atmosphere

Review

Future Climate Change Impacts on European Viticulture: A Review on Recent Scientific Advances

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Abstract: Climate change is a continuous spatiotemporal reality, possibly endangering the viability of the grapevine (*Vitis vinifera* L.) in the future. Europe emerges as an especially responsive area where the grapevine is largely recognised as one of the most important crops, playing a key environmental and socio-economic role. The mounting evidence on significant impacts of climate change on viticulture urges the scientific community in investigating the potential evolution of these impacts in the upcoming decades. In this review work, a first attempt for the compilation of selected scientific research on this subject, during a relatively recent time frame (2010–2020), is implemented. For this purpose, a thorough investigation through multiple search queries was conducted and further screened by focusing exclusively on the predicted productivity parameters (phenology timing, product quality and yield) and cultivation area alteration. Main findings on the potential impacts of future climate change are described as changes in grapevine phenological timing, alterations in grape and wine composition, heterogeneous effects on grapevine yield, the expansion into areas that were previously unsuitable for grapevine cultivation and significant geographical displacements in traditional growing areas. These compiled findings may facilitate and delineate the implementation of effective adaptation and mitigation strategies, ultimately potentiating the future sustainability of European viticulture.

Keywords: grapevine; grapevine yield; grape quality; berry quality; wine grape phenology; viticultural area; climate variability; future climate; European viticulture

Citation: Droulia, F.; Charalampopoulos, I. Future Climate Change Impacts on European Viticulture: A Review on Recent Scientific Advances. *Atmosphere* **2021**, *12*, 495. https://doi.org/10.3390/atmos12040495

Academic Editor: Robert Baxter

Received: 18 March 2021
Accepted: 12 April 2021
Published: 14 April 2021

1. Introduction

Climate change, known as CC, is defined as any change in the state of the climate that persists for an extended period of time (see also Appendix B), and is considered by the vast majority of the scientific community as one of the great environmental concerns facing mankind in the 21st century [1,2]. A steady increase in temperature, as the main measurable effect of CC, is expected to continue to increase globally and major changes are likely to occur in the global hydrological and energy cycles [2,3], resulting in an increase of radiation and of the frequency and severity of extreme weather events [2,4–6].Given its expected important impacts on different sectors of human activity (e.g., agriculture, forestry, energy consumption, tourism) [1], global CC poses a substantial political, economic and social challenge.

Among human activities, agriculture is likely to be particularly exposed to CC risk [7–9] since the weather conditions prevailing during the crops' life cycles are the major abiotic factors for their growth [1,10], determining, therefore, the quantity and quality of agricultural production and ultimately the economic sustainability [11,12].

Europe emerges as an especially responsive area to the temperature rise induced by CC, particularly during the warm season, while continuous warming is projected throughout the 21st century over the continent [13] where negative impacts will predominate, including lower harvestable yields, higher yield variability and a reduction of the suitable areas for the cultivation of traditional crops [7]. Apparently, in the context of the aforementioned climatic evolution, particular attention needs to be paid to prominentperennial crops which are typically grown in Europe where the growingseason mean temperatures already have increased by 1.7 °C from 1950 to 2004 [14,15].

Grapevine (*Vitis vinifera* L.) is included in this category given that it is largely recognised as one of the most important crops cultivated across Europe, playing a key socio-economic role. This continent, with the largest wine production and vineyard area in the world, is home to some of the most important and renowned wine-making regions and wines. These are especially predominant in the Mediterranean region and particularly in the world's top wine-producing countries: Italy, France and Spain [16].

The climate conditions firmly control canopy microclimate, vine growth, vine physiology, yield and berry composition, thus playing a vital role in the terroir (see also Appendix B) of a given wine region. The strong ties between climate and production in terms of quality and quantity have their most intense expressions in the field of viticulture, the science of grapevine cultivation [17–21]. This is clearly evidenced by the location of the worldwide wine regions within relatively narrow latitude belts that provide Mediterranean climatic conditions for high-quality wine production [22–24], but also by the increasing recognition of winegrapes as bio-indicators for the reconstruction of past climate conditions and for documenting global warming due to the climate's variability, primarily due to the thermal availability capable of determining their performance [25–27]. The determinant role of CC on viticulture may be realised through historical evidence since the vineyard area has changed over time. It is characteristic that vineyards planted in southern England from the 10th to the 13th century, which disappeared from the British landscape during the cooling of the Little Ice Age [15,28], were reintroduced there after World War II and have expanded since then. It must be considered that the climate is projected to change significantly during the expected productive life of a vineyard, given that grapevine is a woody perennial plant that may remain economically productive for 50 to 60 years [29].

Among environmental factors, the climate has a greater impact on vine development and fruit composition compared to soil and grapevine variety [30]. Many individual atmospheric factors (e.g., solar radiation, wind, humidity, etc.) influence the growth and productivity of grapevines, but specific thermal and hydrological conditions are among the most important [15,31]. In fact, these are the two factors most frequently addressed in reflections on the possible effects of CC on viticulture [32].

As with many perennial crops, grapevines require both adequately cold periods for hardening and fruitfulness and sufficiently warm periods to ripen quality fruit. Temperature is a crucial factor for the thermophilic heat-demanding grapevine [33] which needs proper values, not only during its vegetative growth and development but also for berry ripening, since it is also highly sensitive to late frost occurrences [22]. Recent research reveals the negative correlation between temperature and, e.g., berry weight, titratable acidity, anthocyanins and the positive correlation with pH and potential alcohol at technological maturity [34].

This crop is traditionally grown in geographical areas where the growing season mean temperature is 12–22 °C [12], with an optimal vegetative response to daily average values from 20 °C to 35 °C. Winter chilling with a base temperature of 10 °C is required to break bud dormancy and to initiate the growing/vegetative cycle [35,36], but also for the storage of carbohydrate reserves in perennial organs (roots, trunk and canes) for the followingyear growth [37,38]. Above 35 °C, vegetation activity is impaired, and in some extreme cases, vineyards may suffer severe and irreversible damage [39,40]. Fruit ripening is also affected under elevated temperatures [41] given the acceleration of the sugar content versus the decrease in grape acidity [31], the alteration of secondary metabolites (e.g., anthocyanins) [42] and therefore the aroma and colouration [43–45]. Prolonged exposure to extremely hot temperatures (e.g., above 35–40 °C) can negatively affect the plant's photosynthetic system [39] and cause severe skin damage in the form of a sunburn, which increases the incidence of, e.g., latent fungal infections in grapes [46]. On the other hand, extremely low negative temperatures in spring may significantly damage grapevine development [22]. The time at which grapevines begin their bud break, flowering and veraison (onset of ripening) is driven by temperature, which therefore influences harvest date, yield and composition [26]. Thus, the thermal conditions determine the length of the different phenological stages during growth and, therefore, the length of the growing season [47].

Annual precipitation and its seasonal distribution are also critical for grapevine development. High soil moisture is needed during budburst, shoot and inflorescence development, followed by dry and stable atmospheric conditions from flowering to berry ripening [14,47–49]. Surplus soil moisture, however, throughout the growing season may promote excessive vigour, resulting in shaded canopies, in detrimental effects on vine performance (e.g., lower bud break, delayed maturity, increased berry weight) and in poor fruit and wine quality [50]. Too much precipitation results in drowned vines, and too much humidity can promote plant epidemiology, thus negatively affecting productivity. Wet summers can be associated with more extensive grape damage or loss probability during the summer preceding the vintage, as well as lower grape yields in the subsequent annual campaign because of bud damage [51].

Although the grapevine is relatively resistant to drought [52], there may be a substantial risk for water availability under severe dryness [53], especially during the early stages of its annual growth cycle [54], by also considering the fact that this crop is mainly rainfed in Europe [55]. Water deficit is one of the leading environmental factors limiting vegetative growth and berry yield [56] as it impairs photosynthesis [57], shoot growth [58] and reduces berry size [59], while it may increase grape tannin and anthocyanin content [60] but also grape malic acid concentration [61].

As long as the water is not a limiting factor, vine photosynthesis increases with light intensity [62]. Owing to the difficulty in separating the effect of light from that of temperature, results on the impact of light on grape phenolics are contradictory. It has been shown, however, that the amount of anthocyanin in grape skins increases with light [63] but is negatively affected by high temperature. Both photosynthesis and stomatal conductance are generally favoured in the more exposed grape leaves, but the latter and clusters are at greater risk for sunburn. On the contrary, less exposed clusters result in lower berry temperatures, generally leading to lower sugar contents and lower anthocyanin concentrations [64,65]. Photosynthesis is also stimulated by atmospheric CO_2 concentration, which may result in greater accumulation of total biomass and harvestable yield [66–68]. However, the relationship between elevated CO_2 and grapevine yield may be strongly non-linear, possibly due to the overall negative effects of increased temperature [32,66]. Although the grapevine is adaptable to different climatic conditions and is resilient to moderate heat and water stresses, it can be severely stressed under extreme weather events. It is very sensitive to frost and hail during its vegetative period [22], while heat waves may also considerably affect physiology and yields [69].

The general procedure for evaluating the impacts of CC on any physical or biological system includes the projection of the future climate (see also Appendix B) with simulations conducted by global climate models (GCMs), the downscaling of the climate projections from a global to a regional scale by using Regional Climate Models (RCMs)which are nested in the GCMs [70–73] and the impact assessment by linking simulation tools such as crop simulation models, plant phenology (see also Appendix B) models and bioclimatic indices) with CC projections [74–77]. GCM simulations have been run under a wide range of scenarios developed by the IPCC (Intergovernmental Panel on Climate Change) which describe plausible evolutions of greenhouse gas emissions and aerosols (RCPs; Representative Concentration Pathways, as the RCP2.6, RCP4.5, RCP6, and RCP8.5) and of divergent CO_2 emission pathways (SRES; Special Report on Emissions Scenarios, as the A2, A1B, B1, etc.) until the end of the 21stcentury [78,79]. Particularly in the last decade, there has been a rapid growth in the availability and reliability of RCM simulations for Europe, owing to projects such as PRUDENCE [80], ENSEMBLES [81] and CORDEX [82].

By considering the crucial relationship between climate and vine performance in conjunction with climate change, which is an ongoing spatiotemporal phenomenon, the unsustainable development of viticulture in Europe seems to be an imminent important scientific research challenge for the future. Thus, in the CC context, several studies have been carried out for the assessment of the potential future impacts of climatic parameters on European viticulture.

In this review, a first attempt for the compilation of scientific research advances on this subject, during a relatively recent time frame (2010–2020), is implemented. This work focuses exclusively on the predicted effects of the projected climate evolution on essential productivity parameters (phenology timing, product quality, yield) and cultivation area alteration. These outcomes are of fundamental importance in highlighting the potential future European viticultural sustainability and in developing the most suitable and sufficient adaptation and mitigation strategies for this purpose.

2. Materials and Methods

We assessed studies that have been published during a relatively recent time frame (2010–2020) that link CC to the future European viticulture in terms of its impacts on plant phenology, product quality, yield and potential cultivation's area alteration.

The primary criterion for the inclusion of a scientific study was that it should be published as an article in a peer-reviewed journal. The focus was on studies published in English as they presumably have international acceptance and are comprehended by the majority of stakeholders, scientists, policymakers and producers. Multiple search queries were conducted within Google Scholar, Scopus and Web of Science by applying different combinations of the keywords shown in Table 1. After completion in December 2020, the retrieved results of a total of 163 articles were further screened on the basis of their absolute relevance to the subject of this review, that is, the description of CC impacts on viticultural productivity parameters (in terms of phenology timing, quality and yield) and cultivation area alteration. For additional literature, a systematic assessment of the references in key publications was implemented. In total, this assessment includes 34 published journal articles presented in Table A1. The articles were sorted alphabetically and accompanied by the specific geographic area where the projections were applied (Table A1, column 1), followed in consecutive order by: a synoptic information on the means of CC projection and impact assessment on the grapevine (Table A1, column 2), a symbolic depiction on the projected changes in climate parameters (Table A1, column 3), a synoptic description of the impacts of CC on grapevine phenology (Table A1, column 4), product quality and yield (Table A1, column 5) and grapevine cultivation areas (Table A1, column 6). Furthermore, a map (Figure 1) labelled with the vine regions referred to in this review has been included.

It must be highlighted that the methods for the CC projections and for the impact assessment on the grapevine are not in the objectives of this work.

Furthermore, the authors' interest is focused entirely on the direct effects of climatic conditions and not on the indirect effects (e.g., the outbreak of epidemiological phenomena under the ideal conditions for the development of pathogens, pests and diseases of the vine).

Table 1. Keywords applied for conducting multiple search queries.

Keywords Related to:			
Climate	**Wine**	**Grape**	**Vine**
climate change	wine sector	grapevine(s)	vine grape yields
climate change projections	wine grapes	grapewine	viticulture
climate change modelling	wine production	grapevine growth model	*Vitis vinifera* L.
climate models	wine yields	grape quality	
regional climate model	wine grape production	grape maturity	vineyard

Table 1. *Cont.*

Keywords Related to:			
Climate	**Wine**	**Grape**	**Vine**
climate variability	wine regions	grapevine yield	
thermal climate	wine quality	grape ripeness	viticultural zoning
regional climate change	wine typicity		
climate risk	winegrapes		
climate simulation	wine production modelling		
climatic factors			

Other supplementary or auxiliary keywords: Agrometeorology; Agroclimatology; European viticulture; temperature; precipitation; rainfall; radiation; warming; global warming; drying; agricultural risk; yield; phenology; phenological model; composition; quality; modelling; berry sugar concentration; berry quality, seasonal temperature, growing season temperature; seasonal precipitation; agriculture; impacts on agriculture; impacts on viticulture; land cover changes; harvest dates; agricultural crops; bioclimatic indices; sugar concentration; titratable acidity; water deficit; Agro-climatic indices; CO_2 effects; growing season; adaptation; crop yields; growth period; flavour development; emission scenario; fruit composition; yield formation; vegetation zones; development stages; crop modelling.

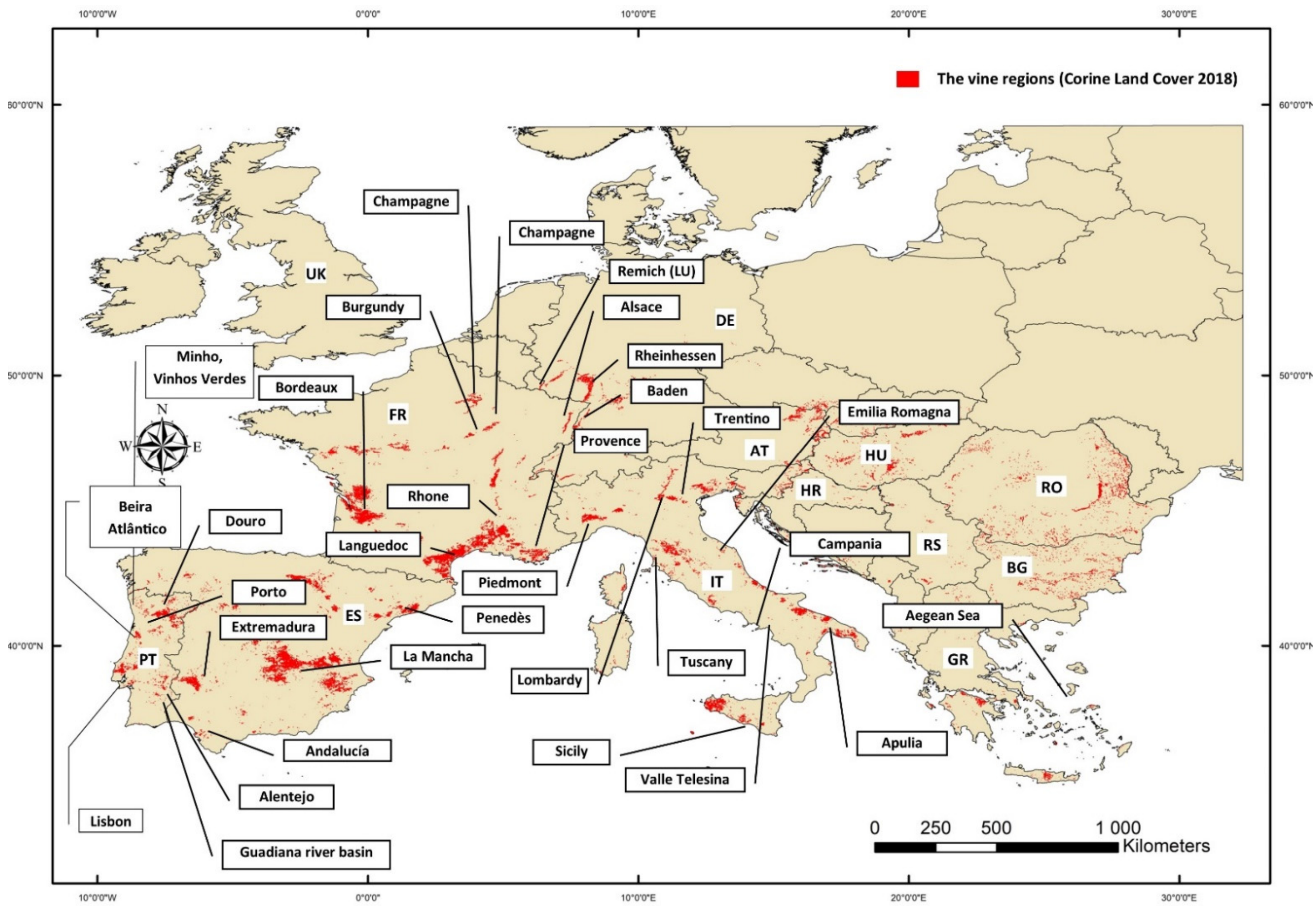

Figure 1. The vine regions referred to in this review.

3. Results

3.1. General Results and Comments

3.1.1. A Few Comments on Past Trends

Scientific research during the past decades has confirmed the sensitivity of grapevines to CC given the wide acknowledgement on the catalytic impact of the thermal stress and dryness on quantitative and qualitative parameters of grapevine, more than other environmental factors. Some of the main observed trends can be described asearlier phenology, rising sugar content and higher alcohol content in the wine, loss of aromas precursors in berries due to earlier maturation, increase or decrease in yields and expansion of areas suitable for wine production [12,83–92].

3.1.2. Potential Future Impacts: The Big Picture

The projected changes over the European continent indicate average warming between 2.5 and 5.5 °C by the end of the 21st century, with higher warming rates in southern regions and towards the northeast [80,93], but also significant increases of the minimum and maximum temperatures in summer and autumn [94] (time periods coinciding with grapevine growing season: April to October in the Northern Hemisphere). The prospects on future seasonal and annual changes in precipitation are more diverse, showing an overall decrease in southern Europe in contrast to an increase towards northern Europe [94].

Future CC projection trends and their potential impacts on the grapevine, as synoptically depicted in Table A1 (Appendix A), seem to be in general agreement with recent and past observations. Apparently, projection results suggest that wine grapes will be negatively affected in southern Europe (e.g., Portugal, Spain and Italy), due to a future increase in the cumulative thermal stress and dryness during the growing season [95]. These changes represent an important constraint to grapevine growth and development, resulting in negative impacts on table quality vines and wine quality [95,96]. Furthermore, the synergistic effect of the projected precipitation will overall decrease, and higher rates of evapotranspiration due to a warmer climate will likely increase water requirements, particularly during summer, in southern Europe [96] and will promote severe water stress over several regions (e.g., southern Spain, Portugal, and Italy), locally reducing yield and leaf area. Regions such as Andalucía, La Mancha (Spain), Alentejo (Portugal), Sicily, Apulia and Campania (Italy) will very likely suffer from severe water deficits [77]. It is also pointed out that the predicted overall decrease of the growing season precipitation is of particular significance for southern Europe given that current precipitations are already low and, in some cases, at the lower limit for non-irrigated grapevine growth, which is not the case for central and western Europe, where current precipitation total values remain high enough for winegrowing feasibility [95]. Thus, the suitability of the most famous wine-producing regions will be endangered, determining a shift from currently suitable areas towards new ones in the future [97]. Conversely, in western and central Europe (e.g., southern Britain, northern France and Germany), future changes will benefit not only wine quality but might also demarcate new potential areas for viticulture [95]. The projected spatiotemporal changes of the aforementioned climatic parameters may significantly modify the current viticultural bioclimatic zones, causing their northward extension up to 55° N, which may represent the emergence of new regions for grapevine cultivation [77]. These tendency is in line with most recent climate predictions based on agroclimatic indexes, which hint to a possible spatial expansion of vine cultivation areas over the northern parts of the Balkans by 15.1% to 28.8% of the studied area [98].

3.2. Specific Results

The fundamental importance of the prevailing future climatic conditions during the grapevine's growing season is widely confirmed through regional CC impact assessments for traditional viticultural areas. In most studies (Table A1), an increase in the growing season mean temperature and a decrease in precipitation are predicted, followed by estimations on the climatic parameters' consecutive impacts on the grapevine.

The projected warmer temperatures are expected to drive earlier development stages and, as a result, will determine a general advancement of grapevine phenology, thus shortening the length of the growth period. These impacts, together with the expected increase in the frequency and intensity of extreme climate events during sensitive phenological phases, may have strong adverse effects on final yield and yield quality, but also on the regions' suitability for grapevine cultivation determining, and thus, a shift from currently suitable areas towards new ones [15,77,97,99–103].

3.2.1. Impacts on Phenology

The projected impacts of the increased warming trend on the further anticipation of grapevine phenological phases reveal that regions with the largest anticipations (up to 40 days) are located in many countries of eastern Europe (e.g., Bulgaria, Croatia, Hungary, Romania) in northern Iberia, in some French regions and Italy. Opposingly, smaller changes (up to approximately 10 days) are shown for western/southern European areas, such as Germany. Furthermore, among phenophases (see also Appendix B), harvest shows the highest timing anticipations [77]. These outcomes are generally agreed with previous studies projecting future advances in grapevine phenological timings throughout Europe [104–106]. In Germany, for example, an acceleration of the phenological development (all main phases) will possibly reach 11 $\pm$ 3 days, with harvest ripeness occurring earlier by 13 $\pm$ 1 days [100]. In Alsace, phenological stages may advance by 8–11 days for budburst and up to 16–24 days for veraison by the end of the 21st century [102]. Projections assessed that climate conditions 3–5 °C warmer than present might advance the characteristic date of veraison by 3–5 weeks for Pinot noir varieties in Burgundy [104]. Projections indicated earlier phenophase onset and shorter interphases for 16 varieties from the Portuguese wine-making regions of Douro, Lisbon and Vinhos Verdes, where veraison showed the largest changes, with an advance of 6–14 days [106]. Future climate scenarios result in general anticipation of harvesting dates by about 7 to 10 days in southern Italy [107]. It has also been estimated that flowering and veraison dates may occur, respectively, 8 and 12 days earlier than present within the next 30 years in Burgundy [108].

Projections implemented for five varieties grown in the Italian Alps revealed phenological advancements of all phenological stages with the advancement of harvest by up to four weeks. These anticipations were more pronounced at higher altitudes following the higher increase in phenological forcing temperature [109]. Similarly, in both the valley and mountain environments of northern Italy, phenological timing was found to advance significantly. Still, the earlier occurrence was pronounced at higher elevations [105], especially for veraison. Further estimations have concluded to a general earlier occurrence of the phenology stages, which follows a latitudinal and longitudinal geographical gradient over Europe. Under future scenarios, a general earlier occurrence of budbreak and flowering stages with a particular relevance on northeastern Europe has been projected, while the effect of warmer temperatures was shown to be greater on late compared to very early and early varieties in the western regions [103].

3.2.2. Impacts on Product Quality

Phenology advancement is expected to consequently affect the ripening period negatively, as grape maturity takes place earlier during the hottest part of the vegetative cycle, commonly occurring in the warmest part of summer. This impact is intensified under extremely high-temperature regimes by affecting biochemical and physiological processes and thus impacting berry sugar-acid and flavonoid levels, colour and aroma, especially for early ripening varieties [85,110–113]. Consequently, currently planted varieties (especially early ripening varieties), which are grown under quite specific conditions today may no longer thrive in the same place under modified environmental conditions in the future [114]. This may be more evident for regions already presenting warm climates (e.g., Alentejo, Douro), where CC may endanger the balanced ripening of grapes and the sustainability of the existing varieties and wine styles [115,116]. However, future warming in the cooler climate regions (e.g., Minho, Beira-Atlântico) may improve suitability for the production of high quality wines [117].

Projections for the Douro region [118] have depicted anticipation of phenophase timings by 6, 8 or 10–12 days until the end of the 21st century for budburst, flowering and veraison, respectively. These shifts towards earlier phenophase onsets can potentially result in changes to the currently established wine characteristics and typicity. In effect, the expected warming may result in unbalanced wines, with high alcoholic content, excessively low acidity and altered colour and aroma [15,119]. Similarly, future climate scenarios which revealed shifts to warmer conditions for the same region were predicted to be prohibitive for quality wine production in the longterm, given that the mean temperature did not remain within the appropriate range for cultivation during the advanced growing season [120].

Due to the projected increase of temperature in Luxembourg during the ripening period, 27 phenological stages were shown to be reached significantly earlier in the future than in the reference period. The ripening period length was predicted to be significantly shortened and thus would occur in the warmer parts of the season, potentially threatening the wine typicity of the traditional grape-growing regions [121].

The significantly increased temperatures and decreased rainfall as projected to occur in viticulture-oriented regions of France might likely result in a shift towards earlier times by 20–40 days and, conversely, new areas in northern France would allow grapes to ripen consistently. Furthermore, a likely small increase of vines' water stress may be expected along with a heavy decrease of water restitution to depth by the vineyard systems. Harmful consequences on essential grape components like aroma precursors and phenolics are also to be expected due to the intense long-term warming of maturation conditions [122].

Projections indicating further climate warming in Croatia [123] associated with more frequent prolonged periods with temperature values exceeding 30 °C and more frequent droughts (proven as very influential conditions on the formation of sugar and acidity concentration in the grape [42,90,124]) were shown to potentially result in significant changes in the characteristics of the grapes (sugar, acid concentration and its ratio). A shifting trend in the date of harvest between different white varieties was demonstrated (e.g., up to 16 days/10 years for 'Grasevina' variety and up to 7 days/10 years for the 'Chardonnay'). These results were combined with sugar content increases and acidity reductions in the wine. The higher probability for unbalanced wines due to higher sugar and lower acid concentrations in the grape was attributed to the projected accelerations in the number of early harvests (less for red and more for white varieties) and to the reductions in the number of later harvests.

Similarly, the increase in growing season temperature projected for Penedès was shown to produce, in the forthcoming years, both the shortening of the phenological timing and of the intervals between phases of different rainfed white varieties (e.g., greater for Macabeo and Parellada than for Chardonnay). The advances in phenology, with the biggest advances of veraison and harvest and the shortening of the growing cycle, were projected to produce ripening under warmer conditions, potentially affecting grape quality [125].

3.2.3. Impacts on Yield

Intercontinental yield projections [77] have indicated large decreases in grapevine productivity of up to 8 t/ha in southern Iberia (Extremadura and La Mancha in Spain and Alentejo in Portugal), in Italy (Emilia Romagna and Lombardy) and along the Aegean Sea, owing to the severe water stress projected for these areas. In opposition, all other regions of Europe were projected to have yield increases in the future, related to the projected improved thermal conditions for grapevine growth, which are particularly evident over eastern Europe. Furthermore, the projected dryness is expected to have the strongest negative impact on yields, in opposition to the positive effects of the enhanced CO_2 concentration. Over central and northern wine-making regions, the increase in CO_2 may partially compensate for increased dryness, resulting in higher yields. Conversely, regions in southern Europe may have to deal with excessive dryness, which should be a significant limiting factor of growth and yield.

Simulation results over the Mediterranean [126] clearly indicated a trend towards warmer and drier conditions for the entire study area, with the lowest annual and seasonal rise in temperature and the smallest reduction in rainfall shown for southern France and the western Balkans, thus having an overall positive future impact on yields. On the contrary, high-temperature increases in combination with significant rainfall decreases were simulated for the southern Balkans, where significant decreases in yields were predicted, suggesting that environmental conditions, in some regions, might become unfavourable for grapevine cultivation. Under warmer conditions, the rate of grapevine development was accelerated, causing the advancement of all phenological phase onsets as well as a shortening of their duration. The latter, in turn, reduced the time for biomass accumulation and ripening, affecting the final yield. The projected negative impact on yields was most evident, among other regions, in the southwestern Balkans (−8.6%), followed by slightly decreasing yields in Bulgaria and Spain (ca. −4%), in Italy, Portugal (−1.5% or less) and along the shores of the Adriatic Sea (1.7% or less), while slight increases were shown for southern France (3.6%). It was also pointed out that intense water stress periods are likely to be more frequent and intense during the entire grapevine's growth cycle due to the decrease in rainfall projected, especially during spring and summer, promoting detrimental effects on both radiation use efficiency and leaf expansion [127] and enhancing the negative impacts on yield. However, the increased CO_2 atmospheric concentration may partially offset these impacts due to the increased efficiency in the way the grapevine uses both water and radiation, therefore reducing the negative effects of temperature and rainfall changes [7,128,129].

The aforementioned results are also consistent with studies conducted over local traditional viticultural areas. For example, decreases in yields were predicted in Tuscany [127] as a consequence of a progressive increase in temperature (future shorter periods for biomass accumulation due to the shorter growth cycle) and a decrease in rainfall. The higher temperatures resulted in higher developmental rates and thus, advanced the timing of the phenological stages, mostly at the higher elevations. This outcome, combined with lower rainfall and longer dry spells during the growing season, resulted in a gradual greater reduction in final yield, especially at higher elevations (by 27% at 400–600 m elevations) with respect to the flat areas (by 12% at 0–200 m elevations). It was also pointed out that the effects of increasing water stress were not compensated for, even by considering the positive impact of rising CO_2 concentrations on photosynthetic activity.

Potential seasonal values of the drier and hotter conditions characterising the Italian Apulia region [130] also showed a negative impact on grapevine production, especially due to a considerable acceleration of the warming rate and a decrease in precipitation in the period from 2001–2050. Results suggested that the evolution of progressively warmer and drier conditions over the next few decades could decrease wine production by 20–26%.

Evaluations on the yield response of rainfed vineyards to the continuous warming and drying in the Guadiana river basin [131] in Portugal displayed evidence on decreases in grapevine yields by 1.5–2% until 2040, and most intensely by 3–5.4% until 2070. It was also commented that, although significant yield losses were exhibited, the overall results suggest that rainfed grapevines will remain viable under the simulated future climate projection scenarios.

On the contrary, positive impacts on grapevine yields have also been projected under future conditions. For example, a net increase in productivity by about 10% by the end of the 21st century, but also an increased occurrence of high production years (from 25% to over 60%) are projected for the Douro region [132]. Wine productivity is shown to be positively affected by wet and cool springs and early summer conditions. Additionally, although the projected early springtime warming may result in higher yields, the earlier harvests during a warmer part of the year due to earlier crop phenology may possibly degrade product quality, while the rising heat stress and/or changes in ripening conditions may limit the projected production in future decades. These yield increases refer to the more humid part of the region (Baixo-Corgo), while projections for the driest areas (Cima-Corgo and Douro-Superior) hint at yield decreases [117].

Earlier studies [133,134] for the more humid parts of the Douro region have also resulted in increases in future production. A slight upward trend in yield until 2050, followed by a steep and continuous increase until the end of the 21st century, when the yield is projected to be about 800 kg/ha above current values, has been projected [133].These predictions demonstrate the beneficial impact of the projected temperature and precipitation conditions during critical stages of the grapevine vegetative cycle, such as anomalously high rainfall in March and anomalously high temperatures and low precipitation in May and June. Similarly, future higher temperatures and lower precipitation during late spring have justified the higher yields, also projected for the same region [134].

According to the above, the potential impacts on grapevine yield under future climates can be very heterogeneous and site-specific. The expected increase in the frequency and intensity of weather extremes [101] will lead to higher inter-annual yield variability, which may affect the whole wine-making sector [14,135,136]. Furthermore, future projections [77,126] point out the possible positive impact of the enhanced concentrations of CO_2, already confirmed by past observations on grapevine development and yield attributes [29,66,68,137]. Higher CO_2 may promote a decrease in plant transpiration rates, which may tend to overcompensate for the increased soil evaporation [138], resulting in reduced evapotranspiration in the future climate [139]. Therefore, it is apparent that the interaction between negative (higher heat and water stresses) and positive (enhanced CO_2 effect on plant physiology) CC effects on yields are expected to lead to different outcomes [29,140].

3.2.4. Impacts on Viticultural Area

Projections on the impact of CC on the distribution of the most important European wine regions [97] show that the increasingly warmer conditions and water deficit over the European domain may alter the climatic profile of the grapevine-cultivated areas in the future. The existing Mediterranean grapevine areas (e.g., Languedoc, Provence, Rhône, etc.) were found to respond to these climatic alterations by their progressive shiftsto the north–northwest of their original ranges, but also by their expansion or contractiondue to changes in within-region suitability for grapevine cultivation, with the likely result of a redistribution of cultivated areas.

As a consequence of a warmer climate, varieties may be shifted from their original cultivation areas to match their climatic requirements and may be replaced with low-quality varieties. For example, the expected future temperature increase and rainfall decrease during the grapevine cropping season (1 April–31 October) in southern Italy will determine the shifting of suitable areas satisfying the thermal and water requirement (41% of the area suitable for Aglianico cultivation will need irrigation to achieve quality grape production) of a specific variety, with a reduction in suitable surface area by approximately 76% in the 2010–2040 and lesser in 2100 [107]. The increasing temperatures may result in reduced quality for those varieties that are cultivated close to their optimum climatic conditions under which they may perform satisfactory yields. As a result, the shifting of high-quality varieties to suitable areas for their cultivation (i.e., by their shifting to higher elevations) is possible in the future. This is demonstrated by projections of a progressive increase in temperature and a decrease in rainfall in southern Italy, where the area potentially suitable for grapevine cultivation is expected to increase with shifts of wine quality areas towards higher elevations (600–800 m elevations) [127]. Similarly, the increasing trend of temperature and drought will affect all wine-producing regions in Greece [141] by impacting positively in mountainous vineyard regions and negatively in islands and coastal regions. Thus, some mountainous areas will become suitable for viticulture, while arid and semiarid regions will be abandoned or forced to take protective measures (e.g., irrigation) for the preservation of their ability to produce high quality wine. The thermal conditions for quality viticulture in Greece [142] projected to be limited to the higher elevation areas have also demonstrated the reduced early ripening varieties' suitability to the predicted shifts towards warmer and drier conditions.

Following higher temperatures, grapevine cultivation areas may expand into regions that today are considered too cold for their cultivation. According to projections [95], several new potential viticultural areas in western and central Europe feature values of growth season lengths greater than the commonly accepted minimum threshold (182 days). This is demonstrated, for example, in Iberia, with some new potential viticultural areas in northwest Spain (regions at high altitude), opening, therefore, the possibility for extending grapevine growth to Iberian regions currently too cold for grapevine cultivation [143]. Warmer and prolonged growing seasons (by up to 50 days by the end of the 21st century), with greater heat accumulation and longer frost-free period with a projected decline in frost frequency, will likely induce shifts in varietal suitability and wine styles in Serbia. As such, projected changes open up the possibility that marginal and elevated areas, previously too cool for the cultivation of grapevines, will become climatically suited for the growing of currently unachievable warmer climate grape varieties [144]. Similar results are projected for Hungary [145], where significantly higher growing season length and the modelled heat conditions suggest that certain regions will favour the cultivation of red wine grape and late-ripening varieties by the middle of the 21st century. Due to climate warming, a significant shift of agroclimatological zones is expected in Austria, resulting in a potential doubling of the suitable viticultural areas by the 2050s [146]. Hungarian southern winemaking regions are also expected to expand under future warming trends, given that predictions over the same time frame show a general shift towards the northeast Great Plain [147]. By projections of higher air temperature increases over south Germany in the future, possible expansions of areas suitable for viticulture, but also changes in suitable wine grape varieties cultivated in important current areas, are foreseen [148].

If the pessimistic future climate scenarios become true, northern European regions will convert to suitable areas for viticulture, whereas the southern regions will be too warm for wine cultivation [149].

4. Conclusions

Increased future warming and dryness will probably result in an eventual overall loss of viticultural suitability in the Mediterranean-like climatic areas of southern Europe, while in central and northern Europe, warming conditions will potentially benefit grapevine cultivation.

Future CC will likely bring about numerous potential impacts on European viticulture, mainly described as additional changes in grapevine phenological timing, disruption of the balance in grape and wine composition and thus the alteration of traditional wine styles, high risk for established typical varieties, increases or decreases in grapevine yields, expansion into areas that were previously unsuitable of grapevine cultivation and significant geographical displacements in traditional growing areas. Grapevine productivity will be negatively impacted (e.g., yield reduction, wine quality degradation) by also considering the potential increase in the frequency and intensity of the upcoming extreme or more intensive weather eventsdue to CC, such as heatwaves, frost events, unpredictable storms and more devastating hailstorms.

These compiled findings may facilitate and delineate suitable proactive measures such as the implementation of effective adaptation and mitigation strategies by the whole sector, ultimately potentiating the future sustainability of the pan-European viticultural industry. In the context of climate change, key elements of adaptation may include, among others, the extensive genetic research for high varietal and rootstock selection potential, new technology developments and innovative agricultural practices for the control of abiotic constraints, such as drought and the exploration of cultivation potential in previous cold regions.

CC is a significant challenge for viticulture in the coming decades. Knowledge on its impacts is of fundamental importance by considering the uncertainty of the rate and magnitude of this phenomenon in the future.

Future planning involves the extension of our research to explore the impacts of CC in the upcoming decades over other crops of great socio-economic importance.

Author Contributions: Conceptualisation, I.C.; methodology, F.D. and I.C.; searching and resources, F.D. and I.C.; writing—original draft preparation, F.D.; writing—review and editing, F.D. and I.C.; supervision, I.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Synoptic description of the impacts of climate change on grapevine phenology, product quality, yield and cultivation area.

[Reference] European Country (Region)	Climate Change Projection and Impact Assessment Methods	Climate Parameters Change	Plant Phenology Change	Product Quality and Yield Change	Viticultural Area Change
Alikadic et al., 2019 [109] Italian Alps (Trentino)	RCMs-ENSEMBLES project; A1B future scenario; 2021–2050 and 2071–2099/phenological model FENOVITIS	(↑) T (notably at higher altitudes)	Earlier harvest, advancement of phenological stages notably at higher altitudes, shorter intervals		
Blanco-Ward et al., 2019 [120] Northern Portugal (Douro Valley)	RCM; RCP8.5 scenario; 2046–2065, 2081–2100)/phenological model	(↑) T (↓) P (↑) WS	Advancement in phenology and shorteningof the budburst to véraison period	(↓) of wine quality	
Bonfante et al., 2018 [107] Southern Italy (Valle Telesina)	RCP 4.5 and 8.5 scenarios; (2010–2040–2100)/thermal index; SWAP model	(↑) T (↑) EP	Anticipation of harvesting dates		Shifting of suitable areas/reduction in suitable surface area
Caffarra and Eccel, 2011 [105] Italian Alps (Trentino)	Statistical down scaling of HadCM3; SRESA2,B2 scenarios; (2020–2029, 2070–2079)/phenological model FENOVITIS	(↑) T	Phenological advancement more pronounced at higher elevations		
Cardell et al., 2019 [96] Europe	RCMs – CORDEX project; RCP4.5 and RCP8.5 scenarios/(2021–2100)/climatic variables; bioclimatic indices	In southern Europe(↑) T (↓) P (↑) EP Towards North Europe (↑) T (↑) P		(↓) of wine grape production (in southern Europe) (↓) of table grape quality vines (in southern Europe)	Northward extension of high quality viticultural areas (in western and central Europe)
Costa et al., 2019 [118] Northern Portugal (Douro/Porto)	RCMs – EURO-CORDEX project; RCP4.5 scenario (2020–2100)/phenological models	(↑) T	Anticipations of phenophase timings		
Cuccia et al., 2014 [104] Central France (Burgundy)	Temperature increase scenarios; (2050, 2100)/phenological models	(↑) T	Advancement of phenological phase (veraison)		

Table A1. *Cont.*

[Reference] European Country (Region)	Climate Change Projection and Impact Assessment Methods	Climate Parameters Change	Plant Phenology Change	Product Quality and Yield Change	Viticultural Area Change
Duchene et al., 2010 [102] Northeastern France (Alsace)	RCM ARPEGE-Climat; A2, B2, A1B scenarios; (2070–2100)/degree day model	(↑) T	Advancement of phenological stages	Possible negative impact on grape quality Possible negative impact on wine quality	
Eitzinger et al., 2009 [146] Austria	RCM-EU-project ADAGIO, SRES A2 scenario (by 2050)/ agroclimatic index	(↑) T			Potential doubling of viticultural areas
Ferrise et al., 2014 [126] Mediterranean basin	GCM; A1B scenario; (2021–2050)/grapevine growth simulation model)	In southern Balkans (↑) T (↓) P In southern France and the western Balkans (↑) T (↑) P	General acceleration and shortening of the phenological stages	(↓) of yield (in southern Balkans) (↑) of yield (in southern France and the western Balkans)	
Fraga et al., 2016 [77] Europe	(GCM/RCM) – EUROCORDEX Project; (RCP4.5, RCP 8.5 scenarios); (2041–2070)/STICS crop model	In southern Europe (↑) T (↓) P (↑) DRS In central northern Europe (↑) T (↑) P	Advancement of phenological timings	(↓) of yield (in southern Europe) (↑) of yield (in central northern Europe)	Northward expansion of viticultural area
Fraga et al., 2016 [106] Northeastern, Northwestern, Central-western, Portugal (Douro, Lisbon, Vinhos Verdes, respectively)	(GCM/RCM) – EUROCORDEX Project; (RCP4.5, RCP 8.5 scenarios); (2006–2100)/phenological models	(↑) T	Earlier phenophase onset and shorter interphases		
Gaál et al., 2012 [147] Hungary	RCM (RegCM3); A1B scenario (2021–2100)/bioclimatic indices	(↑) T			Northeast expansion of grapevine regions

Table A1. *Cont.*

[Reference] European Country (Region)	Climate Change Projection and Impact Assessment Methods	Climate Parameters Change	Plant Phenology Change	Product Quality and Yield Change	Viticultural Area Change
Gouveia et al., 2011 [134] Northern Portugal (Douro Valley)	RCM—PRUDENCE project; (2071–2100); A1, A2 scenarios/ regression model for wine production	(↑) T (↓) P		(↑) of wine production	
Kartschall et al., 2015 [100] Germany	high resolution derivate—STARSdata base; RCP8.5, RCP2.6 scenarios; (2011–2100)/crop simulation model	(↑) T	Acceleration of phenological development, earlier harvest ripeness		
Koufos et al., 2018 [142] Greece	RCM; RCP 4.5, RCP 8.5 scenarios (2021–2050, 2061–2090)/ bioclimatic Indices	(↑) T (↑) DRS	Earlier occurrence of vine phenological stages/earlier harvest	Possible detrimental impacts on wine quality	
Lazoglou et al., 2018 [141] Greece	RCM; A1B scenario (1981–2100)/bioclimatic indices	(↑) T (↑) DRT			Mountainous areas suitable for viticulture
Leolini et al., 2018 [103] Europe	RCM – MARS project;RCP 4.5, RCP 8.5 scenarios (2036–2065, 2066–2095)/phenology model	(↑) T	Earlier occurrence of phenology stages		
Lionello et al., 2013 [130] Southeastern Italy (Apulia)	RCMs; ENSEMBLES/CIRCE projects; A1B scenario; (2001 2050)/linear regression model	(↑) T (↓) P		(↓) of wine production by 20–26%	
Malheiro et al., 2010 [95] Europe	RCM; B1, A1B scenarios; (2011–2100)/bioclimatic indices	(↑) T (↓) P	Growing season length increase	Negative impacts on table vine (in southern Europe) (↓) of wine yield and wine quality (in southern Europe) (↑) of wine quality (in central western Europe)	New potential viticultural areas in central western Europe
Malheiro et al., 2012 [143] Iberia	RCM;A1B scenario; (2041–2070, 2071–2100)/bioclimatic indices	(↑) T (↓) P	Growing season length increase	(↓) of wine yield and wine quality (in southern Iberia)	New potential viticultural areas in northwest Spain

Table A1. *Cont.*

[Reference] European Country (Region)	Climate Change Projection and Impact Assessment Methods	Climate Parameters Change	Plant Phenology Change	Product Quality and Yield Change	Viticultural Area Change
Mesterházy et al., 2014 [145] Hungar	RCMs; ENSEMBLES project; A1B Scenario; (2021−2100)/bioclimatic indices	(↑) T	Growing season length increase		
Molitor and Junk, 2019 [121] Southern Luxembourg (Remich)	RCMs-ENSEMBLES project(2001–2090); scenario/phenological model	(↑) T	Advancement of phenological stages/shortening of ripening period	Potential threat of wine typicity	
Ramos, 2017 [125] Northeastern Spain (Penedès)	RCMs-CMIP5; RCP4.5, RCP8.5 scenarios, (2020–40, 2040–60, 2060–80)/heat accumulation	(↑) T (↓) P	Advancement of phenological stages/shortening of intervals between phases	Potential (↓) of grape quality and grape yield	
Ruml et al., 2012 [144] Serbia	RCM; A1, A1B scenarios; 2001–2030, 2071–2100/agro-climatic indices	(↑) T (↓) P	Lengthening of growing season, earlier ripening	Potential (↑) of grape quality (↑) of grape yields	Marginal and elevated areas climatically suited to viticulture
Santos et al., 2011 [133] Northern Portugal (Douro Region)	GCM/RCM ensemble; A1B scenario; (2001–2100)/grapevine yield model	(↑) T (↓) P		(↑) of grape yields	
Santos et al., 2013 [132] Northern Portugal (Douro Region)	GCM/RCM ensemble; A1B scenario; 2001–2099/regression model for wine production	(↑) T		(↑) of production Potential (↓) of product quality	
Valverde et., 2015 [131] Southern Portugal (Guadiana river basin)	GCM downscaled; A2, A1B, B1 scenarios; (2011–2040/2041–2070)/soil water balance model	(↑) T (↓) P		(↓) of grape yield	
Xu et al., 2012 [108] Central France (Burgundy)	RCM; A2 scenario; 2031–2040/phenological model	(↑) T (↓) P	Advancement of phenological dates		

GCMs: Global Climate Models; RCMs: Regional Climate Models; (↑) Increase; (↓) Decrease; T: Temperature; P: Precipitation; WS: Water Stress; WD: Water Deficit; EP: Evapotranspiration; DRS: Dryness; DRT: Drought.

Appendix B

Glossary

Climate: Climate, in a narrow sense, is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. The climate in a wider sense is the state, including a statistical description, of the climate system [150].

Climate change: A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes, external forces, persistent anthropogenic changes in the composition of the atmosphere or in land use [150].

Terroir: "According to OIV (Resolution OIV/VITI 333/2010), terroir is a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied viticultural and oenological practices develops, providing distinctive characteristics for the products originating from this area. Terroir includes specific soil, topography, climate, landscape characteristics and biodiversity features" [17].

Climate projection: A projection of the response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasise that climate projections depend upon the emission/concentration/radiative-forcing scenario used, which are based on assumptions concerning, e.g., future socio-economic and technological developments that may or may not be realised and are therefore subject to substantial uncertainty [150].

Phenology: Defined as a succession of development stages of living beings throughout a season and in relation to the climate. It applies to vegetal matter but also to animals. For the vine, several notation scales have been published; the most well-known are those of Baggiolini, Eichorn and Lorenz and BBCH4. Baggiolini describes the stages from A (winter bud) to N (maturity), Eichorn and Lorenz from 1 (winter bud) to 38 (maturity) and BBCH from 00 (winter bud) to 89 (maturity) and 97 (leaf-fall). Phenology constitutes a veritable biological clock for the vines, which is useful when comparing vine parcels at an equivalent development stage [151].

Phenophase: An observable stage or phase in the annual life cycle of a plant or animal that can be defined by a start and endpoint. Phenophases generally have a duration of a few days or weeks. Examples include the period over which newly emerging leaves are visible or the period over which open flowers are present on a plant. (See also phenological event) (Note: The definition of the term "phenophase" has not yet been standardised and varies among scientists. The definition presented here reflects the usage of the term on the USA-NPN website [152]).

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