Mitigation and Adaptation Practices to the Impact of Climate Change on Wine Grape Production, with Special Reference to the South African Context

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In South Africa, environmentally and socio-economically sustainable wine grape production is promoted by governmental and private initiatives. All the initiatives contribute to establishing a scientifically based response strategy of agro-systems to ensure sustainable production under future expected climate conditions. South African wine grape producers would probably have to cultivate their grapevines under higher atmospheric CO_2 levels and in warmer, mostly drier, conditions. Due to the projected increase in climatic variability, an effort must be made to improve the resilience of vines against these environmental conditions. Whole-vine functioning and balances should be considered when adjustments are made to current long and short term cultivation practices. All practices should be aimed at promoting the development of a deep, dense and buffered root system that is able to support a well-developed canopy with optimal microclimate that would sustain a high yield of good quality. Mitigation and adaptation strategies would most likely have to be region specific, and small scale terroir data, (which should include both climate and terrain/soil information) may play a critical role in decision-making.

INTRODUCTION

The current concept of climate change does not refer to naturally occurring warming and cooling cycles over extremely long periods of time, but rather to "a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and… is in addition to natural climate variability…" (UNFCCC, 2011). "Warming of the climate system is unequivocal,…, [with] many of the observed changes…unprecedented…" (IPCC, 2014). The increase in anthropogenic greenhouse gas (GHG) concentrations [expressed as carbon dioxide (CO_2) equivalents] is considered to be the main cause of global warming and is due to emissions of mostly CO_2, methane (CH_4) and nitrous oxide (N_2O) into the atmosphere (IPCC, 2014). Observation and monitoring systems, such as the Integrated Carbon Observation System (ICOS) in Helsinki and the Global Greenhouse Gas Reference Network (GGGRN) of the National Oceanic & Atmospheric Administration-Earth System Research Laboratories (NOAA-ESRL) in Colorado, make use of extensive air sample collection networks to determine the concentration levels of GHG. They use various analysing methods, such as gas chromatography for CH_4 and N_2O (ICOS, GML) and infrared absorption (GML) or gas chromatography (ICOS) for CO_2. Concentrations are then expressed as CO_2 equivalent units.

Higher atmospheric GHG levels increase the capture of radiated heat from the Earth (Mozell & Thach, 2014), causing warming of the air and land-ocean surface. Continued emission of GHG will result in further warming and a concomitant higher risk of causing irreversible damage to ecosystems and quality of life for humans. Indeed, certain facets of the climate system (such as ocean temperatures and acidification, sea level rise, soil carbon cycles, etc.) will continue to change for centuries to come, even if GHG emissions cease immediately (IPCC, 2014). Global mean surface temperature at the end of the 21st century will thus be largely determined by the CO_2-equivalent units (CO_2-eq) that have already been emitted in the past.

The risks associated with climate change should be reduced as far as possible and managed in such a way that sustainable development, economic and social well-being, and effective natural resource and biodiversity conservation

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are ensured (IPCC, 2014). Adaptation and mitigation are the two types of action that could be taken against climate change (CCC, 2009). Adaptation is generally focused on how to remedy the current effects that the climate has on natural, biological and socio-economic environments. The impact of these practices is visible within a relatively short period of time. Mitigation is directed at the longer term and addresses the causes of climate change by attempting to reduce or eliminate sources of GHG emissions. These two strategies are complementary (IPCC, 2014) - adaptation can reduce the impact of climate change, but it will not be effective in the long term without supporting mitigating actions.

Any mitigation strategy aimed at the agro-system (farms and surrounding landscapes that provide the environmental, production, social and economic context) should focus on an integrated approach. It should combine measures to decrease energy use and net GHG emission; to decarbonise energy supply (fossil fuel) by replacing it with cleaner sources (biological, wind, solar); and to increase extraction and sequestration of CO_2 from the atmosphere (CAST, 2004). In any crop production system, there is a balance between carbon uptake from and its release back into the atmosphere. Plants take up carbon through photosynthesis and incorporate it as biomass during growth and yield production (CAST, 2004). Soils may also contribute to carbon sequestration in the agro-system, but the capacity would depend on factors such as the soil depth, nutrient and clay content, water holding capacity and the susceptibility of the soil to erosion and mineralisation (Lal, 2018). Carbon is mainly emitted back into the atmosphere due to soil respiration, which is the respiration of the plant roots and soil micro-organisms combined (CAST, 2004). In well-established agro-systems, cultivation practices should be focused on the hoarding and emission of carbon. Firstly, the size of the carbon sink should be increased (IPCC, 2014; Tubiello *et al.,* 2014). This may be achieved by the cultivation of perennial grass crops where possible (CAST, 2004) or by establishing cover crops in working rows of vineyards (Tezza *et al.,* 2019) and orchards. Secondly, cultivation practices should decrease the amount of carbon emission (CAST, 2004). This may be obtained by limiting soil cultivation and thereby protecting the soil against unnecessary degradation and mineralisation (Lal, 20218) which would detrimentally affect the water and nutrient holding capacity of the soil. Maintaining natural vegetation between production units where still possible (Tezza *et al.*, 2019), restoring highly degraded land and wetland to their natural vegetation, and avoiding unnecessary conversion of natural vegetation areas for agricultural production where it is not economically viable, would also increase the carbon sequestration potential of the agro-system.

The expected increase in both water demand and its scarcity will force the agricultural sector, which is currently accountable for 70 % of global freshwater use (IPCC, 2019), to improve water retention in the soil, adapt irrigation strategies to limit water use and consider alternative water sources, such as recycled wastewater for irrigation. Climate Smart Agriculture (CSA) is one such approach aimed at "securing sustainability and resilience [of production systems] while providing economic, ecological and social benefits" (WCG, 2015).

In South Africa, the Smart Agriculture for Climate Resilience (SmartAgri) project commenced in 2014 with the purpose of developing "a practical and relevant climate change response framework and implementation plan specifically for the agricultural sector of the Western Cape" (WCG, 2014). This project is directed by the African Climate and Development Initiative (ACDI) of the University of Cape Town in collaboration with the Western Cape Department of Agriculture, the Western Cape Department of Environmental Affairs and Development and the Agricultural Sector. In May 2016, the SmartAgri climate change response strategy and action plan was launched. Six priorities (conservation agriculture; restoring degraded landscapes; improved catchment management for water security and job creation; energy efficiency; "climate-proofing" the Western Cape's agri-processing sector and integrated knowledge system for climate smart practices) were highlighted to be focused on by both government and industry (WCG, 2016). Recent studies confirmed the critical role that human decisions can play in improving the resilience of the agricultural sector to climate change (Morales-Castilla *et al.,* 2020).

This manuscript has two focus areas. The first comprises climate change within the context of the South African wine industry. The second discusses challenges faced by the South African wine industry and possible adaptation and mitigation strategies that may be applied during the production of wine grapes, with reference to the concept of "terroir".

Climate and Wine Grape Production

Since the grapevine is indigenous to the Mediterranean region and was mostly cultivated over narrow climatic and geographical ranges (mid-latitude regions) it was originally thought to be sensitive to changes in climate (Jones & Webb, 2010). However, new wine regions in tropical and meso-tropical climates started to emerge (Mira de Orduña, 2010) and currently, grapevines are cultivated on six of the seven continents across a wide climatic range (Schultz, 2016). It is clear that the grapevine has in fact a natural ability to adapt to the environmental conditions in which it is grown. Due to this eco-physiological adaptation capacity (plasticity) of the grapevine, it is not sufficient to use only bioclimatic indices when evaluating a region for quality wine production (Schultz, 2011; Seguin & Garcia de Cortazar, 2015). Furthermore, the large physiological and morphological differences between grape cultivars allow successful wine grape production over a wide range of climates (Anderson *et al.,* 2008; Keller, 2010). However, for every region, there are climate limits outside which viticulture will cease to be sustainable (Morales-Castilla *et al.,* 2020; Santos *et al.,* 2020).

Climate models are often used to determine the suitability of a region for a specific purpose, such as wine grape production. Average temperature as a single factor is commonly used (Webb *et al.,* 2007; Hall & Jones, 2009; Hannah *et al.,* 2013), but temperature models are not able to discern between regions based on climate variability (Hunter & Bonnardot, 2011). Another option is to integrate climatic factors within one model, as was done by Webb *et al.* (2013) with temperature and precipitation, but this is also insufficient should the total effect of the complete climate system on

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wine production be the objective. Regions with similar mean temperature and precipitation may differ significantly in terms of the timing and frequency of the precipitation, the diurnal temperature range or the occurrence of extreme climatic events.

Hunter and Bonnardot (2011) combined temperature and potential photosynthetic activity to quantify the impact that temperature may have on grapevine physiological behaviour at specific locations. They concluded that the use of mean climatic indices is not sufficiently discriminatory and may lead to the zoning of only apparently homogeneous terroirs. It is therefore necessary to assess climatic suitability of a region at fine scale (regarding time and space) to better determine the potential for grapevine growing at a specific location/terroir, especially in regions with a complex terrain (Hunter & Bonnardot, 2011; Quénol *et al.,* 2017; Sturman *et al.,* 2017). Fraga *et al.,* (2016) coupled dynamic crop models, which simulate plant growth and development, with high-resolution climate simulations to generate future projections of yield, phenology and possible stress indicators for grapevines. Even sophisticated methods such as these have their limitations, since certain assumptions and generalisations are always required in the programming (Fraga *et al.,* 2016). Other factors, such as air relative humidity and wind speed that affect evapotranspiration, are often omitted (Bois, 2019), thereby decreasing the accuracy of model-based predictions.

The application value of any model is dependent on the resolution level and accuracy of the data available. In the Western Cape of South Africa, actively logging weather stations are currently still sparsely distributed and producers in the agriculture sector have limited access to high resolution climate data. A study was done to investigate the possibility of using remote sensing data of mean land surface areas as alternative technology to supplement weather station data (Southey, 2017). The strong linear relationship found between remote sensing data and weather station data indicated that the former could be used for temperature estimates where weather stations are not yet present.

The Western Cape has a very complex topography. There is large variation in elevation (Fig. 1), slope gradients and aspects as well as a long coastline with various degrees of exposure to the sea breeze effects from both the Indian and Atlantic oceans, which is intensified by the cold Benguela current of the latter (Carey, 2001; Hunter & Myburgh, 2001; Bonnardot *et al.,* 2002). There is also significant variation in soil type regarding texture, depth and water and nutrient holding capacity (Hunter & Myburgh, 2001). All of these result in a variety of meso climates within very short distances (Hunter & Bonnardot, 2011; WCG, 2015; Midgley *et al.,* 2016) that often require small scale (spatial) adaptation of agricultural practices to accommodate the specific local growth conditions. Integrated online platforms already exist that provide detailed information to the agricultural sector on climate, terrain and soils to better understand the topographical and climatic complexity of the Western Cape as a region, but also down to farm and vineyard block level (Southey, 2021).

The South African Context

The production of wine grapes, as with any agricultural crop, is strongly dependent on natural resources. Initiatives to encourage environmentally and socio-economically sustainable grape and wine production are becoming an increasingly integral part of both production and marketing. Sustainable Wine South Africa (SWSA, n.d.) is an alliance between the Wine of Origin (WO) and Integrated Production of Wine (IPW) schemes of the Wine and Spirits Board (WSB). A certification seal was implemented in 2010 that was the first of its kind in the world (Fig. 2). Producers must

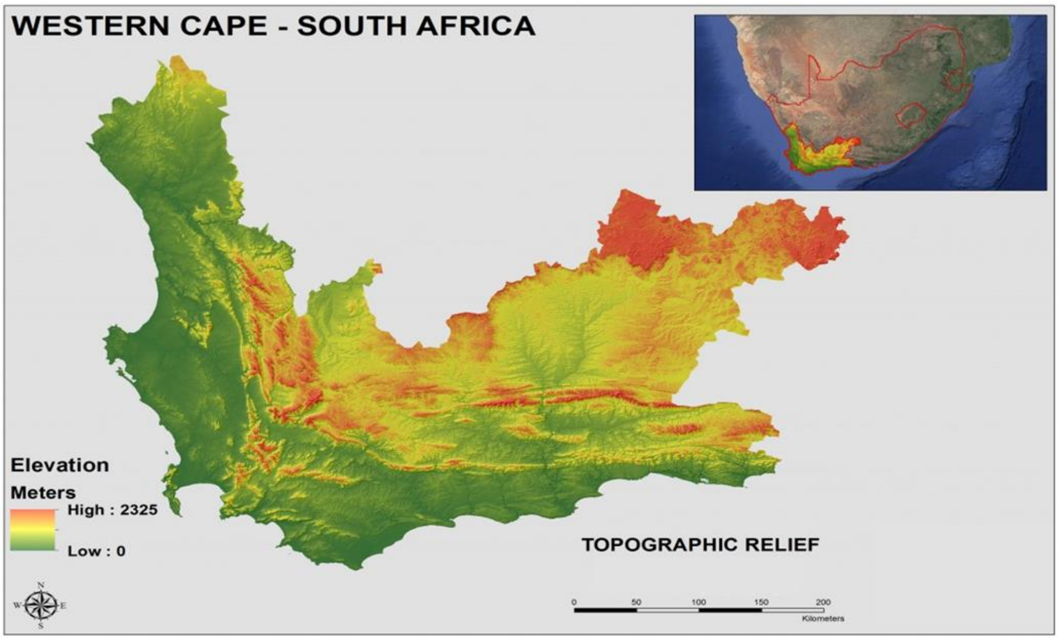

FIGURE 1
Topographic relief map indicating the elevation variation in the Western Cape of South Africa (Visualviticulture, 2017).

prove compliancy with set regulations in order to qualify for certification. This seal serves as guarantee of integrity and sustainability. "Integrity" confirms the origin (100 % of content), vintage (at least 85 % of content) and cultivar(s) (at least 85 % of content) information on the bottle label. "Sustainability" declares that the grapes were produced and the wine was made according to strict environmental guidelines (originally drafted in 1998 and updated annually), while biodiversity was protected and waste water treated.

The Confronting Climate Change (CCC) Initiative is linked with sustainable agriculture and was originally conceptualised by the South African fruit and wine industries in 2008. The aim of this project is to support these industries in determining their current GHG emissions and developing solutions to mitigate the impacts of climate change (CCC, n.d.). In the unpublished report of 2019 that focused on wine grape production in South Africa, it was stated (based on combined data from 2011-2018) that wine grape production emits 3-4 t CO_2-eq/ha (gross value) into the atmosphere. This is relatively low compared to table grapes (9-10 t CO_2-eq/ha), stone and pome fruit (9 t CO_2-eq/ha) and citrus (7 t CO_2-eq/ha) (CCC, 2019). These values were obtained from normalised, graded data from the current database, which represents less than 10 % of the wine industry (in hectares) (A. Blignaut, personal communication, 2019). However, when expressed as kg CO_2/kg fruit produced, the emission was higher for wine grapes (0.41) than for pome fruit, stone fruit or citrus (Fig. 3), because of the relative lower yield per hectare of wine grapes (A. Blignaut, personal communication, 2019).

The three main contributors to GHG emissions on wine grape farms are electricity (46 % to 48 %), fuel consumption (28 %) and the use of fertilisers (20 %) (Fig. 4). The electricity use is primarily related to irrigation, while fuel consumption comprises all traffic during the production process (spraying of pesticides and herbicides, fertilisation, pruning, harvesting, etc.). Emission values would most probably differ between regions, cultivars used, and the type and efficiency of cultivation practices, but due to the small representing sample it is difficult to make deductions. However, it is clear that these three aspects should receive special attention when developing strategies to decrease GHG emissions on any farm. Greenhouse gas emissions as a result of the winemaking process is calculated separately and does not form part of this data.

South Africa is the 7th (2020) largest wine producing country (by volume) in the world, with a production of 1040 million litres of which 65 % is white and 35 % red (SAWIS, 2020). About 35 % of the total volume of wine produced is exported, with the majority being in bulk. However, bulk wine decreased consistently over the last years, from 66 % of exported volume in 2013 to 59.8 % in 2018 (SAWIS,

FIGURE 2
Certification seal of Sustainable Wine South Africa (SWSA, n.d.).

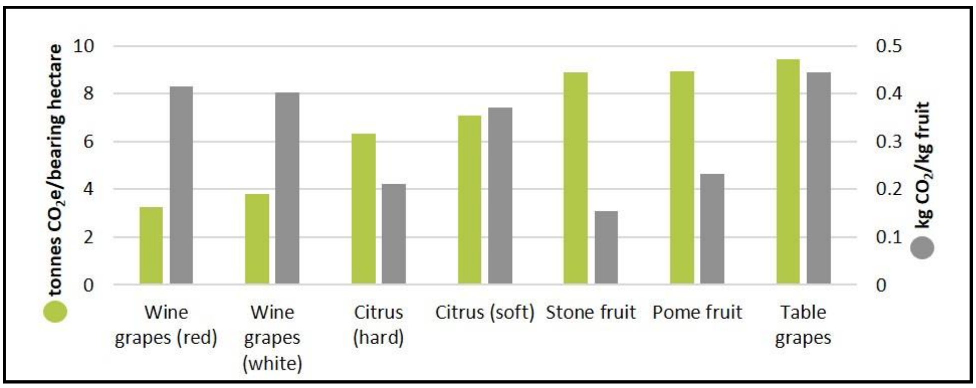

FIGURE 3
Comparison of GHG emissions of respective fruit industries in South Africa (CCC, 2019).

2018) and 57.1 % in 2020 (SAWIS, 2020). Reasons for this trend may partially be ascribed to the better performance of packaged wines and the EU Trade Agreement that increased the duty-free quota for South African wines from 50 to 110 million litres per year (DKC, 2015; SAWIS, 2015). The five largest international markets (per volume) for South African wines are the United Kingdom, Germany, Netherlands, USA and Sweden (SAWIS, 2020).

There are 2693 primary wine grape producers in South Africa of which 74 % produce less than 500 tons of grapes per year (Table 1) (SAWIS, 2020). Only five producers harvest more than 10 000 tons of grapes per year. The 529 wine cellars comprise of 457 private wine cellars, 45 producer cellars and 27 wine producing wholesalers. The smaller wine producers are in the majority, with 70 % of the cellars crushing 500 tons of grapes or less per vintage.

A variety of cultivars are planted, but 82 % of all the vineyards in South Africa comprise of eight cultivars – Chenin blanc, Colombar, Cabernet Sauvignon, Sauvignon blanc, Shiraz, Pinotage, Chardonnay and Merlot noir (Fig. 5) (SAWIS, 2020). In total, there are 92 005 hectares of wine grape vineyards, 55.4 % planted with white cultivars and 44.6 % with red.

Ten geographical units are demarcated under the Wine of Origin scheme of which the Western Cape is the largest, comprising of five regions - Breede River Valley, Cape South Coast, Coastal Region, Klein Karoo and Olifants River (WOSA, 2021). The wine industry accounted for 1.1 % of South Africa's GDP in 2019 and contributed R55 billion to the economy – 56 % of which originated in the Western Cape (FTI, 2021). A further amount of R7.2 billion was generated through tourism. The South African wine industry provides 269 096 employment opportunities over the entire value chain (the majority being classified as either unskilled or semi-skilled) of which 36 406 are in the tourism industry (FTI, 2021) and 62 % employed in the Western Cape. The latter province is thus clearly a critical role player in the South African wine industry.

The Concept of Terroir

The OIV resolution (OIV/VITI 333/2010) defines the viti-vinicultural terroir as "a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied viti-vinicultural practices develops, providing distinctive characteristics for the products originating from this area". Three important aspects may be extracted from this definition:

- interaction between the physical and biological environment
- applied viti-vinicultural practices
- a distinctive product character

Interaction between the physical and biological environment

This interaction refers to the optimization over time of the physiological activity of the grapevine (scion-rootstock genotype) under the site-specific growth conditions in order to produce satisfactory grape quality and to ensure economic sustainability. The better the fit between the physical environment (climate and soil) and the grapevine, the less intervention through cultivation/management practices is required and the higher the expected grape quality. This reduces input costs and increases profitability while limiting detrimental effects to the environment.

An integrated research approach is required with multi-disciplinary focus areas. Improved and expanded knowledge on eco-physiological mechanisms in the plant in response to all environmental factors and cultivation practices seems crucial (Schultz, 2011; Martínez-Lüscher *et al.,* 2015),

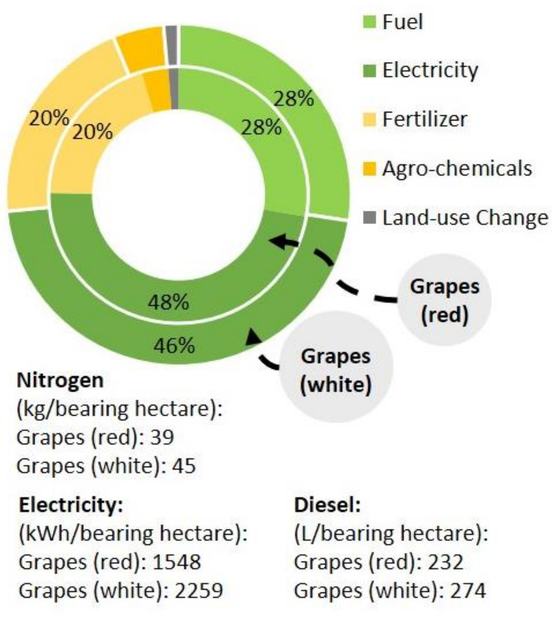

FIGURE 4
Sources of GHG emissions in wine grape production (CCC, 2019).

while it should ideally be combined with molecular, genetic, anatomical, and plant physiological studies (Schultz & Stoll, 2010).

Over the last few decades, in accordance with prediction models, the average temperature during the grapevine growing season has increased in most of the global wine producing regions. This warming was not uniform, with higher warming rates in the Northern than in the Southern Hemisphere and a higher increase at higher than at lower latitudes (Jones *et al.,* 2005; Webb *et al.,* 2013). Using long-term climate data over the last four decades, Southey (2017) found a warming trend in the Western Cape, especially during the spring and summer months (September to March), with the interesting exception of September that had a cooling trend. This increase in average temperature was mostly due to the increase in maximum temperature (1 °C to 2 °C), rather than the increase in minimum temperature (0.6 °C to 1 °C). Should this trend continue, grapevines will grow and grapes will ripen under gradually warmer conditions, albeit with higher day-night temperature amplitude, in South Africa. However, clear spatial differences were found, which again indicate the need for fine scale demarcation in climate and terroir research.

Higher average winter temperatures were also reported for the months between April and July (Southey, 2017). This may have a negative effect on dormancy and bud break,

TABLE 1
Structure of the South African wine industry in 2020 (SAWIS, 2020).

Production Category (tons of grapes)	**Number of primary grape producers**
1 – 100	1 043
> 100 - 500	950
> 500 – 1 000	331
> 1 000 – 5 000	347
> 5 000 – 10 000	17
> 10 000	5
	2693 (total)
Production Category (tons of grapes)	**Number of wine cellars**
1 – 100	209
> 100 - 500	160
> 500 – 1 000	49
> 1 000 – 5 000	59
> 5 000 – 10 000	16
> 10 000	36
	529 (total)

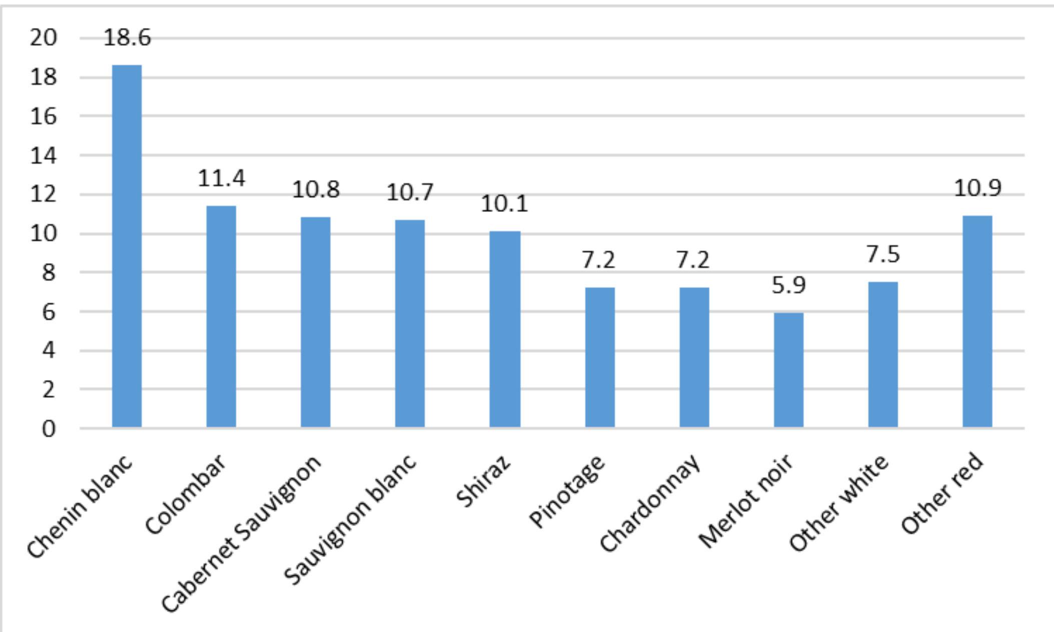

FIGURE 5
Distribution of main wine grape cultivars as percentage (%) of total cultivated area in 2020 (SAWIS, 2020).

since exposure to low temperatures during endodormancy increased both the budding rate and percentage (Dokoozlian, 1999; Pérez & Rubio, 2021). Increasing temperatures during spring, when buds are in the ecodormancy phase, stimulate bud break (Pérez & Rubio, 2021). The combination of higher winter temperatures and lower early spring (September) temperatures in the Western Cape may thus increase the occurrence of uneven and delayed budding and initial shoot growth. Although there is no direct link between the time of flowering and the onset of grape ripening (véraison) (Vondras *et al*., 2016), a high degree of asynchronous flowering may result in an uneven onset of véraison of the berries, which may cause uneven berry size and ripening. The effect of uneven berry ripening is often mitigated in the vineyard by harvesting the grapes later at a higher ripeness level (Gray & Coombe, 2009; Barbagallo *et al*., 2011), causing a shift in the aroma and volatile profile of the wine (Hunter *et al*., 2014; Terblanche, 2019).

The expected temperature increase during berry ripening could be to the advantage of current cooler regions (Cabré & Nuñez, 2020), where warming may increase growth and improve grape and wine quality, as found in the Mosel and Rhine Valleys in Germany (Jones *et al.,* 2005). Although higher temperatures may further enhance growth and yield in warmer regions (should water be available), the quality may decrease due to unbalanced ripening profiles and fruit composition (Van Leeuwen *et al.,* 2008). Fraga *et al.,* (2016) reported an altered wine style under higher ripening temperatures. However, it is possible that the higher temperatures may exceed the optimum levels for specific cultivars within certain regions (Jones *et al.,* 2005; Cabré & Nuñez, 2020). This may force a change in cultivar choice.

Expected changes in the rainfall (and other forms of precipitation) patterns are not as reliable as those of temperature, but generally climatic models indicate a wetter climate for higher latitude countries and regions (such as New Zealand, the Mosel Valley and the north of Oregon) and a drier climate for Southern Europe, Australia and South Africa (Webb *et al.,* 2013). The reliability of the rainfall will also be less with regards to amount, intensity, timing, geographical distribution and annual variability (Wooldridge, 2007). Based on Global Circulation Models and downscaled rainfall projections, the Western Cape should expect a decrease in winter rainfall over most of the province (Midgley *et al.,* 2016) and a shorter core-season (Midgley *et al.,* 2005). However, the complex topography contributes to the high level of uncertainty reported at regional level, due to the possible increase in orographic rainfall during spring and autumn on windward slopes (Midgley *et al.,* 2016). Long-term data seem to suggest that the timing of winter rainfall is moving to late winter and early spring (Southey, 2017), albeit with high levels of variability.

Water availability is considered to be the most limiting factor for agricultural production in South Africa (Benhin, 2006). The Western Cape has experienced water shortages over the last decade, with strong (and increasing) competition between the agricultural industry, urbanised regions and environmental reserves (Schulze, 2016). Although the Western Cape is the province with the most registered dams in South Africa (1592 out of 5592 – RSA, 2019), the majority are small and mainly used for irrigation (Midgley *et al.,* 2016). Sufficient water storage capacity will always be a critically important factor, especially within the context of climate change. Montmasson-Clair & Zwane (2016) found that South Africa is currently underprepared for the occurrence of future droughts.

The water requirement of vineyards (300-700 mm) is higher than the annual mean precipitation in many winegrowing regions (Medrano *et al.,* 2015a). In most of the viticulture regions of South Africa, the amount of precipitation is not sufficient to meet the water demands of the grapevine (Hunter & Myburgh, 2001). According to Van Zyl and Van Huyssteen (1980), producing grapevines cultivated in the coastal region of the Western Cape require approximately 500 mm of water between September and April of which an average of 300 mm is normally contributed by rainfall. The grapevine industry therefore depends strongly on irrigation during the dry summer months – for instance, in the Berg River catchment area, almost 90 % of all agricultural irrigation water is allocated to table and wine grape cultivation (Midgley *et al.,* 2016).

The combination of higher environmental temperature and limited available water may accelerate soil salination in the root zone of the grapevine, either due to increased evapotranspiration (Wooldridge, 2007; Keller, 2010), or to the lack of good quality irrigation water (Anderson *et al.,* 2008). This may result in wines being described as "brackish", "seawater like" or "soapy" (Mira de Orduña, 2010). Higher evapotranspiration may also increase water stress in the vines, which may have a negative impact on yield (Fraga *et al.,* 2016).

Atmospheric CO_2 continues to rise, with current levels at 416 ppm (NOAA-ESRL, 2021) compared to about 340 ppm in 1980. This is considered to be the main cause of warming (IPCC, 2014) and increased CO_2, together with increased temperature, would therefore be an inseparable combination in future climates. When combined with the expected decrease in water availability, it is clear why multi-factorial research on the interactive effect of these climate factors on plant response (growth and physiological functioning) was identified as an important and unavoidable objective (Hunter *et al.,* 2010; Salazar-Parra *et al.,* 2012; Zinta *et al.,* 2018) to meet the global challenge of climate change for the wine industry of the future (Schultz & Stoll, 2010).

There are more factors to consider in the physical environment than CO_2, temperature and water availability. Soil is one of the two main factors (the other being climate) that support high quality wine production (Leibar *et al.,* 2015). The location of a specific soil will also determine its characteristics. Mountainous sites are considered to be sensitive to climate change (Caffarra & Eccel, 2011) with cooler soils that dry out faster (Hunter & Myburgh, 2001) than soils situated in lower lying regions. Higher soil temperatures will cause increased rates of nitrogen mineralisation (Schultz, 2016), with concomitant soil degradation and structure decline. Soil management strategies to sustain soil structure and improve its water and nutrient holding capacity are critical due to the direct impact on plant water status, vine functioning and eventual grape composition (Van Leeuwen & Destrac-Irvine, 2017). Increased effective soil depth, improved water holding capacity and good drainage will enhance deep root penetration that would help to buffer grapevines more effectively against adverse climate conditions and sustain the production of good quality grapes.

Due to changed migration patterns, the occurrence of pests and diseases is increasing in areas that were previously considered too cool, and therefore uninhabitable (Tate, 2001; Anderson *et al.,* 2008; Mira de Orduña, 2010). The biggest challenges with regard to crop protection are the higher survival rate of pests and diseases during the warmer winters, and the afore-mentioned change in species within a specific region (Santos *et al.,* 2020). Climate change may therefore also affect crop protection practices, which may have to be adapted at regional level.

Applied viti-vinicultural practices

Even before the relatively new concept of "climate change" was introduced, producers used to adapt their cultivation practices according to the prevailing climatic conditions to consistently produce a good quality product (Clingeleffer, 2010; Hunter *et al*., 2010; Neethling *et al.,* 2013). However, short-term adaptation strategies (that could be executed within one growing season) may serve as protection against specific threats (Santos *et al.,* 2020), but will be less effective in regions already close to temperature limits for grapevine cultivation (Morales-Castilla *et al.,* 2020).

Over the last few decades, phenological events shifted backwards due to the changing climate, with earlier bud break, flowering, véraison and harvest, especially in cooler wine producing regions (Koch & Oehl, 2018). Shorter time intervals between phenological stages (Jones & Davis, 2000) were generally noted, which may translate into smaller optimum harvest windows for quality wines (Jones, 2007) and a compression of harvest dates (Anderson *et al.,* 2008). Grape ripening now tends to occur during the warmer and drier months in summer (Mozell & Thach, 2014; Fraga *et al.,* 2016), with higher respiration rates resulting in accelerated ripening with higher sugar concentrations (among other things also due to higher transpirational water loss from berries); a lack of phenolic and flavour expression; lower acid levels; higher pH, and an overall unbalanced juice composition (Jones 2007; Van Leeuwen *et al.,* 2008; Keller, 2010; Mira de Orduña, 2010; Koch & Oehl, 2018). Adaptation of cultivation practices may delay berry ripening and ensure that it still occurs during the milder temperatures later in the growth season (Van Leeuwen *et al.,* 2019). Although the importance of delayed ripening *per se* is relative to the context of the region (and not that relevant in South Africa compared to certain regions in the Northern Hemisphere), related recommendations may be considered locally to manage or extend the harvesting window and prevent logistical problems at the cellar due to compressed ripening. Late pruning in warm areas may delay harvest by postponing the onset and decrease the rate of ripening (Moran *et al.,* 2019), while lighter pruning may also serve to delay véraison and harvest (Clingeleffer, 2010; Zheng *et al.*, 2016; Van Leeuwen *et al.,* 2019) by increasing the reproductive:vegetative growth balance. However, this type of intervention requires serious circumspection. Although it may cause delayed fruit ripening, a too high reproductive:vegetative balance (overcropping) may result in impaired berry set and smaller berries (Weaver & Pool, 1968), while colour development in the grapes and reserve accumulation in the vine may be deleteriously affected (Weaver & Mccune, 1960; Weaver & Pool, 1968). In the long term, weaker vines with lower yield potential may be the likely result (Weaver & Mccune, 1960).

Since the impact of climate change is highly heterogeneous across cultivars, regions and even vineyards (Jones *et al.,* 2005; Fraga *et al.,* 2016), effects on viticulture will depend on the cultivar/rootstock combination and the cultivation strategies followed within a specific terroir. In order to protect the grapevine against detrimental effects caused by climate change and to improve its resilience, a total cultivation strategy should be adopted regarding both long term practices (starting with site selection and soil preparation) and short term seasonal practices (Hunter *et al.,* 2010).

Site and cultivar/rootstock selection

Climate models are often used in combination with crop models to generate future projections of yield, phenology and possible stress indicators for grapevines. Especially in regions with a complex terrain (Hunter & Bonnardot, 2011; Quénol *et al.,* 2017; Sturman *et al.,* 2017), the assessments should be done on a fine scale (regarding time and space) to better reflect the specific terroir. Neethling *et al.,* (2013) conducted interviews with producers in the Loire Valley in France regarding their adaptive response to climate variability. The physical characteristics of a vineyard site very often caused producers to adapt their standard cultivation practices in a vineyard. is. Thus, there is a need for real-time, accurate information available to producers on local conditions to aid decision-making.

Where changes in climate are relatively gradual, grape growers may prefer (with due reason) to rather adapt cultivation practices of an existing vineyard than incurring the cost of replacing/re-grafting vineyards (Morales-Castilla *et al.,* 2020). However, in regions where climate change is considered to be of more eminent threat, conditions might necessitate the re-establishment of vineyards with different cultivars known to the growers or even with cultivars that are not traditionally planted in the specific region. Due to the lifespan of plantings and the cost involved in vineyard replacement (Schwab & Maass, 2010; Edwards *et al.,* 2017), a timely cost analysis (on vineyard and winery level) is advised (Mozell & Thach, 2014) to determine whether only cultivar replacement is required or whether the cultivation of other crops should be considered (Bonfante *et al.,* 2010).

Regional changes in cultivar spectra are already occurring (Koch & Oehl, 2018) and it may be expected that lesser-known cultivars better suited to the regional environment (current and predicted) would increasingly be established (Keller, 2010). More than 4000 wine grape cultivars were listed by the OIV in 2013 (OIV, 2013), which indicate the large genetic variability and plasticity of the grapevine genome (Medrano *et al.,* 2015a; Bota *et al.,* 2016). These cultivars should be evaluated under regional conditions to select new possibilities based on ideal traits, such as adaptability to variable climate conditions (Clingeleffer,

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2010); balanced fruit:leaf area ratio and optimal berry composition (specifically colour and flavour) when ripening under high temperatures (Clingeleffer *et al.,* 2013); late season ripening to extend the harvest (Van Leeuwen *et al.,* 2008; Duchêne *et al.,* 2010; Schwab & Maass, 2010); and efficient physiological use of water (WUE), particularly under conditions of water stress (Clingeleffer *et al.,* 2013; Bota *et al.,* 2016).

A change in cultivars might be compelled by climate change, but is prohibited in certain wine producing countries (e.g. France, Italy and Germany) by legislation and tradition where only approved cultivars may be established according to the regional cultivar/quality classification (Webb *et al.,* 2013; Morales-Castilla *et al.,* 2020). In countries where such legislation does not exist, such as South Africa, Australia, the USA, China, etc. cultivar replacement should pose fewer problems.

The sensitivity of the scion cultivar to climate change may be reduced by the rootstock choice (Southey, 1992). Under such circumstances, the most important characteristics for rootstocks seem to be moderate vigour (Clingeleffer, 2010); tolerance to soil salinity (Keller, 2010) and tolerance to low soil water conditions and drought (Serra *et al.,* 2014; Hunter *et al.,* 2016; Simonneau *et al.,* 2017; Peccoux *et al.,* 2018). The rootstock may also affect the phenology of the scion and could possibly be used to manage and control the time of ripening (Van Leeuwen *et al.,* 2019).

Modification of the grapevine genotype to incorporate desirable traits is possible, but its practical application is prevented by policies and legislation (Anderson *et al.,* 2008). In the long term, genetic improvement of cultivars (scion and rootstock) is one of the better strategies to support sustainable wine production systems (Torregrosa *et al.,* 2017) and it could be advantageous for wine industries to invest in breeding programmes (Jones, 2010), despite it being slow and expensive (Bota *et al.,* 2016).

Soil preparation

Good soil management practices should prevent soil degradation and erosion, while improving physical, chemical and biological properties. Excessive tillage would cause soil degradation (Keller, 2010; IPCC, 2019), negatively affect most soil microbes and their activity (Santos *et al.,* 2020), and increase evaporation from the soil (Schultz, 2000). Clean cultivation would increase soil erosion and CO_2 release from enhanced breakdown of organic matter where increased precipitation intensities are expected (Schultz & Stoll, 2010). Evaporation and the risk for erosion may be decreased by covering the soil surface with straw or organic mulch (Keller, 2010; Medrano *et al.,* 2015a; Santos *et al.,* 2020). According to Blanco-Canqui *et al.,* (2015), cover crops improve soil structure, water infiltration and retention, moderate soil temperature (more optimum conditions for grapevine root growth), increase biodiversity and microbial properties, recycle nutrients and suppress the growth of weeds. Cover crops also contribute to CO_2 extraction from the atmosphere and the carbon sequestration potential of the agro-system (Tezza *et al.,* 2019). It is generally advised that vineyard soils are covered by green vegetation during the rainy season (Santos *et al.,* 2020), while care should be taken in arid and semi-arid regions to avoid excessive vine stress due to competition with the cover crops for water and nutrients (Schultz & Stoll, 2010).

Root growth and distribution are largely affected by physical (Van Huyssteen, 1988) and chemical (Conradie, 1988) soil properties and it is therefore critical that any potential limitations to root penetration and distribution are eliminated during soil preparation. Above-ground growth as well as root growth were improved by deeper soil preparation (Conradie *et al*., 1996). Since these effects were more pronounced in dryland vineyards, it was deduced that the deeper penetrating roots were able to exploit the available soil volume better for the uptake of water and nutrients (Van Huyssteen, 1988).

Planting of new vines

During the first season after planting, strict weed and pest control should be applied and water stress of the young vines avoided (Creasy & Creasy, 2009; Jackson, 2014). Young grapevines are generally well-supplied with water and nutrients (especially nitrogen) to maximise vegetative growth (Myburgh *et al.,* 1996) in an attempt to reap a harvest already in the second season (Keller, 2005). The latter is not advisable, since it may have a negative impact on longevity of the vine. The promotion of shoot growth in the young vines will ensure strong root growth due to the positive relationship between aerial and subterranean growth (Hunter & Volschenk, 2001; Archer & Hunter, 2005, 2010). Canopy growth depends on the root system for the provision of water, minerals and hormones, while a good canopy development and micro climate would enhance root growth through the supply of carbohydrates, amino acids and hormones. A well-developed root system, in combination with judicious management practices, would buffer the vine against adverse climate conditions or environmental stress for the rest of its productive life (Archer & Hunter, 2010).

Vine training, spacing, row orientation, trellising and canopy management

The higher expected vigour in future climatic conditions (where water supply is not limited) may necessitate adjustments in vine training and trellising systems. In South Africa, where high vigour in warmer regions has been the norm for many years, it was found that higher trellis systems (bunch zone further away from the soil surface) improve the micro climate inside canopies by decreasing the average leaf and bunch temperature (Zeeman, 1981). On the other hand, shorter grapevine trunks (as obtained by the Guyot or goblet systems) may promote water use efficiency in the vine (Santos *et al.,* 2020) and improve drought resistance (Van Leeuwen *et al.,* 2019), probably due to the smaller vine size. However, this may be over-simplified, since higher evaporation rates from goblet vines than vines trained onto larger training systems have been measured, due to higher ambient air temperature and air movement in the canopies (Van Zyl & Van Huyssteen, 1980).

A good understanding and application of the inherent balance between shoot and root growth and between vegetative and reproductive growth (Hunter & Volschenk, 2001; Archer & Hunter, 2005, 2010) will increasingly be required to manage vineyard vigour and to translate that into sustainable yield and quality. Young vine training, the choice of vine spacing (Archer *et al.,* 1988; Hunter 1998a, 1998b), the type and size of trellising system and thus the perennial structure of the vine (Hunter & Volschenk, 2001) as well as the orientation of vineyard rows (Hunter *et al.,* 2010, 2016, 2017) are all tools for the producer to optimise the canopy micro climate (radiation, air flow, temperature) in which the leaves photosynthesise and the bunches ripen.

The extent and timing of canopy management practices directly affect microclimatic conditions and thus eventual grape quality (Hunter, 2000; Hunter & Volschenk, 2001; Volschenk & Hunter, 2001; Hunter *et al*., 2004). Any change in micro climate would alter energy dynamics within the canopy and inside the vine itself, which would affect grape ripening, composition and the eventual wine style (Hunter *et al.,* 2010). Management neglect or injudicious execution of cultivation practices may lead to under-utilisation of the site potential (also determined by soil, climate, and scion-rootstock genotype) for grape growing and wine quality (Hunter & Bonnardot, 2011; Hunter *et al*., 2011).

Irrigation and fertilisation

Water scarcity is expected to become one of the main challenges in many viticultural areas and it is therefore important to improve the water use efficiency of the vine for long term sustainability (Salazar-Parra *et al.,* 2012; Mozell & Thach, 2014; Fraga *et al.,* 2016). The amount of water required per irrigation depends on many factors, such as the soil texture (a lower frequency with larger volume per irrigation is advisable for compact, silty, clayey and general duplex soils), seasonal climatic conditions, the scion-rootstock combination, vigour of the growth, and viticulture practices (Hunter & Myburgh, 2001). The correct type of irrigation system may increase water supply efficiency and thereby the saving of water (Van Zyl & Van Huyssteen, 1988). Alternative sources of irrigation water (such as wastewater from wineries) may also be cautiously considered in order to reduce the impact of grapevine cultivation on natural water resources (Myburgh & Howell, 2014). Such water sources should be tested very well before large-scale applications are considered. Judicious deficit irrigation increases the water use efficiency (WUE) of the vineyard (Clingeleffer, 2010) while simultaneously saving water. The success of deficit irrigation practices is strongly dependent on the interaction between the genotypes (scion cultivar/rootstock) and the environment in which it is grown (Medrano *et al.,* 2015a).

Conradie *et al.,* (1996) found (on a granitic Glenrosa soil in the Stellenbosch area) that soil-derived N is sufficient to supply the required N of the vine for the first three years after soil preparation and that additional N fertilisation would only be required from the fourth year onwards. On sandier soils, N fertilisation would probably have to commence sooner. It may be prudent to re-investigate the practice of providing nutrients, especially nitrogen (N). Ill-considered addition of N could lead to over-supply (especially on heavier soils) and a waste, since N uptake, shoot growth and yields seem to reach plateaus in response to increasing N in the soil (Spayd *et al*., 1993; Keller & Koblet, 1995). The unutilised NO_3 in the soil could be leached out of the soil profile and may also result in the eutrophication of nearby water sources and rivers (Good & Beatty, 2011).

According to Myburgh *et al.,* (1996) the water requirement of grapevines (on the same site) during their first two years of growth is 55.4 % and 34.5 %, respectively, lower than the amount of irrigation generally required by an established vineyard in full production. It is important that fertilisation programmes and irrigation scheduling be done in accordance with the soil conditions and the specific requirements of the vineyard as determined by its age, vigour and yield potential. In the Western Cape with predominantly acid soils (Conradie, 1988), an abundance of N in the presence of adequate soil water may increase the production of N_2O, thereby further contributing to GHG emissions (Good & Beatty, 2011; Saayman, 2016).

Vineyard relocation

It is commonly predicted that (more) vineyards will be established at higher latitudes and higher elevations in future where projected climates will be more conducive to high quality production (Jones *et al.,* 2005; Duchêne *et al.,* 2010; Keller, 2010; Hannah *et al.,* 2013; Fraga *et al.,* 2016, 2017; Cabré & Nunez, 2020). The current European regulations may however prevent expansion to other regions, since there are strict specifications for Wines of Origin regarding the production area, vineyards, cultivars, and winemaking practices (EFOW, 2019). Moving vineyards to higher elevations also have disadvantages, such as the difficulty of access and the risk of erosion and damage by field fires (Wooldridge, 2007). Also in South Africa, wine grape producing areas are gradually expanding eastwards to the Cape South Coast region, where the current climate is comparable with the climate experienced in the Coastal Region a few decades ago (Southey, 2017). According to Hannah *et al.,* (2013), vineyards are known to have long-lasting effects on the environment and their relocation may lead to conversion of natural vegetation, with substantial implications for conservation of ecosystems. Furthermore, existing viticultural areas may not necessarily be abandoned in the process and the vines may be replaced by other crops or the areas utilised for urban development.

There is a growing preference by consumers for environmentally friendly produce (Hannah *et al.,* 2013; Medrano *et al.,* 2015b), which might serve as an incentive for the wine industry to investigate, quantify and reduce its GHG emissions (and therefore its impact on climate change) and improve the management and conservation of natural resources (Schultz, 2016). The carbon and water footprints are also becoming increasingly important in food and wine trades and concerns about the water footprint (WFP) of grape and wine production are raised (Medrano *et al.,* 2015a).

Any decision made or action performed should be based on real data and scientific knowledge with a good understanding of its multi-faceted effects on the agro-system (Fig. 6). The ultimate goal is the attainment of "harmony between grape and wine production, the environment and social aspects, while still maintaining economic viability" (Hunter *et al.,* 2011).

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Distinctive product character

Within any specific region, grape ripening dynamics are expected to change (even with adapted cultivation practices) with an increase in ambient temperature, resulting in a shorter overall harvesting period (Anderson *et al.,* 2008; Clingeleffer *et al.,* 2013). Due to earlier and faster grape ripening, unbalanced juice composition (previously mentioned) may affect the typical flavour profile and mouth-feel normally associated with that region. This is more relevant to warmer regions, since in cool climates a faster and more complete ripening process may even result in improved wine quality (Jones *et al.,* 2005). Within limits, the wine quality and style may be controlled by changing the harvest date to meet certain ripeness criteria (Hunter *et al.,* 2004; Nadal & Hunter, 2007; Hunter & Bonnardot, 2011; Hunter *et al*., 2014; Hunter & Volschenk, 2017; Terblanche, 2019).

The altered grape and juice composition and balance may also require adaptation of practices in wineries. A higher grape sugar content may lead to sluggish or stuck fermentations (with associated risks of the development of off-flavours) that might require the development of new wine yeasts that are better adapted to the new conditions (Anderson *et al.,* 2008). However, the potential higher alcohol levels of such wines may cause practices such as the dilution of grape juice and/or the removal of alcohol from wines to become more widely used (Mira de Orduña, 2010). The increased importance of temperature control in the cellar would increase the cost of infrastructure (Anderson *et al.,* 2008). It is thus expected that higher investment as well as more interventions in the cellar will be required to support desired aroma and wine styles, but within the boundaries of local winemaking regulations (Mira de Orduña, 2010).

A gradual change in wine styles across estates (within production regions) seems unavoidable (Wooldridge, 2007; Jones, 2010; Koch & Oehl, 2018), but it would not be a major problem should the market accept changes in the typicity of wines (Duchêne *et al.,* 2010) and the taste of the consumer evolves with the changes in wine style (Tate, 2001).

Current winemaking regions are associated with their distinctive wine style or cultivar, be it as a result of official legislation (Anderson *et al.,* 2008; Webb *et al.,* 2013) or more informal means, such as experience, local culture and tradition (Trombi *et al.,* 2011), or the production of consistently outstanding quality (Davis *et al.,* 2019). Wine regions are often major socio-economic role players that contribute significantly to national exports and tourism (Fraga *et al.,* 2017). The rural tourism sector depends to a large extent on the surrounding vineyards and the abandonment of traditional cultivars and/or changes in the crops cultivated may have serious repercussions for local tourism, the economy and culture. It is imperative that these concerns are considered at various levels, since socio-economic issues, politics and regulations also have significant impact on the wine industry (Mozell & Thach, 2014).

CONCLUSIONS

The challenges faced by the wine industry in South Africa are similar to those in the rest of the world. It is foreseen that producers will have to cultivate their grapevines in higher atmospheric CO_2 levels and in warmer, mostly drier conditions. Climatic variability is also projected to increase, which would necessitate an improvement in the resilience of grapevines against adverse and fluctuating growth conditions. The need for producers to access and apply available climatic, environmental and technical information to ensure sustainable production is expected to increase. Dedicated research and knowledge transfer would make it possible to put timeous strategies in place to increase the adaptive capacity of the industry. Most of the adaptation practices that are recommended in this paper to address the different

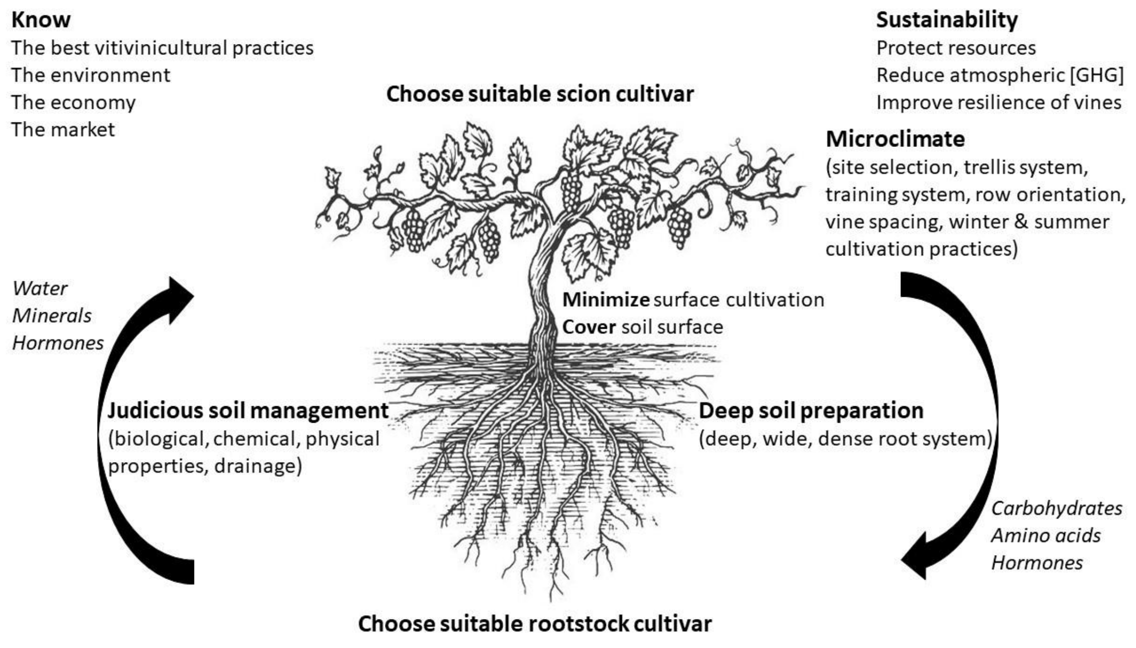

FIGURE 6
Diagram depicting some of the factors relevant to environment-friendly, sustainable grape and wine production.

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climatic conditions in future are based on research already done in various regions of the world. Improved collaboration and knowledge transfer between wine producing countries at international level may show that the climatic future of a particular region is already a reality in another.

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