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The impact of climate change on the winegrape vineyards of the Portuguese Douro region

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Abstract In this paper, we analyse the impact of spring temperature (ST) and soil water (SW) on wine production volume (WPV) for the period 1933 to 2013 in the Douro region. We employ a state-space regression model to capture possible structural changes in wine production caused by a change in ST and/or SW. We find that the ST explains about 65 % of the variability of WPV. In contrast, the summer SW level increases the R_{adj}-square to 83 % and the Akaike criterion value was lower. We also find interesting dynamic properties of SW and ST. The immediate impact of an increase in SW is negative for WPV, while the SW that is in the ground, i.e. from the previous 2 and 3 years, have a positive effect on actual WPV. Moreover, the individual changes of ST and SW have similar dynamic impact on WPV. Our main finding is that climate change does not only change the variables in question but also the winegrape vineyards adding to the negative impact on WPV levels. As a result we observe a shift of the relative importance away from ST to SW.

1 Introduction

Viticulture and wine production is one of the agribusinesses where the impact of any ecological change, especially anthropogenic climate change is particularly noticeable (van Leeuwen et al. 2004; Deschenes and Kolstad 2011; Urhausen et al. 2011). In the Douro region, as in many other wine regions, the last decades were characterized by a large inter-annual fluctuation in wine

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production levels (Lobell et al. 2007; Cunha and Richter 2012), which may be further exacerbated by climate change in the future (Jones et al. 2005b), despite noticeable advances in vineyard technologies. Climate changes beyond tolerance thresholds cause adverse agronomic, economic and social effects for vineyards as well as wine producers (Clingeleffer et al. 2001; Cunha et al. 2010); furthermore, future climate scenarios also point to an increase in annual variations of wine production volume (WPV) in several (Portuguese) wine regions (Jones et al. 2005b; IPCC 2007). Consequently, governmental agencies, the wine industry and researchers have become more alert to the problems caused by climate variability and are looking for ways to manage them (Cunha et al. 2003; Quiroga and Iglesias 2009; Olesen et al. 2011; Jones 2012; Dunn et al. 2015).

Based on the most recent scenarios of global and regional climate, climate variability represents a serious challenge for many wine regions. In particular, Jones et al. (2005b) compare the average climates of two periods, 1950–1999 and 2000–2049 for the 27 most important wine regions. Their results suggest that temperatures during the growing season could increase by an average of 1.3 °C. The greatest increase in temperature (2.9 °C/50 years) is projected to occur in Portugal. Moreover, they show that many wine regions are at or close to their optimum growing season temperature for high quality and WPV already.

Therefore, a temperature change of 2.9 °C would imply that existing winegrape varieties could not be suitable for these regions anymore. This in turn may then lead to the development of new grapevine varieties and/or change of the crop production (Moriondo et al. 2013). The Douro region is one of the most arid wine regions of the world, with strong and consistent post-flowering water shortages (Jones 2012; Moriondo et al. 2013); hence, if climate change has an impact on dynamic behaviour of WPV, it should be measurable in the sensitive winegrape vineyards of the Douro region.

Many of the assessments of climate change on crop development and yield, which apply crop physiology, and other detailed processes focussing on crop growth and development, were carried out with field-scale crop simulation models (e.g. Bouman et al. 1996). The impact of climate change on crop yield has been simulated using general or regional circulation models as well as the crop-growth-monitoring systems. These were then combined with stochastic weather generators to analyse the impact of climate change on crop yield (e.g. Supit et al. 2012; Briche et al. 2014). Some of these models use simulations of CO_2 crop physiological outcomes from FACE studies for several crops (Ainsworth and Long 2005), including grapevines (Bindi et al. 2001). The first simulation model used for quantification of the effects of climate change scenarios on grapevine yield variability was developed by Bindi et al. (1996). Recently several process-based models were developed for grapevines which aim at simulating the development, quality and yield at field scale (e.g. Cola et al. 2014; Fraga et al. 2015). However, the perennial nature of the grapevine and its permanent structures (roots and woody stem), which provide carbon and nutrient reserves, are highly influenced by the past years' agroclimatic conditions (May 2004; Guilpart et al. 2014). Consequently, the development of grapevine simulation models is an important task as many of the carry-over effects on growth or cropping are still not fully understood (Vasconcelos et al. 2009), thus explaining the lack of sound, estimated and validated crop simulation models which are able to correctly predict the impact of climate on WPV (Moriondo et al. 2015; Cunha et al. 2016). Moreover, global warming and CO_2-enriched environments were not taken into account in the process-based models, which limits the applicability of these models for assessing the impact of climate change on wine production (Moriondo et al. 2015).

Because of the issues mentioned in the preceding and the data requirements of simulation models, many previous studies to assess the impact of climate change on crop yield, have assumed an historical probability distribution (e.g. Vossen and Rijks 2001; Santos et al. 2010; Lorenzo et al. 2013). The use of such distributions assumes stationarity of the data-generating process and typically assumes a constant linear trend mimicking technological progress. Although this linear trend describes the overall long-term trend in production, it does not reflect the implicit structural breaks in production and the information contained therein (Chen and Chang 2005; Quiroga and Iglesias 2009). Moreover, the results are limited to regional applicability and the explanatory power is typically very low, frequently less than 50 % (Lobell et al. 2007; Lorenzo et al. 2013). Under non-stationary conditions, the probability density function is not constant and therefore estimation errors are used to reduce the prediction bias when evaluating the impact of climate on crop yield for example; yet, in the literature it is common practice to use the stationarity assumption.

Long-term analysis on crop production might take into account the effect of the structural evolution of vineyard and climate variability. The climate in general affects wine production directly, but as production technology changes, there is a non-constant impact (or spillovers) of climate onto WPV, which translates into changing lead/lag relationships between WPV and climate. Therefore the detection of structural changes in crop production time series should take this into account, especially in models where climate plays an important direct or indirect role (Quiroga and Iglesias 2009); hence, a state-space regression, capable of detecting and incorporating structural changes (including trend; Cunha and Richter 2012), provides the flexibility needed to accommodate these features. For this reason, we use the Kalman Filter (Wells 1996) to estimate the WPV of the Douro wine region.

This paper provides a dynamic analysis of the impact of spring temperature (ST) and soil water in summer (SW) on WPV from 1933 to 2013 in the Douro region. We are particularly interested in modelling the impacts of climatic changes (if there are any) which would reflect themselves in a change of the structure of the winegrape vineyards in the Douro region. The foreseeable climate warming endangers the sustainability of the WPV in the Douro region. Therefore, modelling the impact of climate change on WPV is an important instrument for developing mitigation strategies and for anticipating the agronomic and economic impact on this region.

2 Material and methods

2.1 Douro region and wine production data

The research was carried out in the Douro Wine Region of northeast Portugal which has gained notoriety from the quality of its main product, port wine. We use the total annual WPV data (1933–2013) for the Douro region ("Porto" and "Douro" categories; hL × 1,000) provided by the Instituto dos Vinhos do Douro e Porto (IVDP 2015 and electronic supplementary material, ESM1).

2.2 Meteorological data and soil water balance

The meteorological observations for the years 1933–2013 were collected in the weather station of Peso da Régua (41°10′N, 7°47′W), located within the Douro region. The meteorological data (ESM1) consist of daily observations for mean, maximum and minimum temperatures (ST; °C) and precipitation (R; mm).

In this work, metrics of vineyard SW status for the period 1933 to 2013 were simulated by using the Vineyard Soil Irrigation Model (VSIM). The VSIM has been used for simulation of daily and seasonal SW balance for vineyard based on climate (rainfall, temperature), soils (texture, rooting depth), and leaf area index. The background and computation of VSIM is fully described in Pierce et al. (2015) and Johnson et al. (2006) and the validation for the Douro region is presented electronically (see ESM2).

2.3 Kalman filtering

We estimate the temporal behaviour of WPV using an Autoregressive Distributed Lag Model of order p and q (ARDL; p,q), where p and q are determined by statistical tests and q represents the impact of the exogenous variable X, i.e. ST or SW. In order to allow for possible changes of the parameters, we allow all estimated parameters to change over time by applying the Kalman filter to the chosen model as follows:

$$Y_t = \alpha_{0,t} + \sum\nolimits_{i=1}^{9} \alpha_{i,t} Y_{t-1} + \sum\nolimits_{j=0}^{9} \beta_{j,t} X_{t-j} + \varepsilon_t \tag{1}$$

were Y_t is the annual WPV, and

$$\alpha_{i,t} = \alpha_{i,t-1} + \eta_{i,t}\, and\, \beta_{j,t} = \beta_{j,t-1} + \vartheta_{i,t} \tag{2}$$

and ε_t, $\eta_{i,t}$, $\vartheta_{i,t}$ ~ $i.\ i.\ d.\ (0, \sigma^2_{\varepsilon,\eta,\vartheta})$·$\alpha_s$ are the unknown coefficients to be estimated. We employ a general to specific approach (starting with $p = 9$), to obtain the final Eqs. (1) and (2) we eliminate insignificant lags (ESM3); the maximum number of lags was determined by the Akaike information criterion (AIC, unit less).

To confirm the final specification identified, for each individual regression we applied a set of diagnostic tests (shown in the Table 1) and we ran two separate regressions. Thus, we estimated the influence of each variable SW and ST on WPV separately which allowed us to develop a ranking with respect to which variable is more important for WPV and by doing so we avoided multicollinearity, which makes models inestimable.

As mentioned in the previous, the Kalman filter yields a set of parameter values for each point in time; hence, a particular parameter could be significant for all points in time; or at some periods but not others; or it might never be significant. These parameter changes are at the heart of this paper as they imply changes in the lag structure.

3 Results

3.1 Volatility of wine production

Wine production has always been volatile in terms of output variance. The time-series of WPV in the Douro region from 1933 to 2013 are presented, showing evidence of an upward trend in WPV (see ESM1). Additionally, this time series contains changes in its "typical" cyclical behaviour (in terms of increasing variance), which may be caused by structural breaks (which in turn may be caused by climate effects). In any case, this variation makes a common regression very difficult, as we need to distinguish systematic changes from random ones; the Kalman Filter is able to detect these structural changes (trend included).

Table 1 Regression results for wine production volume (*WPV*) and mean spring temperature (*ST*) and soil water in summer (*SW* for the period 1933–2013 in Douro region. Estimation by Kalman filter using 70 observations[a]

Model summary and model adequacy		Independent variables			
Statistics	Value	Variable	Coeff	SE	T-Stat
Dependent variable (WPV)					
Mean (hL × 10^3)	1,138.68				
SE	296.81				
Spring temperature (ST)					
Degrees of freedom	65	Constant	−237.34	1.46E-05	−1.6E + 07
Radj-square	0.654	WPV (1)	−0.074	0.047	−1.564
SE of estimate	267.30	WPV (5)	0.217	0.043	4.989
Total squares of residuals	5001563	ST	104.36	3.14	33.19
Akaike information criterion	317.29	ST (2)	−6.87	2.66	−2.58
Ljung-box test: Q	22.11	ST (3)	−22.59	2.86	−7.90
Soil water (SW)					
Degrees of freedom	64	Constant	598.12	42.53	14.06
Radj-square	0.832	WPV (1)	0.046	0.076	0.605
SE of estimate	231.75	WPV (3)	0.127	0.104	1.217
Total squares of residuals	3759665	WPV (5)	0.332	0.106	3.14
Akaike information criterion	283.06	SW	−5.42	0.23	−23.40
Ljung-box test: Q	20.89	SW (2)	2.04	0.15	13.36
		SW (3)	2.76	0.20	13.74

[a] We employ a general to specific approach (starting with $p = 9$) to obtain a final specification for Eqs. (1) and (2)

The number after each dependent variable represents the lag to the actual season. For example WPV (3) and WPV (5): are, respectively, the 2nd and the 5th lag of WPV

SE standard error

3.2 The effect of temperature on wine production

Table 1 shows the regression results between ST and WPV for the final point in time (2013). The R_{adj}-square stands at 65 % and the AIC is at 317. At the end of the sample (2013), the current ST as well as the STs of the previous 2 and 3 years have a significant impact on the WPV. However, the impact differs with the lag: the current ST has a positive impact and the ST of the previous years have a negative impact on WPV (Table 1); note that the first and the 5th lag of WPV are significant.

However, it is worthwhile to note, that only Table 1 shows the numerical values of the estimated coefficients for the last year of observation due to lack of space. Before the end of sample, the numerical values of the coefficients may have been different.[1] Although our model does not say what exactly causes the increase of the numerical value of the coefficient of ST on WPV, we argue that this is due to global warming (Jones et al. 2005a).

[1] This ability of the Kalman Filter to allow estimated coefficients to vary over time is precisely the reason why we are using it.

3.3 The effect of soil water on wine production

Table 1 also presents the effects of SW level on WPV for the last point in time 2013. In comparison to the model for ST, the R_{adj}-square is now higher (83 %). As this model has the lowest AIC value (283 in comparison to 317), this is the more preferred model of those presented in this paper, which does not mean that the previous model is irrelevant; therefore, our result is that SW is clearly more important to WPV than ST when it comes to predicting WPV. It is worth noting that the AIC is also not constant over the time. Only towards the end of the sample does the AIC of soil water become smaller than the temperature. Hence, SW has become *more* important in correlation to climate change as will be shown in the following.

For the period 1933 to 2013, the effects of SW in WPV are dependent on the timing (Table 1). The immediate effect of an increase in SW is actually negative, whilst the SW that is in the ground, i.e. from the previous 2 and 3 years, has a positive effect on WPV.

4 Simulations of the impact of temperature and soil water

Having established the causal relationships between WPV, ST and SW, the next question is what can we learn from the temporal behaviour of the ST and SW? Therefore, we have simulated the dynamic impact of a ST and SW changes in line with the climate scenarios for these two variables in the Douro region.

Future climate conditions in the Douro region were examined by Jones (2012) and Santos et al. (2013) using IPCC SRES projections from the HADCM3 ensemble models for three greenhouse gas emission scenarios (B2, A1B, and A2) and three future time slices (2020, 2050, and 2080). The future projections for the climate in the region from this assessment agrees with other studies for Europe, Iberian-Peninsula, and Portugal (IPCC 2007; Giorgi and Lionello 2008; Fraga et al. 2016). The average annual temperatures, predicted to rise for all emission scenarios, range from 1.4 to 3.3 °C by 2050. During the growing season the region may experience substantial drying with precipitation reductions of more than 20 % by 2080.

We used the estimated regression coefficients to simulate a ST increase by 1 °C (16.1 °C to 17.1 °C) and 3 °C (16.1 °C to 19.1 °C). For the latter increase we modelled two scenarios: one where the 3 °C increase comes immediately (shock) and one where the temperature increases gradually by 3 °C over time. In other words, the ST increases from 16.1 to 17.1 °C (1 °C change) or 19.1 °C (3 °C change) and remains constant at 17.1 °C or 19.1 °C, which is in contrast to the gradual increase of ST by 3 °C over 40 years. Our time frame for these simulations is 40 years starting in 2013 as the system reached a steady state well before 40 years (*ceteris paribus*).

We also simulate a decrease of SW in summer by 30 mm (156–126 mm; decrease of 20 %). Here, we simulated two developments: the shock scenario, where SW is reduced immediately by 20 % and stays on that level and a gradual decrease of SW over 40 years.

We did these climate simulations separately for ST and SW. When the simulations for ST were performed, we assume that there is enough SW available to support plant growth. We therefore separately estimated the effects of SW on WPV, assuming that ST would remain constant. Most likely one effect will not be isolated from the other, which also highlights the issue of multicollinearity.

4.1 Simulations of the impact of temperature

Figure 1 presents the impact of ST change scenarios on the WPV. The 1° instant increase of ST leads to an increase of production by 144 MhL (12.7 %) after the first 4 years and falls afterwards. Two years later, production increases slightly again before the system rests at its steady-state value at 1,330 Mhl, around 133 MhL more than at the beginning of the experiment. Remarkably, the system is stable after 23 years when it reaches a steady state. From a time-series point of view, this indicates a stationary process, i.e., after a shock, the system returns to a steady-state value. It is worth noting that this is a partial experiment in the sense that everything else is being kept constant. If at the time of the ST increase, rainfall drops, then the results will be different.

Having analysed the impact on the system of a 1 °C increase in temperature, we are now investigating the effects of a 3 °C instant increase. The experiment is the same as before, just that we increase the ST by 3 °C and keep it constant thereafter (Fig. 1). The pattern of WPV over years is similar to the 1 °C increase apart from a higher steady-state value (Fig. 1). In this case, the new steady state production value is 1,520 MhL, an increase by 329 MhL (29 %). In the first years, production increases by 387 MhL (34 %) and then falls again.

In the last experiment, the 3 °C increase of ST were distributed linearly over the 40-year period (Fig. 1). The difference to the simulation of ST instant increase is that the increase to the new steady-state value of WPV is much slower, which is of course the result of the design of the experiment. At the beginning of the sample, the slight increase in ST (about 0.08 °C) actually leads to a small reduction in production before it picks up. The reduction is 8 MhL (0.7 %) for 1 year, while the year after, it rises by 53 MhL (5 %) and falls again. After 13 years, the system follows a consistent linear trend upwards. We can hypothesize the ST in Douro is, actually, a limiting factor for many of temperature-dependent grapevine-physiological processes that occur in spring.

Given that we have estimated a dynamic structure, we now investigate the importance of the system change. We do this in the form of a comparative analysis, i.e. we compare two

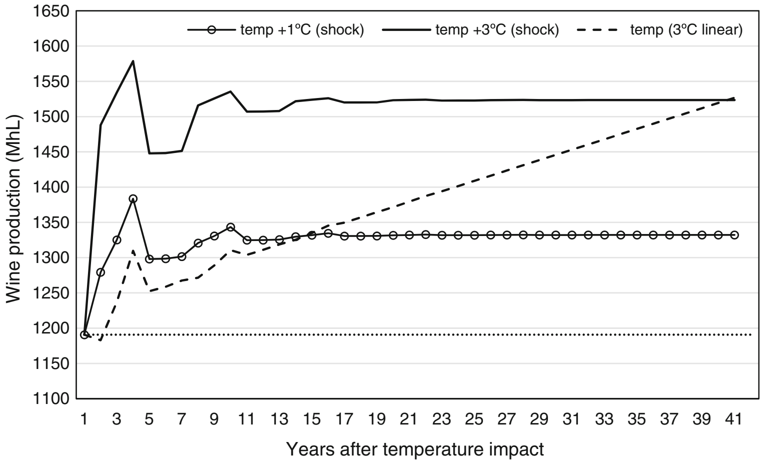

Fig. 1 Simulations for the effects of a 1 °C and 3 °C (immediately and gradually over 40 years) increase of spring temperature (ST) on wine production volume (WPV). We omitted the years after the 41st year as the system is at steady-state value as temperatures do not increase any further

systems: one before a change and one after a change. It is important to note that in this experiment we kept the data constant. So both systems work with the same ST and SW input for both years/states. Figure 2 shows a simulation which compares 1980 with 2013 using the first experiment (ST increased by 1 °C). We only used the estimated regression coefficients from 1980 and 2013, respectively. We tested for the statistical difference of the two states (years) and were able to reject the null of identical coefficients for these 2 years; moreover, both years represent a state that was in place for more than 3 years.

Over time the change of the model's structure leads to a decrease in WPV; however, both structures have different steady states if the same input is chosen. The difference in the steady state makes up around 100 MhL (−7.6 %), where the smaller amount of WPV is due to the model's structure in 2013.

As a result, an increase in ST alone does not lead to a reduction of WPV. What is more important is that the change of climate has changed the link between ST and WPV. Also, we can only observe a temporary higher production volatility before the system reaches a steady-state value in both states. Without any further changes, this steady-state value is reached fairly quickly (see ESM3 for an explanation).

4.2 Simulations of the impact of soil water

Now we shall investigate the impact of two simulations for SW decrease (Fig. 3). In the first experiment we distribute the 30 mm decrease linearly over the 40-year period. The reduction in SW leads first of all to an increase in WPV for the first 3 years and only then is production reduced to 790 Mhl, although after 8 years there is a slight increase in production. After 23 years the production stabilised at 780 MhL (−7 %); interestingly the decrease of WPV to the new steady-state value is non-linear.

One explanation for the stability of the system is certainly that the SW decrease used in this simulation is fairly small. So in the next simulation we reduced the water supply by 30 mm, but held the SW constant after the initial fall of SW. As in the previous simulation, the instant decrease of SW by 30 mm leads to an increase in WPV by 250 Mhl after 3 years. Water supply was reduced immediately and then held constant at the lower level. WPV then falls to below its

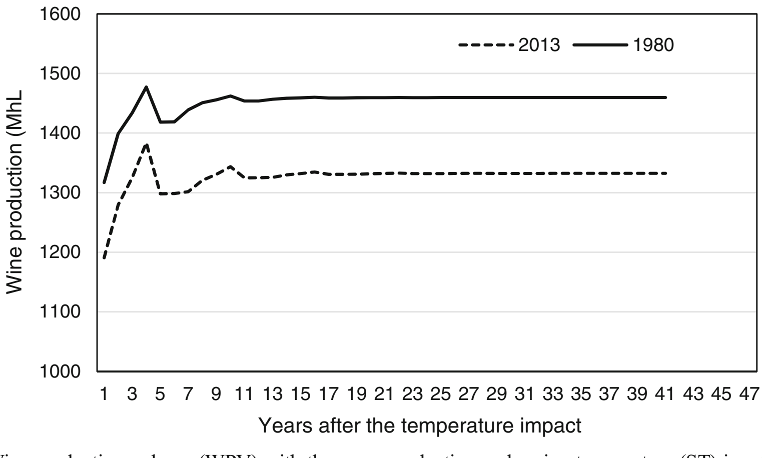

Fig. 2 Wine production volume (WPV) with the same production and spring temperature (ST) input data, but using the lag structure of 2013 and 1980

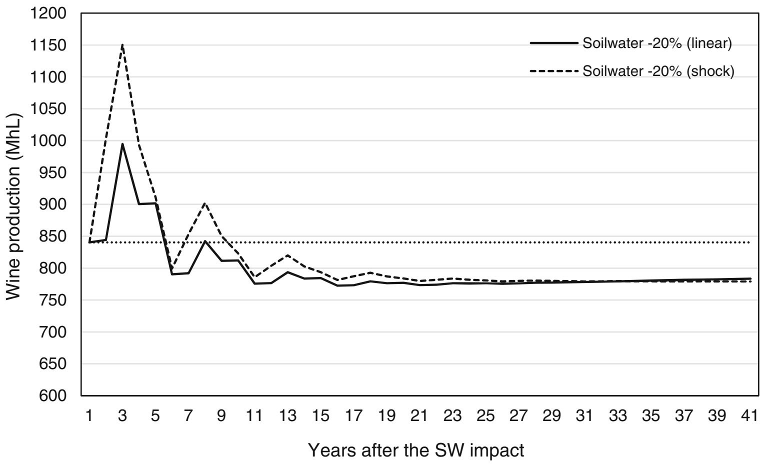

Fig. 3 Simulations for the effects of 30 mm (immediately or gradually over 40 years) decrease of soil water (SW) on wine production volume (WPV). The reduction represent about 20 % of the mean soil water starting with the first period

starting value to 799 MhL after 6 years. After 8 years, production is on a local peak 50 Mhl higher than the starting value and falls after that to below the starting value. There is a small increase again after 13 years, but this time the increase does not pass the initial value. The system is stable at around 780 MhL (−7 %) and remains constant. Evidently, this bigger shock led to a higher volatility of the system.

Like in the case of the ST, most adjustments are finished after 13 years. Given that the behaviour of the system is very similar to the ST instant change, this supports the hypothesis that a particular vineyard surface in Douro can only support a certain WPV level and, consequently, an increase on WPV has to be offset later.

Comparing the model structure with 1980, it is evident that if the model structure of 1980 was present, WPV would be almost twice as high as it was in 2013 in terms of its steady-state value (Fig. 4). The steady-state value of the 1980 model structure is 1,355 Mhl compared to

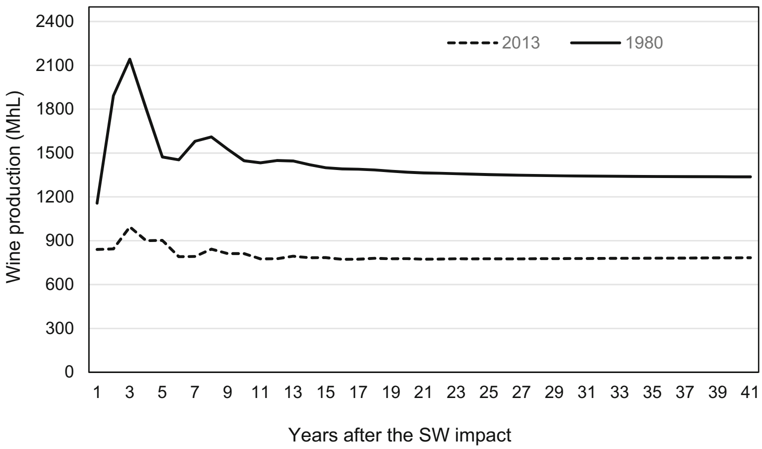

Fig. 4 Wine production volume (WPV) with the same production and soil water (SW) input data, but using the lag structure of 2013 and 1980

775 Mhl for the 2013 model structure, a result which highlights our argument that climate change may not only result in reduced SW, but also in a change of the model/vineyards. It also highlights why SW is the restricting factor: a reduction by 20 % leads to a reduction by 50 % in WPV if the previous winegrape vineyards is taken into account, an effect that is bigger than with ST (7.6 % reduction). It is also obvious that the 2013 vineyards are more resilient than the 1980 ones, given that the instant changes were identical in both cases.

5 Discussion

The Douro is one of the most arid wine regions of the world with strong and consistent post-flowering water and thermal stress (Chaves and Rodrigues 1987). Since most of the vineyards in the Douro region are non-irrigated and most of the rain occurs outside the vegetative growth cycle, SW should be an important factor of the temporal variation of WPV in Douro. In this paper, we used SW data for the period 1933 to 2013 which were simulated by using the VSIM for the Douro region.

We have modelled the impact of ST and SW level on the WPV for the period 1933 to 2013 using a state-space model. We used two individual regressions in order to avoid multicollinearity, i.e. the two explanatory variables may be correlated with each other making the model not estimable anymore. More importantly, modelling the impact of the two variables separately allows us to decide via the AIC criterion which model/variable is preferable to each other with a clear statistic, which underlines our results, as the AIC is 283 in the case of SW and 317 in the case of ST. This alternative approach was partially presented in previous studies analysing the impact of climate dynamics on WPV (Cunha and Richter 2012), vegetation growth (Cunha and Richter 2014) and economic applications (Hughes and Richter 2009b).

The in-season ST is directly correlated with WPV and could explain about 65 % of its inter-annual variability (Table 1). The simulation results suggests that actual ST in Douro is generally below the optimum level of the main grape temperature-dependent physiological processes related with crop yield that occurs during spring such as flowering development, anthesis and fruit-set (May 2004; Vasconcelos et al. 2009; Cunha et al. 2016). Also, high ST plays an important role in triggering the different phenological stages, with great impact on SW stress avoidance and, consequently on WPV (Urhausen et al. 2011). Further, high ST is negatively correlated with late frosts spells (Briche et al. 2014). The positive effect of in-season ST on WPV agree with the previous studies on the Douro region (Gouveia et al. 2011; Santos et al. 2013) and, northwest Portugal (Fraga et al. 2014), Spain (Lorenzo et al. 2013), Germany (Bock et al. 2013) and California (Lobell et al. 2007).

When the SW was incorporated, the R_{adj}-square increased and the AIC was lower. The SW explains about 83 % of the variability of WPV. In contrast to the current SW, a decrease in the SW of the previous 2 or 3 years has a negative impact on WPV (Table 1), which confirms previous studies on the Portuguese regions of Douro (Cunha and Richter 2012) and Minho (Fraga et al. 2014). The significant negative effect of SW during the summer in the WPV of the current year is in line with the findings of other authors for different wine regions (Jones and Davis 2000; Bock et al. 2013; Lorenzo et al. 2013; Fraga et al. 2014).

During the current year, a high SW tends to favour the development of epidemic diseases (Pearson and Goheen 1990) and, consequently, lower the WPV; however, non-irrigated vineyards exposed to consecutive years with both hot ST and low SW may lose their grapevine vigour. Consequently, the accumulated reserves of carbon and nutrients in the permanent structure are greatly reduced (e.g. May 2004; Vasconcelos et al. 2009). These reserves can play a critical role in bud fertility, which is directly related to the WPV of the following seasons, as indicated by our results. Grapevines, like most other perennials crops, commence forming their inflorescences (floral induction) during the previous seasons and this process is highly influenced by the SW level (Guilpart et al. 2014). According to Clingeleffer et al. (2001), the number of inflorescences is an important component of production that accounts for 60–80 % of the year-to-year yield variation in grapevine. Therefore, the predictors used in the developed model are biophysically sound and are supported by the relationship between both ST, SW and the eco-physiological development of the major grapevine yield components.

The individual simulated changes of the ST and SW have a similar impact on the dynamics of the WPV (Figs. 2 and 4). Generally, the impact of these variables on the WPV is stable once the system returns to steady state. The interesting part here is that although the qualitative nature of the changes are different for the variables (ST or SW), the amount of time it takes to get into the steady state is almost the same. This phenomenon occurs although the individual regressions are different to each other; hence, one would expect a different dynamic behaviour; yet, the dynamic properties are very similar. It seems that a particular area can only support a certain WPV level. Changes to this system can therefore only have a temporary effect, but not a permanent one, unless all other determinants of WPV will support and increase WPV, which in this scenario they do not (all other variables stayed the same). As a result, an increase in WPV has to be offset later and the estimation results show that this offsetting already starts a year later. Our results are complementary with those from Maxwell et al. (2016), who found in California that radial growth rings of grapevine show at least a 1-year lag with soil moisture, while yield does not. These findings confirm our results, especially in terms of how vines have lagged effects to soil moisture and how there may be steps in changes.

We also simulated the effects of the changes of winegrape vineyards in the Douro region. To this effect we compared the vineyards of 1980 with the ones in 2013. We found that although the nature of the change was the same as in the previous simulations, the change of the winegrape vineyards resulted in lower WPV, especially with respect to the available SW. Hence, we recognise a shift of the relative importance away from ST to SW. Despite SW explaining about 80 % of WPV, ST still explains about 60 %, *ceteris paribus*. In the context of the aforementioned climate scenarios for Douro region, which pointed out that due to warming and more infrequent rainfalls, SW will be the limiting resource for WPV and, therefore, will become relatively more important for the WPV than ST. However, temperature is also important for SW, and the two are linked in a complex manner. Because soil-water demand is positively related to the temperature through increases in vapour pressure deficiency, increased temperatures are likely to be associated with increased water loss in the vineyards. Therefore, if temperature warms without a compensating increase in precipitation, vineyards become increasingly water stressed, which in turn leads to decreases in WPV where the irrigation was not possible.

We also found that the 2013 winegrape vineyards are more resilient than the 1980 ones in the sense that its volatility after a simulated change is smaller. As a result, we found that climate change does not only affect WPV via reduced water availability and increased ST but also by changing the entire winegrape vineyards, a point that especially needs to be taken into consideration if WPV levels are to remain constant.

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