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Late spring frost impacts on future grapevine distribution in Europe

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ABSTRACT

Viticulture is a worldwide agricultural sector with a relevant economic importance, especially in regions where the climate and environmental conditions meet requirements for the production of high quality wines. The impact of climate change combined with the increased frequency of extreme events predicted for the next future has already shown its potential detrimental effects on viticulture suitability, but few studies currently explored the effect of long-term climate change and extreme events by considering the inter-varietal variability of grapevine. In this study, the combined effect of mean climate change and extreme events (frost events at budbreak and suboptimal temperatures for fruit-set) under future scenarios (RCP 4.5 and 8.5 for two time slices 2036–2065 and 2066–2095, respectively) was evaluated considering four grapevine varieties with very early, early, middle-early and late phenological cycles. The UniChill model calibrated for these varieties was applied in Europe to assess phenological dynamics (budbreak and flowering) using the outputs of a statistical downscaling procedure. Frost impact around budbreak stage as well as the impact of suboptimal temperature around flowering was estimated under present and future scenarios. The results showed a general earlier occurrence of budbreak and flowering stages with a particular relevance on northeastern Europe. The effect of warmer temperatures had a greater effect on late compared to very early and early varieties in western regions. The frequency of frost events at budbreak ($T_{min} < 0$ °C) showed wide variability across Europe, with a strong decrease in western regions (e.g. Spain and UK) and an increase in central Europe (e.g. Germany) for future scenarios. The decrease in the frequency of frost events was especially evident for very early and early varieties. The impact of suboptimal temperatures at flowering evidenced a significant variability across a latitudinal gradient while this effect did not show significant results when comparing cultivars and scenarios. The results of these studies highlighted that in a warmer climate frost events rather than stress at flowering will reshape the distribution of grapevine varieties in Europe.

1. Introduction

Viticulture is a worldwide agricultural sector with a relevant economic importance and a long history of development and evolution (Johnson, 1985; Terral et al., 2010). The most famous wine-producing regions are located in narrow geographical areas with optimal combinations of environmental and human factors, which are described by the *Terroir* concept (Seguin, 1988, 1986; Van Leeuwen et al., 2004). The long history of viticulture adaptation that identifies a specific *Terroir* contributes to characterizing the profile and features of its high-quality wines. However, the high specificity of these climatic niches exposes grapevine growth to the effects of climate change.

More specifically, mean seasonal climate change, inter-annual variability and the increase in frequency and magnitude of extreme weather is expected to strongly affect viticulture in the main wine-producing regions. The impact of mean climate change on the current viticultural regions has already been shown by several authors (Duchêne and Schneider, 2005; Jones et al., 2005; Santos et al., 2012, 2011). Some authors highlighted that warmer temperatures will determine an earlier occurrence of grapevine phenology with a consequent negative impact on grape yield and quality (Fraga et al., 2016; Hannah et al., 2013; Jones et al., 2005; Moriondo et al., 2013; White et al., 2006). These changes will therefore also have detrimental effects on the suitability of the most famous wine-producing regions, determining a shift from current suitable areas towards new ones in the future (Hannah et al., 2013; Moriondo et al., 2013). According to Fraga et al. (2016), viticulture is predicted to reach 55°N by 2070 with a consequent potential increase of wine-producing areas. Although the combined effect of mean climate and variability has long been indicated as detrimental for grape yield and quality (White et al., 2006), climate

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change impact assessments performed so far on grapevine according to different approaches did not consider these possible impacts (Ferrise et al., 2016; Fraga et al., 2016; Hannah et al., 2013; Moriondo et al., 2013).

Moreover, the combined effect of mean climate change and extreme events (i.e. days with $T_{max} >$ 30–35 °C, or days with $T_{min} <$ 0 °C) have a greater impact compared to just the long-term climate change (Ramos et al., 2008; White et al., 2006). In this case, the reduction of suitable areas for high-quality wine production is expected to exceed 50% (White et al., 2006). In particular, the frequency of frost impacts has increased over the last years in different regions (i.e. France, Brun and Cellier, 1992; Canada, Quamme et al., 2010; England, Mosedale et al., 2015; Romania, Bucur and Babes, 2015). However, future warmer temperatures are expected to to move in advance late frost events more than budbreak, leading to a reduction of frost damage in some wine-producing areas (Molitor et al., 2014; White et al., 2006).

On these bases, studies are currently investigating the detrimental effects (i.e. high crop yield variability, decrease in suitable crop areas, etc.) of changing climate conditions on the most valuable crops such as wheat or grapevine (Giannakopoulos et al., 2009; Moriondo et al., 2010; Olesen and Bindi, 2002; Tomasi et al., 2011). A frequently adopted approach is to apply macro-scale analysis for a spatially-explicit assessment of changes affecting grapevine growing suitability at regional, national or continental level (Hannah et al., 2013; Moriondo et al., 2013). Area suitability for growing grapevines is generally evaluated with climatic indices based on a limited number of variables, e.g. heat accumulation and day length during the growing season (Huglin, 1978; Winkler et al., 1974; Zapata et al., 2017). In this context, Jones et al. (2010) showed a spatial analysis on climate variability across wine-producing regions in NW United States using four climatic indices (Huglin Index, Winkler Index, biologically effective degree-day index and average growing season temperatures), which are combined for improving the description of climate and suitability of the regions. Tonietto and Carbonneau (2004) used three complementary indices (Huglin Index, Dryness Index and the Cool Night Index) for a multi-criteria climate classification of the most important wine-producing regions. Other studies, such as White et al. (2006), suggest that the use of these indices should be combined with others able to capture the extreme events effect. In this context, the study of Gabaldón-Leal et al. (2017) showed the impact of mean climate change and extreme events around olive tree flowering.

Building on these premises, the aim of this study is to estimate the dynamics of budbreak and flowering of varieties characterized by very early (VE), early (E), middle-early (ME) and late (L) phenological cycles (Fila, 2012) according to the mean variability of the climate and the unpredictable and severe effect of extreme events. The study includes: (i) the use of a chilling-forcing model for evaluating the impact of climate change on grapevine phenology at European scale; (ii) the assessment of extreme events effect through the estimation of phenological stages (budbreak and flowering).

2. Materials and methods

2.1. Climate datasets

The impact of climate change and future climate variability was evaluated considering Representative Concentration Pathways (RCP; 4.5 and 8.5) proposed by the fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5, IPCC) (IPCC, 2014). The daily outputs of the Aire Limitée Adaptation dynamique Développement InterNational (ALADIN) Regional Climate Model (RCM) (https://www.medcordex.eu/; Ruti et al., 2016) spaced 44 × 44 km, were statistically applied over an observed gridded weather (OBS) dataset covering Europe (MARS project; http://mars.jrc.ec.europa.eu) using Long Ashton Research Station-Weather Generator LARSWG; Semenov and Barrow, 1997) at a spatial resolution of 50 × 50 km.

According to the proposed procedure, OBS observed daily weather data such as minimum and maximum temperature and rainfall (T_{min}, T_{max} and R) for the period 1980–2010 were firstly used to calibrate LARS-WG.

After calibration, 300 years of synthetic daily weather were generated for each grid point at a spatial resolution of 50 km (n° grids = 1732) in Europe to represent the baseline (Present period; Pr).

The daily outputs of ALADIN RCM were used to derive climatic factors to perturb the present baseline. These were expressed as monthly average differences of T_{max} and T_{min} and relative change in rainfall between the relevant RCM baseline (1980–2010) and two different time slices for RCP 4.5 and RCP 8.5, namely: RCP 4.5 2036–2065 (Low CO_2 emission scenario 2036–2065; L1), RCP 4.5 2066–2095 (Low CO_2 emission scenario 2066–2095; L2), RCP 8.5 2036–2065 (High CO_2 emission scenario 2036–2065; H1) and RCP 8.5 2066–2095 (High CO_2 emission scenario 2066–2095; H2). These differences were computed for each RCM grid point covering the European domain.

The relative change in standard deviation of T_{max} and T_{min} and duration of wet and dry spells of R were also calculated. These gridded delta changes were applied over the relevant grids of OBS dataset to perturb the climatology of the baseline. Given the mismatch between the spatial resolution of OBS and RCM, a nearest neighbor approach was used to overlap the different grids finally generating stochastically 300 years of daily data for each 50 × 50 km grid point.

The weather variables obtained for present and future climatic conditions were then used as input of the phenological model for evaluating the responses of changing climate at European NUTS2 region scale (http://ec.europa.eu/eurostat/web/nuts/overview).

2.2. Phenology model

'UniChill' is a Chilling-Forcing (CF) model proposed by Chuine (2000) used for evaluating the grapevine response to different climate change conditions. In relation to the traditional forcing models, which accumulate heat units starting from a fixed date under the assumption that chilling requirement has already been met, (Chuine et al., 1999; Hunter and Lechowicz, 1992), CF model estimates the endo-dormancy duration (the period in which budbreak is inhibited by endogenous factors). Using this kind of model appears more appropriate for future scenario analysis, as winters are predicted to become milder and shorter (Schultz, 2000; Tate, 2001), with a very likely influence on dormancy (García de Cortázar-Atauri et al., 2009).

The length of the endo-dormancy period is calculated by accumulating chilling units from the 1st of September until a critical sum (*Crit*) is reached, which quantifies the specific chilling requirement of the genotype. Starting from this moment, forcing units are accumulated until the specific forcing requirement is met, which initiates budbreak (eco-dormancy refers to the period during which dormancy of the buds is caused by environmental conditions). Flowering date is calculated in a similar manner: starting from the previous stage the forcing units are accumulated until another critical sum is reached. In this context, the simulation is considered failed if flowering is not reached before the 31st of December of the year following the beginning of chilling accumulation.

Table 1 shows the equations to calculate chilling (Eq. (1)) and forcing units (Eq. (2)). Budbreak stage is described by both equations while flowering stage is described only by Eq. (2).

2.3. Grapevine varieties

The phenological traits of four grapevine varieties (*Vitis vinifera L.*) were considered for evaluating the effect of mean climate change and extreme events, by means of the UniChill model.

The budbreak and flowering parameters proposed by Fila (2012) for a VE (Glera), E (Chardonnay), ME (Merlot) and L variety (Cabernet Sauvignon) were applied on all grid points in Europe. The varieties