terroir affecting grape production (OIV 2010; Jones and Davis 2000). Base temperature of 10 °C is one of the most important climatic thresholds for budburst in grapevines (Winkler 1974).

Climate is a key factor driving phenology, vine growth and physiological development, thereby affecting the production and quality of grapevine (OIV 2010; Keller 2010; Costa et al. 2019). Furthermore, vineyard's geographical distribution is affected by climatic variables (Fraga et al. 2019). Weather parameters such as temperatures, solar radiation, rainfall pattern and inter-annual seasonal variability affect vine productivity as discussed by Fraga and Santos (2017). Extreme weather events, e.g. heat waves, hailstorms, excessive rainfall and late spring frost, have detrimental impacts on grapevine productivity (Greer and Weedon 2013; Mosedale et al. 2015).

### 22.3.2 Topographic Features

Topographic features such as land elevation and slope are of significant importance for viticulture (Jones et al. 2004; Yau et al. 2013). Surface elevation affects the temperature in vineyards at farm scale as vertical temperature gradient, and it exerts a strong influence on the site suitability and varietal selection (Magalhaes 2008). Solar exposure to vines is affected by the degree of slope; thus, it has a main impact on canopy microclimate, viticultural management, water drainage and soil erosion in vineyards (Zsofi et al. 2011).

### 22.3.3 Soil Requirements

Soil consists of organic and inorganic matter, and it is a source for providing water and nutrients which are critical for grapevine growth, physiology and yield responses. It is a key part of terroir and an important factor for viticulture (Magalhaes 2008). In fact, the composition of berries is influenced by the soil's physical and chemical properties and hence affects wine quality (Mackenzie and Christy 2005). Grapevines are well adapted to a wide range of soils; however, poorly drained soils and areas with exceptionally high salinity levels are considered as unsuitable. Light soils with high water-holding capacity are preferred for grape cultivation. Similarly, the water-holding capacity of soils is also essential and has a direct effect on vine performance (Yau et al. 2013; Field et al. 2009). Grapevines are moderately sensitive to salinity, and yield is affected by it. Nevertheless, vine yield is not affected up to 1.5 mmhos/cm, while 10% reduction at 2.5, 25% at 4.1, 50% at 6.7 and 100% at 12 mmhos/cm have been observed. Deep fertile soils result in high yields, but in less fertile soil or soil with limited depth, yield is usually poor. Nutrient requirements of grapevine are 100–160 kg/ha N, 160–230 kg/ha K and 40–60 kg/ha P. More nitrogen is required during early spring when the vines are undergoing rapid vegetative and inflorescence development. Nevertheless, nitrogen level must be low during ripening to prevent excessive vegetative growth (FAOSTAT 2016).

## 22.4 Climate Change and Viticulture

Climate change is no doubt the major challenge that the viticulture industry has to deal with in the coming decades. Significant changes in temperature have been observed during the past century which include, surface temperature increase of 1.06 °C over a period of more than 100 years, however major increased, i.e. 0.85 °C occurred over the past two decades (IPCC 2014a). Air temperature variations were prominent, i.e. 2–5 °C increase in traditional viticulture zones in different parts of Europe (Christensen et al. 2007). Climatic projections for the twenty-first century indicate temperature increase in different ranges, i.e. stabilization at 1.5 °C higher than the current reference period to more than 4 °C increase in the mean global temperature (IPCC 2014b). The key driver of the temperature increase has been the emission of greenhouse gases; among these, $CO_2$ is more pertinent in terms of volume and effect (IPCC 2014b). Atmospheric $CO_2$ levels have increased from 280 $\mu L\ L^{-1}$ (preindustrial) to more than 400 $\mu L\ L^{-1}$ in 2016, with predicted a rapid increase for the end of century, i.e. 421–936 $\mu L\ L^{-1}$ (Meinshausen et al. 2011). Furthermore, a decrease in rainfall has been observed in major viticulture regions, particularly, Southern Europe (IPCC 2014a; Christensen et al. 2007), and it is expected to decrease further in the future.

### *22.4.1 Elevated $CO_2$ and Impacts on Viticulture*

The global concentration of $CO_2$ has increased from 280 to 400 ppm; this increase was more rapid after 1950 as indicated in Fig. 22.5. The rise in $CO_2$ levels may change the global viticulture outlook. As an outcome of elevated $CO_2$ levels in the future, grapevine physiological activity and growth may be affected.

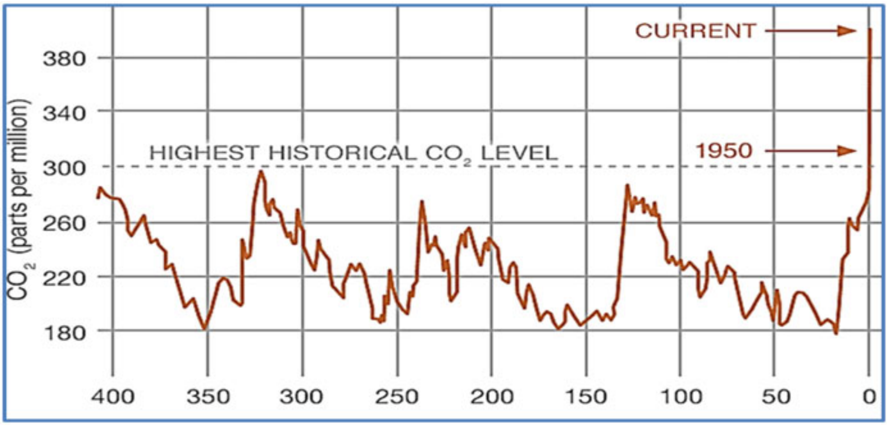


**Fig. 22.5** Historical and current atmospheric CO2 level. (Courtesy of NASA)

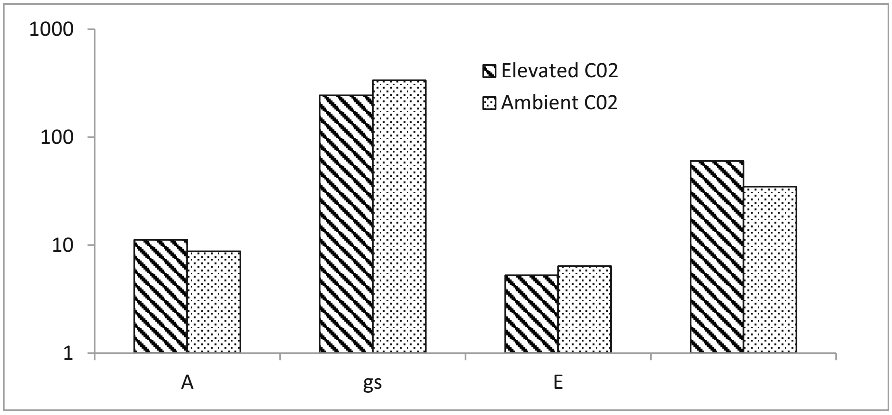


**Fig. 22.6** Effect of elevated $CO_2$ on the rate of photosynthesis (A), stomatal conductance (gs), transpiration rate (E) and photosynthesis/stomatal conductance (A/gs) in vine leaves. (Moutinho-Pereira et al. 2009)

#### 22.4.1.1 Effect of Elevated $CO_2$ on Vine Physiology

The effect of elevated $CO_2$ on physiological responses of table grape cultivars is shown in Fig. 22.6. Leaf physiological and anatomical characteristics and vine productivity were accessed for grapevine (*V. vinifera* L.) cultivar Touriga Franca under high $CO_2$ level of 500 ppm compared to ambient $CO_2$ level, i.e. 365 ppm. Photosynthetic rate, water use efficiency (WUE), leaf thickness and Mg concentration with C/N, K/N and Mg/N ratios were increased under elevated $CO_2$; however, stomatal density and N concentration were decreased. On the other hand, transpiration rate (E), stomatal conductance (gs), leaf water potential, photochemical efficiency (Fv/Fm), SPAD value and transmitted red/far-red light were not significantly

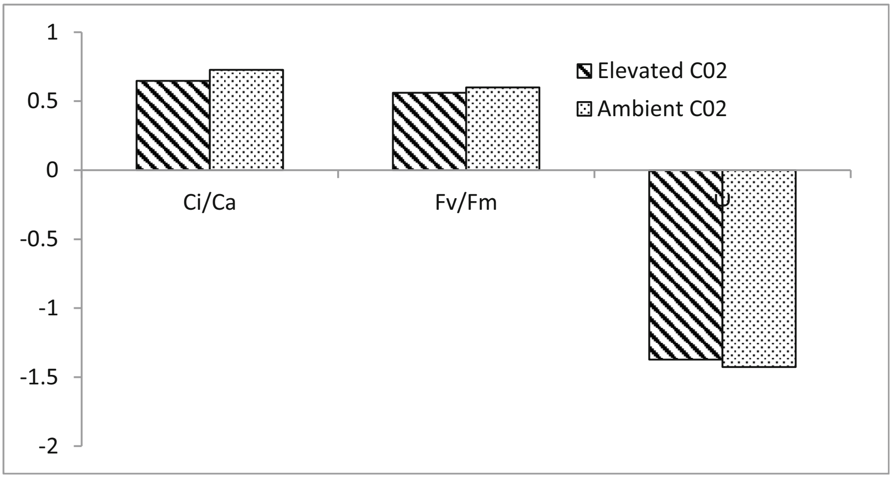


**Fig. 22.7** Effect of elevated $CO_2$ on internal $CO_2$/ambient $CO_2$ concentration (Ci/Ca), photochemical efficiency (Fv/Fm) and water potential. (Moutinho-Pereira et al. 2009)

affected by higher $CO_2$ levels (Moutinho-Pereira et al. 2006, 2009). It is obvious that the photosynthetic activity (A) in grapevine will increase in the future in response to rising $CO_2$ levels, while stomatal conductance (gs) and transpiration would decrease; however, the ratio of photosynthetic activity to stomatal conductance will increase (Fig. 22.6). Rising $CO_2$ will also affect Ci/Ca ratio and Fv/Fm ratio negatively, while water potential levels will slightly increase as shown in Fig. 22.7. These trends depict that the climate challenge would have a profound impact on the physiological responses of grapevine.

#### 22.4.1.2 Vine Growth, Yield and Anatomical Characteristics

Elevated atmospheric $CO_2$ levels affect the growth and anatomical characteristics of grapevine. Data presented in Fig. 22.8 show that elevated atmospheric $CO_2$ levels resulted in the decreased thickness of total parenchyma, palisade parenchyma, spongy parenchyma and palisade/spongy parenchyma ratio. Despite significant changes in anatomical characteristics along with leaf mass per unit area, may be due to higher light red/far-red light ratio, the stomatal conductance and SPAD values were not much affected as indicated in Table 22.1. Enriched $CO_2$ also increased vine yield, number of clusters, cluster weight, number of shoots per vine, pruning weight, shoot weight and Ravaz index (Table 22.2) as indicated by Moutinho-Pereira et al. (2009) and Wohlfahrt et al. (2019). The yield gain due to elevated $CO_2$ was demonstrated under free air carbon dioxide enrichment (FACE) experiments. Recently, increased vine growth and vigour owing to higher rates of photosynthesis under elevated $CO_2$ have also been noticed (Wohlfahrt et al. 2018). Available records from literature also indicate that higher photosynthetic activity owing to

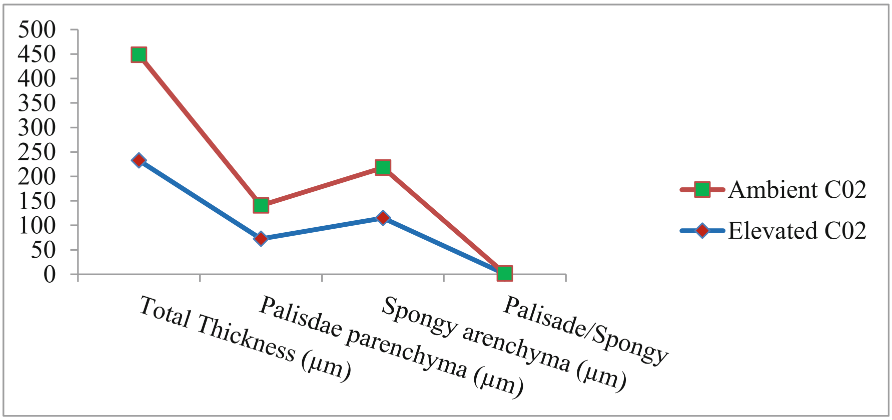


**Fig. 22.8** Effect of elevated $CO_2$ on grapevine anatomical features

**Table 22.1** Effect of elevated $CO_2$ on grapevine stomatal density, SPAD value, infrared light and leaf mass per unit area

| $CO_2$ scenario | Stomatal density | SPAD | Red/far-red | LMA ($g \cdot m^{-2}$) |
|---|---|---|---|---|
| Elevated $CO_2$ | 147.85 | 45.25 | 0.202 | 83.6 |
| Ambient $CO_2$ | 147.85 | 44.45 | 0.187 | 72.6 |

**Table 22.2** Effect of elevated $CO_2$ on grapevine yield, vegetative growth, light interception, leaf mass and Ravaz index

| $CO_2$ scenario | Vine yield (kg) | Clusters per vine | Cluster weight (g) | Shoots per vine | Pruning weight (Kg) | Shoot weight (g) | Ravaz index |
|---|---|---|---|---|---|---|---|
| Elevated $CO_2$ | 5.22 | 15.57 | 336.23 | 14.83 | 0.75 | 52.13 | 8.13 |
| Ambient $CO_2$ | 7.28 | 17.97 | 403.33 | 17.90 | 1.04 | 64.73 | 7.13 |

**Table 22.3** Effect of elevated $CO_2$ on main elements ($g\ kg^{-1}$) in grapevine leaves

| $CO_2$ scenario | C | N | P | K | Ca | Mg | Fe |
|---|---|---|---|---|---|---|---|
| Elevated $CO_2$ | 507 | 21.5 | 1.56 | 6.80 | 17.0 | 3.94 | 158 |
| Ambient $CO_2$ | 497 | 23.7 | 1.63 | 5.78 | 19.2 | 2.01 | 152 |

elevated $CO_2$ would favour yield with higher biomass accumulation (Goncalves et al. 2009; Kizildeniz et al. 2015; Edwards et al. 2016, 2017). The main leaf elements, i.e. N, P, K, Ca, Mg and Fe, were also affected as indicated in Table 22.3. Hence, the effect of $CO_2$ enrichment on vine phenology will be positive if not complicated by other factors (Moutinho-Pereira et al. 2006, 2009). But, it may not be so in the future due to rising temperature, berry ripening in hot summer and drought effects coupled with rising $CO_2$. It is obvious here that grapevine leaf anatomical and growth characteristics are affected by rising $CO_2$. Among quality traits, sugars, acids and berry size were more affected, while juice, wine quality, anthocyanins and proanthocyanidins were not affected by $eCO_2$ (Martinez-Luscher et al. 2015; Bindi et al. 2001; Salazar-Parra et al. 2012; Wohlfahrt et al. 2021). Recently, it is indicated that elevated $CO_2$, i.e. 700 ppm, in combination with elevated temperature, i.e. +4 °C, decreased anthocyanin and sugar decoupling due high temperature for cv. Tempranillo (Arrizabalaga-Arriazu et al. 2020).

## *22.4.2 Effect of Water Stress on Viticulture*

Precipitation is an important climatic factor, which affects water availability and use by grapevine (Ferreira et al. 2015). Moderate water stress has some positive effects, e.g. wines of high quality are associated with slight water stress during berry ripening. Dry weather conditions during ripening are favourable for high-quality wine production (Greenspan 2005; Munitz et al. 2017). Severe water stress during early developmental stages may considerably delay the growth and development of grapevine. On the other hand, excessive soil water during the growing season results in vigourous vines, more disease incidence and connected problems which negatively affect wine quality (Magalhaes 2008; Vanden and Centinari 2021). Contrarily, excessive rainfall near maturity is unfavourable, as it causes sugar dilution and diseases (Keller 2010; Munitz et al. 2018; Pellegrino et al. 2005). The impact of water stress depends on vine development stage, e.g. optimal soil moisture levels during budburst, shoot growth stages and inflorescence development are crucial for better vine growth (Poni et al. 1994). Water stress at these stages negatively affects shoot growth, floral cluster development and berry set as discussed in the next sections.

### 22.4.2.1 Phenology, Growth and Yield Under Water Stress

Water deficit in the beginning of active growth period after dormancy break negatively affects budburst as the rate of mobilization is affected. Rapid shoot growth occurs after budbreak mainly at the expense of stored food reserves in vine during the preceding vegetative cycle (Keller 2005). However, water deficit at active growth phase reduces vine growth, e.g. reduction in shoot growth 20 days after budbreak was noticed for cvs. Cabernet Sauvignon, Pinot Gris and Merlot when midday leaf water potential reached 1.0 MPa (Greenspan 2005; Shellie 2006). Similar reduction in leaf area of cv. Merlot due to water stress was observed by Munitz et al. (2017). Relatively prolonged exposure to moderate water deficit increases root-to-shoot ratio (Chaves et al. 2010). The most active period for vine growth is between budbreak and veraison, and a maximum growth is reached during the early growth cycle usually 60 days after budbreak (Junquera et al. 2006;

Ben-Asher et al. 2006; Munitz et al. 2016; Intrigliolo and Castel 2010). Vine growth then progressively decreases until a vegetative standstill is reached near veraison.

Similarly, reproductive growth correlates with water availability at different developmental stages of the vine. The relationship between yield and water availability from budbreak to harvest was observed in cv. Cabernet Sauvignon (Junquera et al. 2006). Reduced vine yield may be associated with intense and persistent water deficit as it reduces bud fertility along with poor inflorescence development. Vine fertility is reduced by both limited and excessive water availability. Water deficits near flowering limit ovary growth, leading to smaller berries, but the effects on pollen formation and germination and pollen tube growth are even more severe. For instance, sugar uptake and starch accumulation in developing pollen grains are limited under water deficit conditions, causing sterility and poor inflorescence development and fruit set (Keller 2010, 2005; McCarthy 2005).

#### 22.4.2.2 Effects on Vine Physiological Processes

Water stress causes physiological changes, such as reduced leaf photosynthetic activity in response to stomatal closure. Leaf stomatal closure acts as the first line of defence for vines from withering due to heat and drought stress. However, transpiration is a unique component of the radiation energy which is converted into latent heat through the regulation of stomatal closure (Lovisolo et al. 2010). Under high vapour pressure deficit (VPD) levels, stomatal conductance declines up to a threshold. For instance, stomatal conductance of cv. Chardonnay significantly declined at temperatures above 30 °C and high VPD (Poni et al. 1994; O'Neill 1983). Transpiration is the main component of energy balance and provides a cooling mechanism through leaves in plants (Naor et al. 1993) and helps keep leaf temperatures in permissible limits. Even a relatively lower leaf transpiration may lower the leaf temperature by a few degrees and help maintain growth and avoid wilting to a limited extent.

#### 22.4.2.3 Effects on Grape Berry Quality and Composition

Berry total soluble solids (TSS) give an estimation of berry ripening. Rapid TSS as Brix accumulation takes place under water deficit conditions. For example, higher TSS levels per berry weight have been recorded for rainfed vines compared to irrigated vines as indicated by Intrigliolo and Castel (2010) and Esteban et al. (2002). During berry ripening, acid contents of the berry decrease with an increase in pH. A positive relationship between water availability and total acidity was indicated by Intrigliolo and Castel (2010) and Junquera et al. (2012). Increases in titratable acidity due to water stress regardless of the developmental stage were indicated by Girona et al. (2009) for cv. Tempranillo. Higher tartaric acid and lower malic contents were recorded in water deficit vines of cv. Doña Blanca under warm conditions (Uriarte et al. 2017). Similarly, for cv. Tempranillo/110R, (Santesteban et al. 2011) obtained higher titratable acidity values in the higher irrigation treatments. Contrarily, insignificant effects of irrigation treatments on acidity, pH, malic acid and tartaric acid were noticed in cvs. Monastrell/1103 Pa, Cabernet Sauvignon and Merlot as indicated by Munitz et al. (2016). Romeroz et al. (2013) and Acevedo-Opazo et al. (2010).

Water stress early in the season negatively affects vigour, berry size and photosynthetic rate which ultimately lowers acidity and phenolic contents (Esteban et al. 2002; Salon et al. 2005). Controlled deficit irrigation is used to improve berry ripening and wine quality (Uriarte et al. 2015), e.g. elevating the levels of terpenes by modulating structural and regulatory genes (Cramer et al. 2013). Water deficit stimulated the biosynthesis of anthocyanins and phenolic contents (Rogiers et al. 2011). Moreover, the timing and intensity of water deficit affect the metabolism, colour, aroma and flavour compounds of berries. Certainly, water deficit increases the skin-to-pulp ratio in berries compared to well-watered grapevines (Zufferey et al. 2012) while enhancing skin tannin and anthocyanin contents. Increased biosynthesis of anthocyanins in response to water deficit causes differences in colour development (Rossouw et al. 2017).

## 22.5 Effect of Elevated Temperature on Viticulture

Higher temperature during the active growing season strongly affects grapevines because it is a major driver of developmental stages of grapevine (Parker et al. 2013) and global warming is expected to accelerate phenological events. The phenological shifts at key developmental stages have a strong influence on vineyard management. Moreover, heat events during maturation period will affect wine quality and typicity. Extreme heat stress during the ripening period abruptly reduces grapevine metabolism. It may result in higher sugar levels and lower acidity with potential increase in chances of wine spoilage, hence affecting grapevine production and quality attributes (De Orduna 2010; Fraga et al. 2018) as discussed in Sects. 3.3.1, 3.3.2, and 3.3.3.

### *22.5.1 Phenology, Growth and Yield Under High Temperature*

Grapevine phenology is a good indicator of heat stress and may be used to evaluate the effects of climate change on vine developmental stages like flowering, veraison and grape ripening (Greer and Weston 2010; Bernardo et al. 2018). Air temperature is the key factor driving the timing of phenological stages (Fig. 22.9) along with the duration of phenophases in grapevine (Kose 2014); hence, it affects the inter-annual variability in vine yield and berry quality (De Orduna 2010; Fraga et al. 2014).

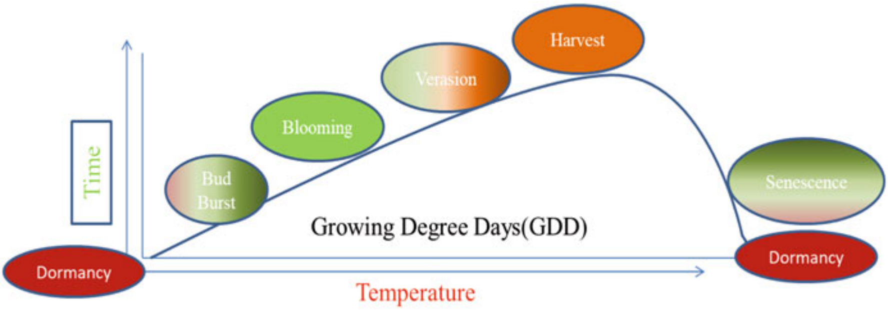


**Fig. 22.9** Thermal time model for studying the growth stages of temperate perennial crops

Rising temperature trend is expected to advance grapevine phenology and derive berry ripening during the warmest period of the year (Webb et al. 2007; Duchene et al. 2010) interferes with the quality traits (Van Leeuwen and Seguin 2006). Phenological shifts of 10–24 days from 1975 until 2015 have been noticed in south-west Germany give an alarming situation for global viticulture (Koch and Oehl 2018). Shortening trends for the periods budburst to flowering, flowering to veraison and veraison to maturity have been recorded due to elevated temperatures, e.g. flowering to veraison interval shortened about 1 day for every 5 years (Jones and Davis 2000; Tomasi et al. 2011; Duchene and Schneider 2005). A similar trend with strong correlations between maturity timing and the maximum springtime temperatures under Australian conditions was noticed (Jarvis et al. 2017). The most obvious phenological shifts recorded are for blooming and veraison (Caffarra and Eccel 2011). Similarly, grapevine harvest dates are associated with maximum air temperatures (Koufos et al. 2020). However, significant trends were not observed for the shortening of the veraison to maturity period (Cameron et al. 2021). Previously, it was indicated that among a range of temperature variables, maximum temperature for March–April influenced flowering and veraison timings (Malheiro et al. 2013).

A significant advance is expected in the onset timings of grapevine phenological stages; however, the phenophase duration depends on soil type and grape variety (Fraga et al. 2013; Bernardo et al. 2018). Phenological advancement for 2–3 weeks is expected until 2050, and this advancement is more apparent for the northern hemisphere vineyards (Neethling et al. 2017; Van Leeuwen et al. 2019). In a related study, it was depicted that in the future, many areas presently considered suitable for grapevine production would be eliminated with 81% reduction in acreage for premium quality grape at temperature above 35 °C (White et al. 2006).

Moreover, elevated temperatures are considered detrimental for the reproductive performance and consequently yield of grapevine (Keller et al. 2010), and for temperature at 40 °C, reduction in flowers per inflorescence under warmer conditions was by one-third. Previously, it has been established that day temperature of 35–40 °C near flowering is highly detrimental for good fruit set with lower ovule fertility, hence fewer berries per cluster (Ebadi et al. 1995; Ewart and Kliewer 1977;

Kliewer 1977). Furthermore, pollen germination is also highly temperature sensitive, e.g. in grapevines (Staudt 1982), less pollen germination was noticed at 15 °C, while temperature at 28 °C is considered optimum for better pollen germination and pollen tube growth (Rajasekaran and Mullins 1985). High temperature near flowering negatively affects the carbohydrate contents of pistil and pollen tube growth with lower fruit set (Snider et al. 2011; Pagay and Collins 2017). Furthermore, short periods of extreme temperatures are considered highly detrimental particularly for key developmental stages, e.g. flowering and fruit set, which may negatively affect vine yield and berry quality (Ferris et al. 1998; Hedhly et al. 2005; Prasad et al. 1999).

### 22.5.2 *Fruit Quality and Composition*

Rising temperature owing to global warming is expected to change the composition of grape berries. The rate metabolism of grape berries depends on air temperature, whereas elevated temperatures beyond ambient level perturb metabolic pathways and cause changes in the biosynthesis of several important metabolic compounds crucial for maintaining quality (Blancquaert et al. 2018). Elevated air temperatures promote berry sugars coupled with the degradation of berry organic acids. In a rising temperature scenario, juice and wine acidity would be more drastically affected compared to sugar contents as indicated in Fig. 22.10. Such weather conditions would result in unbalanced wines having higher alcohol contents due to high sugars and lower acidity and deprived of essential aromatic compounds (Kose 2014; Van Leeuwen and Destrac-Irvine 2016). Relatively lower titratable acidity has been observed at 30 °C compared to 20 °C (Poudel et al. 2009). Under heat stress

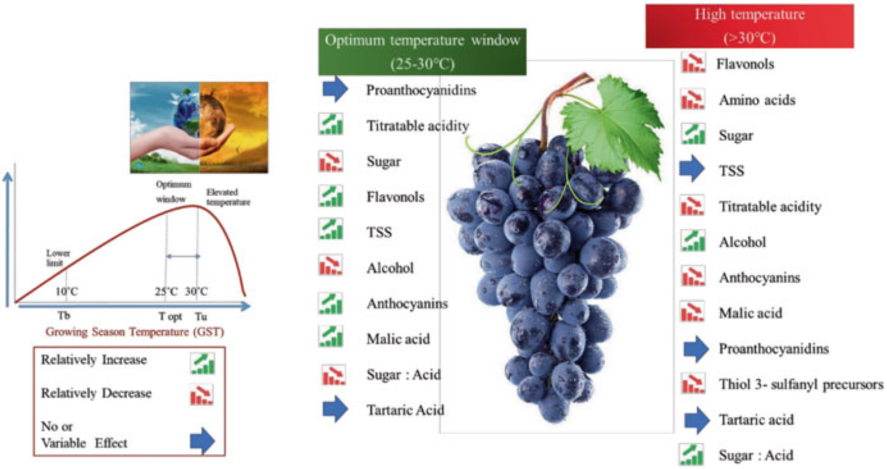


**Fig. 22.10** Key quality traits of grape berries under ambient and elevated temperatures

conditions, potassium concentration of berries increases near maturity along with high pH value and lower total acidity (Bernardo et al. 2018). Moreover, malic acid is metabolized relatively faster than tartaric acid at elevated temperature, and the optimum temperature for malate biosynthesis is 20–25 °C; however, a major decrease in its biosynthesis has been noticed at 40 °C (Keller 2010).

For most of the grapevine varieties, optimum temperature at maturation stage for the biosynthesis of aroma compounds is 20–22 °C (Van Leeuwen and Destrac-Irvine 2016). Berry colour development is reduced when air temperature exceeds 30 °C, and higher temperatures (above 37 °C) cause major decline in berry colour along with higher volatilization of aroma compounds (Bernardo et al. 2018; Neethling et al. 2017). Total sugars of grapes and ethanol contents of wines have also increased, e.g. wines with ethanol levels have increased by 3% during the last few weeks (Neethling et al. 2012). Anthocyanins are the main pigment-imparting compounds in berries largely found in the skins of coloured varieties, e.g. red grapes. Elevated temperatures lower anthocyanin contents and flavour compounds of berries grown in temperate areas (Poudel et al. 2009; Yamane et al. 2006). Moreover, reduction in delphinidins, anthocyanins, peonidin and petunidins based anthocyanins contents of grape berries was noticed, however biosynthesis of malvidin derivatives was less affected under high temperature conditions (Bernardo et al. 2018).

### *22.5.3 Elevated Temperature and Grapevine Physiology*

Among physiological functions, photosynthesis is directly affected by temperature variations as highlighted by Sharma et al. (2019) and Luo et al. (2011), and it is reduced earlier before the onset of other symptoms of high temperature beyond optimum limits. The optimum temperature window differs among species (Xiao et al. 2017; Kun et al. 2018), and for grapevine, it lies between 25 and 35 °C (Ferrandino and Lovisolo 2014). When temperature goes below 10 °C, most of the physiological processes are weakened. On the other hand, heat acclimation mechanisms are activated when the temperature reaches 35 °C, (Bernardo et al. 2018; Greer and Weedon 2012). Similarly, extremely high temperatures, e.g. 40 °C or above, may cause the disruption of the photosynthetic apparatus of plants. Reduction in photosynthetic activity at 45 °C compared to 25 °C has been quantified up to 60% by Lamaoui et al. (2018). Similarly, it was observed (Xiao et al. 2017) that photosynthetic activity does not decrease up to 35 °C; however, it is limited above 40 °C, and this reduction in photosynthesis may be attributed to 15–30% lower stomatal conductance (Lamaoui et al. 2018). The discussion also bears forth that heat and drought stresses are related to each other and reduced stomatal conductance may increase the effects of heat stress due to rise in leaf temperature (Costa et al. 2012). The effects of heat stress on vine stomatal conductance vary among cultivars, and it was noticed that for a common wine cultivar Touriga Nacional, under mild heat stress conditions, leaf stomata remained open which might be beneficial for lowering the leaf temperature to retain normal photosynthesis (Wang et al. 2010).

The lower leaf photosynthetic activity under high temperature might be attributed to disturbed vine biochemical processes, e.g. reduction in ribulose-1,5-bisphosphate (RuBP) regeneration along with the activation of ribulose bisphosphate carboxylase oxygenase (Rubisco) activity (Wen et al. 2005). Under heat stress, photosystem II (PSII) is suspended earlier, and other cellular functions are disrupted as it is highly temperature sensitive (Ferrandino and Lovisolo 2014; Bensalem-Fnayou et al. 2011). Thermal stress even for short periods, e.g. 15 min at 40 °C, may cause irreparable damage to thylakoid membrane permeability and functioning of PSII in grapevines (Ferrandino and Lovisolo 2014; Liu and Fang 2011). Recently, it was revealed that for heat treatments at 35 °C and 40 °C, photosynthetic activity was reduced significantly; however, total chlorophyll contents, chlorophyll fluorescence and thylakoid membrane leakage were not much affected for cvs. Cabernet Sauvignon and Junzi vines (Nievola et al. 2017). For more elevated temperature at 45 °C, lower total chlorophyll contents and increased fluidity of thylakoid membrane were observed along with other obvious stress symptoms. Moreover, structural disarrays of thylakoids have also been reported in prolonged heat stress conditions, i.e. for 3 months. Injury to thylakoid structures is associated with a deterioration in chlorophyll contents which indicates the inhibition of PSII (Hu et al. 2020; Kadir et al. 2007). Hence, chlorophyll fluorescence may help to identify changes in photosynthetic apparatus as an indicator for heat stress tolerance in grape cultivars (Kadir et al. 2007).

Leaf transpiration increases under elevated temperature as observed by Greer (2019) that transpiration rates in grapevine increased up to five times for the corresponding increase in temperature from 15 to 40 °C. This increase in transpiration activity was from 0.5 mmol $m^{-2}$ $s^{-1}$ to about 2.5 mmol $m^{-2}$ $s^{-1}$; however, further increases in temperature (45 °C) did not affect leaf transpiration. Similarly, for cv. Semillon, substantial increase in transpiration was observed with increase in leaf temperature above 35 °C; the increase is mainly to meet up the enhanced evaporative cooling demands (Keenan et al. 2010). In another related study, four time increases in transpiration of cv. Chardonnay were noticed as the temperature increased from 15 to 30 °C, while this rate was even higher for cv. Cabernet Sauvignon at 35–40 °C (Keller 2010). A linear trend for the transpiration rates was noticed with temperature increase from 20 to 40 °C. Moreover, genotypes have varying responses to temperature, e.g. relatively higher transpiration rates have been observed for cv. Semillon vines compared to many other cultivars (Rogiers et al. 2009); thus, its cooling capacity owning to better transpiration may help to retain the canopy temperature relatively lower than the atmospheric temperature. In addition to climatic variables, the quality and growth of grapevine vegetative and reproductive growth, ripening and yield may also be affected by vineyard management such as pruning type, crop load, training systems, grafting and timings of cultural practices as discussed by Winkler (1974). It is highly crucial to acquire the knowledge of the varietal specificities for high-quality grape production (Jones and Davis 2000).

Henceforth, optimizing vineyard management is required for enhancing vineyard productivity and profitability.

## 22.6 Adaptation Strategies for Viticulture in the Wake of Climate Change

The elaborated climate change impacts on viticulture make it imperative to plan and apply suitable adaptation measures. It included short-term adaptation measures and changes in viticulture management practices and techniques, such as irrigation scheduling, protection from sun burns, improving water use efficiency (WUF) and devising long-term adaptation strategies such as selection of suitable varieties and identifying new suitable viticulture regions for a sustainable crop production (Fraga 2019) in consultation with stakeholders is an upheaval task for modeller, policy makers and viticulturists.

In order to adapt viticulture, physiologists and breeder must focus on improving water use efficiency (WUE) to minimize the impact of elevated $CO_2$ and climate change by integrating the knowledge from genomics and phenomics to incorporate characteristics from promising QTLs. Moreover, improvements in photosynthetic efficiency and WUE by introducing C4-like characteristics in C3 plants coupled with modelling approaches need to be focused (Ahmed and Ahmad 2019). Climate change necessitates identifying new genotypes and incorporating resilience such as heat and drought tolerance from wild cultivars. Moreover, the existing viticulture may not remain suitable for premier-quality table and wine grape cultivation under future climate; hence, identifying new viticulture zones based on crop heat unit requirements is the need of time. Furthermore, improving vineyard management practices, e.g. pruning, thinning and canopy management for maintaining vine balance, is necessary to cope with these challenges.

## 22.7 Conclusion

Currently, global viticulture is facing sustainability challenge owing to climate change. Rising $CO_2$ coupled with high temperature and lower rainfall negatively affected grapevine production. Phenological advancements with poor inflorescence development, less fruit set and low yield have been observed in many viticulture regions. Although elevated $CO_2$ levels may have some positive impacts on photosynthetic activity, the overall impact in conjugation with increasing temperature and water stress would be negative. Moreover, the physiological activities of vines such as photosynthesis activity, stomatal conductivity and water use efficiency are also severely affected under heat and drought stress. Similarly, key quality attributes of wine and table grapes, e.g. berry sugar, acidity levels, polyphenols and anthocyanin, may not reach desirable levels for premier-quality grape production. The impact of climatic trends on viticulture would be more in the coming decades, e.g. major grapevine cultivars originating from cooler climates would not be able to withstand heat stress. Indigenous and wild grapevine germplasm from relatively warm and dry regions may serve as an alternative. Henceforth, it is crucial to identify the key components of grapevine regulatory networks controlling heat stress response and acquisition of tolerance against environmental stresses for sustainable viticulture.

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