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PROJECTIONS OF CLIMATE SUITABILITY FOR WINE PRODUCTION FOR THE COTNARI WINE REGION (ROMANIA)

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Abstract: Climate projections have revealed the perspective of changing the climate of the world's wine regions in the coming decades by diversifying heliothermal resources. Research in the Cotnari winegrowing region over the past decade has shown that the local climate has been affected by such developments especially after 1980. This research continues the series of studies on the climate of the Cotnari winegrowing region through projections of the climatic conditions for the 2020-2100 time period based on the RCP 4.5 scenario. Average annual temperature, warmest month temperature, precipitation during the growing season, length of the growing season and the Huglin, IAOe and AvGST bioclimatic indices for the 2020-2050, 2051-2080 and 2081-2100 time periods indicate the evolution of Cotnari area climate towards suitability for red wines and loss of suitability for the white wines. Climatic suitability classes for wine production, shift between 2020-2100 to the higher, cooler zone of the winegrowing region, narrowing down their surface and disappearing successively at the maximum altitude of 315 m asl. They are further replaced from the lower zone by classes specific to warmer climates. The suitability for white wines, specific to wine region, disappears at the maximum altitude of 315 m asl around 2060, being replaced by climate suitability for the red wine production. The average temperature of the growing season will exceed 19.5°C after 2080, becoming unsuitable for the production of red quality wines of *Cabernet Sauvingnon* variety. After 2050, in the lower zone of the winegrowing region the warm IH5 class, suitable for Mediterranean varieties such as *Carigna*n and *Grenache* will install, as compared to temperate IH3 class which characterizes today

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the lower zone and allows the production of white wines of the local *Feteasca albă, Grasa de Cotnari, Frâncușa* and *Tămâioasa românească* varieties. The results suggest the need to develop strategies for adapting the viticulture of the Cotnari area to climate change.

Introduction

The Cotnari winegrowing region is by its age, reputation, expansion and quality of wine, one of Romania's most valuable wine regions. Until the Second World War, this vineyard was one of the most well-known in Europe (Brostrom and Brostrom, 2008). The alteration of the viticultural potential as a consequence of climate change predicted by reference studies (Moriondo et al., 2013; Hannah et al., 2013) raises concerns in this wine region too.

Research over the last decades reveals a severe impact of climate change (IPCC, 2014) on both grapevine and wine areas. The grapevine reacts to climate change by earlier phenophases (Menzel and Fabian, 1999), early grape ripening, higher sugar accumulation and lower acidity of grapes (Duchêne and Schneider 2005). Wine areas are affected by changing the specific climate and suitability for the wine production (Jones et al., 2005; Irimia et al., 2017, 2018c; Quénol et al., 2017).

The impact of climate change on viticulture, predicted for the XXI century is still more important: areas suitable for viticulture will shift to higher latitudes and altitudes, winegrape varieties and type of wines of traditional wine regions may change (Kenny and Harrison, 1992; Stock et al., 2005; Moriondo et al., 2013; Hannah et al., 2013) and in order to preserve the specific local wine production, measures will be needed to adapt viticulture (Keller, 2010; Quénol, 2014).

Recent research on the impact of climate change on Romania's viticulture reveals the modification of the multiannual averages of bioclimatic indices specific to vine areas, the expansion of the suitable area for viticulture and important shifts on latitude and altitude of climatic suitability for the wine production (Bucur and Dejeu, 2016; Irimia et al., 2018a, 2018b).

The Cotnari winegrowing region is also affected by these changes. Studies carried out in the area revealed changes in its specific types of climate suitability and their shifts on altitude during the 1960s to 2013 (Irimia et al., 2014a; Irimia et al., 2018a). Similar developments are also recorded in neighboring winegrowing regions (Irimia et al., 2018c). Climate studies developed in Romania show that the climate change manifests strongly in the NE region of the country where the Cotnari winegrowing region is located (Piticar and Ristoiu, 2012; Sfică et al., 2015).

This study continues the research on Cotnari winegrowing region climate developed in the recent years (Sfîcă et al., 2014; Irimia et al., 2014a; Irimia et al., 2018a) and aims to predict the future evolution of climate suitability for viticulture in this area. The multiannual averages and the spatial distribution of bioclimatic indices in the 2005-2100 period are examined for this purpose and, depending on these, the types of climatic suitability for viticulture that will characterize area in the future are estimated.

The study is based on simulations of temperature and precipitation in the RCP 4.5 climate scenario available in EURO-CORDEX (https://www.euro-cordex.net/). There are four Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5, RCP6, and RCP8.5. Each RCP represents a possible increase in net radiation (+2.6, +4.5, +6.0, and +8.5 W m^{-2}) expected in 2100 compared with pre-industrial values. These scenarios are issued from an international project gathering 30 climatic centres: the CMIP-5 (Coupled Model Inter comparison Project) aiming to assess Atmosphere-Ocean General Circulation Models (AOGCMs) for the next decades. RCP4.5 is an intermediate scenario with an increase of greenhouse gases emissions until the 2040's followed by a decrease.

1. Material and methods

1.1. Study area

The studied area is the Cotnari winegrowing region, located at 47°20'50"N lat. and 26°56'37"E long. and represented by about 2,000 ha of vine plantations, distributed between 106 to 315 m above sea level (asl.) (Fig. 1). The local climate is *Dfb* according to Köppen-Geiger classification (Peel et al. 2007). The current cultivated grapevines (*Vitis vinifera)* include four Romanian white winegrape varieties: *Grasă de Cotnari, Fetească albă, Tămâioasă românească* and *Frâncușă*. In the last decade, Romanian red winegrape variety *Feteasca neagră* has been planted in the area and the red wine prodution has started.

1.2. Methodology

Simulations for this study were extracted from the EURO-CORDEX database (https://www.euro-cordex.net/index.php.en). The observation data from the Cotnari weather station for the period 1986-2005 was used to validate the EURO-CORDEX simulated data for the same time period.

The daily maximum, minimum temperature and precipitation data for the location of the Cotnari weather station were extracted from EURO-CORDEX database for the 2005-2100 period, according to RCP 4.5 scenario. Starting from these basic climate parameters, several climate parameters and indices were computed: annual average temperature (AAT, °C), the warmest month temperature (TWM, °C), the length of the growing season (LGS, days), precipitations (PP, mm), the actual heliothermal index (IHr). Because the sunshine duration parameter was not

available in the EURO-CORDEX data, we used a 10 year projected average value resulting from the extrapolation of the linear trend for this variable (Irimia et al., 2018a). This value was used for computation of the IHr and the IAOe indices.

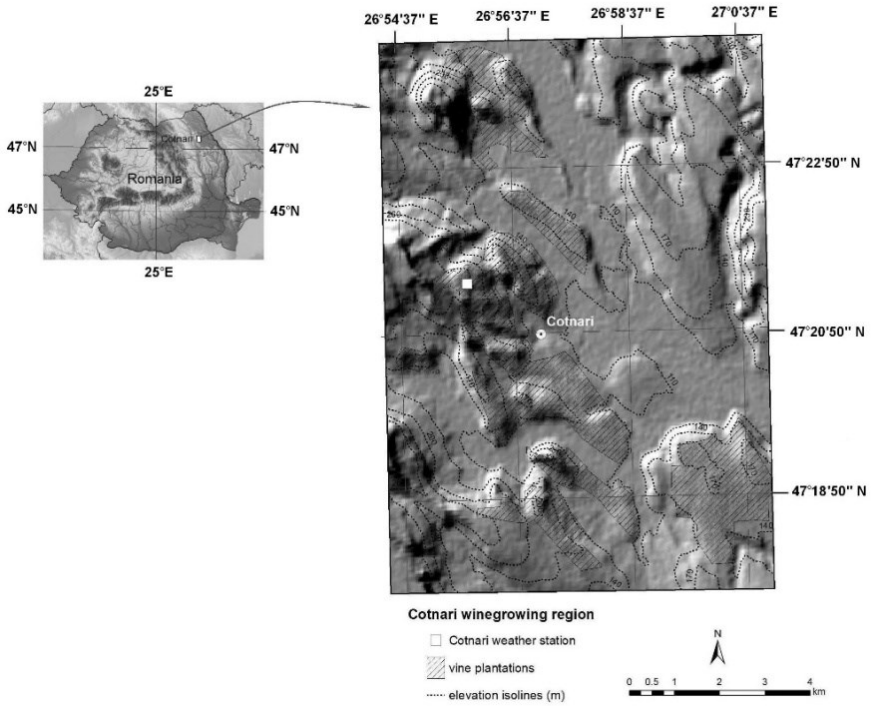


Fig. 1 Map of the Cotnari winegrowing region

Future climate suitability for the wine production of the Cotnari wine growing region is analyzed according to the mean and spatial distribution of the IH and AvGST indices for the periods 2005-2020, 2021-2050 and 2051-2080. The definitions, classifications and significance of these indices are set out below:

Huglin index (IH), (Huglin, 1978) provides information on the thermal resources of wine-growing areas and on their suitability for winegrape varieties. The IH is computed for April 1st to September 30th, according to the formula:

$$IH = \sum_{01.04}^{30.09}\left[(Tmj - 10) + (Txj - 10)/2\right] x\ k$$

where: Tmj is the daily mean air temperature; Tx is the daily maximum air temperature; k is the length of daily coefficient.

Its values are grouped into six classes, corresponding to the groups of varieties whose grapes reach maturity in the respective ranges of values (Table 1).

Table 1. Classes for the Huglin index (IH) and their corresponding winegrape varieties (Huglin, 1978)

Value	Abreviation	Type	Variety
≤ 1500	IH_1	Very cool	Too cold for grape cultivation
> 1500 ≤ 1800	IH_2	Cool	Riesling, Chardonnay, Sauvignon blanc
> 1800 ≤ 2100	IH_3	Temperate	Cabernet franc, Cabernet Sauvignon
> 2100 ≤ 2400	IH_4	Temperate-warm	Grenache, Syrah, Aramon, Carignan
> 2400 ≤ 3000	IH_5	Warm	Warm enough for all winegrapes
> 3000	IH_6	Very warm	Too warm for grape cultivation

Growing season average temperature (AvGST) (Jones, 2006) is calculated by taking the average of the seven months of the growing season (April 1 to October 31). The result is classified into five groups according to *cool, intermediate, warm, hot*, and *very hot* climate-variety maturity types (Table 2). The AvGST correlates to the maturity potential for winegrape varieties grown across many wine regions.

Table 2. Classes for the AvGST and their corresponding winegrape varieties (Jones, 2006)

Range	Type	Variety
< 13°C	Too cool	Too cold for grape cultivation
13 - 15°C	Cool	Riesling, Pinot gris, Traminer
15 - 17°C	Intermediate	Cabernet franc, Pinot noir, Chardonnay, Sauvignon, Semillon
17 - 19°C	Warm	Cabernet Sauvignon, Merlot, Grenache, Syrah, Carignan
19 - 24°C	Hot	Raisins
> 24 °C	Too hot	Too hot for grape cultivation

In order to visualize how climate change is likely to affect the spatial distribution of vine suitability, we produced maps for the AvGST and IH indices, for the 3 time periods accounted for in the present study. The maps were achieved starting from the average indices values at Cotnari station location, using altitude temperature and precipitation gradients for Romania's territory and a 30 m resolution DEM. The continuous spatial distribution of indices was then classified according to vine suitability (Huglin, 1978; Jones, 2006; Irimia et al., 2014). We used Excel/XLSTAT trial version (Addinsoft, 2018) for statistical processing of data and ArcGIS software (ESRI, 2018) for spatial modelling.

2. Results

2.1. Evolution of some climatic parameters during the 2005-2100 time period.

According to the simulation, the AAT will increase between 2005 and 2100 with a trend of 0.04°C yr^{-1}, from 9.2°C in 2005 to more than 13°C after 2080 (Fig. 2a). AAT averages, higher than 12°C and projected for 2060-2100, may become challenging for quality wine production in the area. AAT increase is associated with a TWM increase from 20.4°C at the beginning of the period to more than 24°C in 2100, with a trend of 0.04°C yr^{-1} (Fig. 2a). In this case, exceeding the upper limit of 22°C, specific to quality wine-producing areas in Romania (Oşlobeanu et al., 1991) is estimated to occur around the 2060s. Due to the increase of temperatures, LGS will expand from 168 days in 2005 (Fig. 2b), to more than 180 days during the 2080-2100.

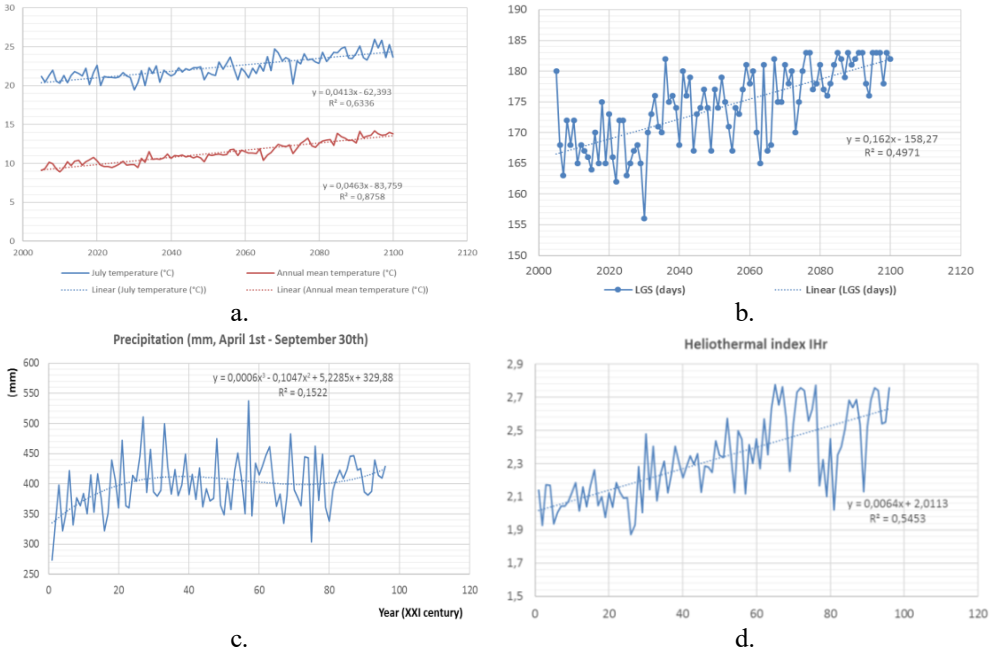


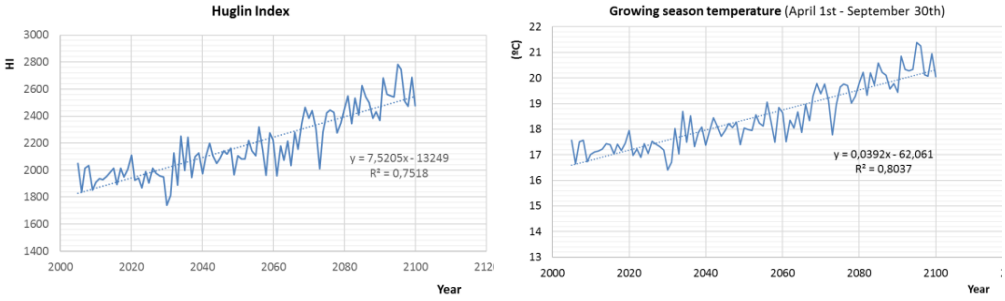
Fig. 2 Projections based on the RCP 4.5 scenario of the annual average of some climatic parameters between 2005 and 2100 for the Cotnari area: a. annual average temperature (AAT) and temperature of the warmest month (TWM); b. lenght of the growing season (LGS); c. precipitation during the growing season (PP); c. actual heliothermal index (IHr).

As for the PP, projected climatic averages show a slight increase, with an annual trend of 0.39 mm yr^{-1}, from an average of 331 mm in 2005 to 410 mm after

2080 (Fig. 2c). However, this slight increase will not be able to compensate increasing evapotranspiration generated by the rise in temperatures, which is reflected by the increase in IHr values, from 2.04 to 2.48 between 2050-2080 and almost 2.7 between 2080-2100 (Fig. 2d).

2.2. Averages and suitability for viticulture of the IH and AvGST indices for the 2005-2100 time period. According to projections, the IH will increase with an annual trend of 7.52 units yr^{-1}, from an average of 1967 units between 2005-2020, to over 2500 units after 2080 (Fig. 3a). The rise in the Huglin index indicates the evolution of the current *temperate* class (IH3) to *temperate-warm* class (IH4) after 2030 and to *warm* class (IH5) currently specific to regions such as Malaga (Spain) or Marsalla (Italy), after 2080. Averages of IH indicate the shifts from suitability for *Cabernet Sauvignon* and *Merlot* between 2020-2060, to suitability for Mediterranean varieties such as *Grenache* and *Carignan* after 2060. IH increase will be inconsistent between 2020 and 2100. However, the IH variability will mark more favorable or less favorable years for wine quality, which is a particularity of viticulture (Jones and Hellman, 2003).

A similar evolution in the case of AvGST, which increases by 0.03°C yr^{-1}, shifting during the present period 2005-2020, from the current *intermediate* class (15-17°C) to the *warm* class (17-19°C). The *warm* class maintains until 2080 (Fig. 3b). After 2080 AvGST will shift to *hot* class (19-24°C), but with annual variations that will reach 20...21°C, excessive temperatures, unsuitable for the red wine varieties (Jones, 2006).



a. b.

Fig. 3 Projections of the annual average of bioclimatic indices for the 2005-2100 period for the Cotnari winegrowing region: a. Huglin index (IH); b. average growing season temperature (AvGST).

2.3. Projections of spatial distribution of the IH and AvGST indices for the 2005-2080. According to simulations, the spatial distribution of the classes of the two indices will evolve in the Cotnari area towards an expansion of suitability for red wines (Fig. 4).

Concerning the Huglin index (IH), between 2005-2020, 20.7% of the area is characterized by *temperate* class (IH3) and 79.2% by *temperate-warm* class (IH4) (Table 3); this favorable pattern changes over time until the *temperate* class (IH3) disappears and the *temperate-warm* (IH4) and *warm* classes (IH5) diminish. At the same time the IH classes shift to higher altitude (Table 4): between 2005-2020 the

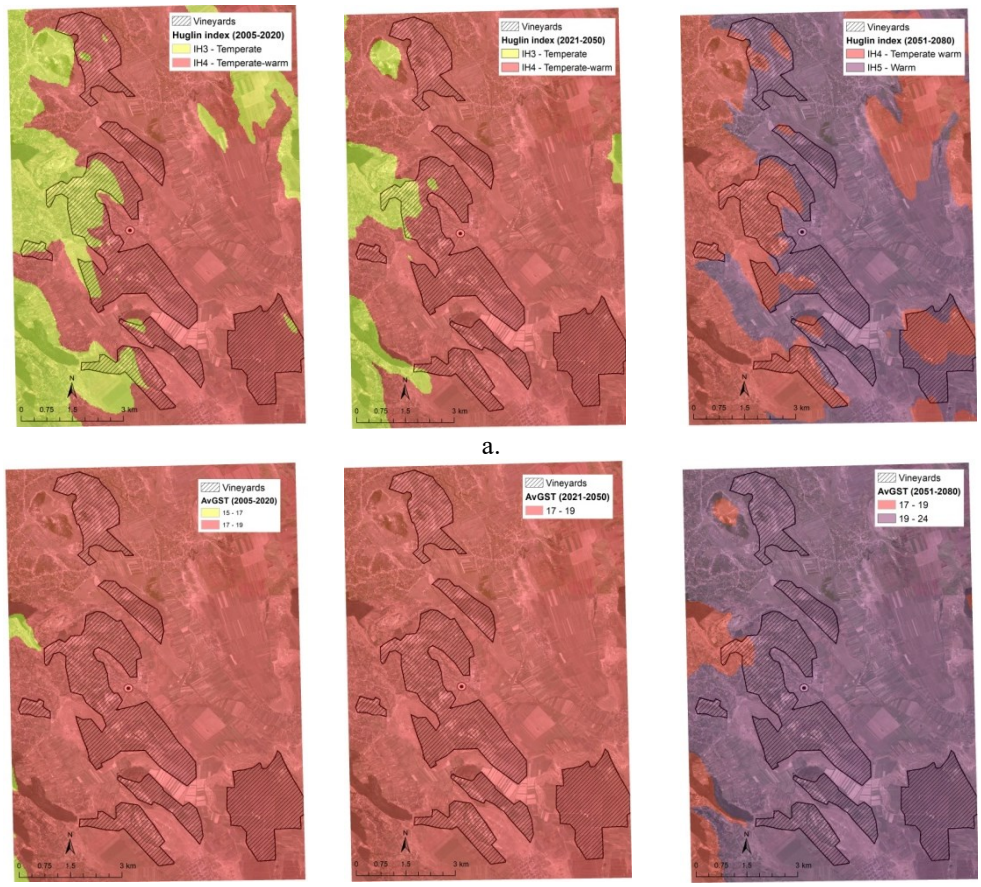


Fig. 4 Simulations based on the RCP 4.5 scenario of the spatial distribution of the Huglin index IH (a) and of the average growing season temperature AvGST (b) for the 2005-2020, 2021-2050 and 2051-2080 time periods, for the Cotnari winegrowing region.

low area (106 m asl) is characterized by the *temperate-warm* class (IH4) while the high area (213.7 m asl) by the *temperate* class (IH3); between 2021-2050 both classes shift to higher altitude; in the last period 2051-2080 *temperate* class (IH3)

disappears at the maximum altitude (315 m asl), being replaced by the *temperate-warm* class (IH4), while in the low area at 136.7 m asl, the *warm* class (IH5) installs.

It is also noticeable that the area characterized by each climatic class narrows down as it moves to a higher altitude (Table 3 and Table 4): shifting from 213 m asl between 2005-2020 to 257 m asl between 2021 and 2050, the *temperate* class (IH3) narrows from 421.5 ha to 100.8 ha; *temperate-warm* class (IH4) shifting from 156.24 m asl between 2021-2050 to 188.14 m asl between 2050-2080, diminishes from 1933 ha to 966.7 ha.

Table 3. Statistics for the simulated spatial distribution of the bioclimatic indices IH and AvGST for the Cotnari wine growing region

Bioclimatic index	2005-2020			2021-2050			2051-2080		
	Class*	ha	%	Class	ha	%	Class	ha	%
IH	IH3	421,5	20,7	IH3	100,8	4,9	IH4	966,78	47,5
	IH4	1612,3	79,2	IH4	1933,11	95,0	IH5	1067,13	52,4
AvGST	warm	2033,9	100	warm	2033,9	100	warm	52,6	2,5
							hot	1981,2	97,4

* IH3 – temperate; IH4 – temperate warm; IH5 – warm; AvGST warm=17…19°C; AvGST hot=19…24°C

Table 4. Statistics for the simulated elevational distribution of the IH for the Cotnari wine growing region, for the 2005-2020, 2021-2050 and 2051-2080 time-periods.

	Statistics for altitude (m, asl)				
	Min	Max	Range	Mean	STD
2005-2020					
IH3 - Temperate	180,55	315,45	134,90	213,73	29,27
IH4 - Temperate-warm	106,08	180,53	74,45	147,47	18,89
2021-2050					
IH3 - Temperate	227,74	315,45	87,71	257,02	22,13
IH4 - temperate-warm	106,08	227,66	121,58	156,24	26,64
2051-2080					
IH4 - Temperate-warm	158,34	315,45	157,11	188,14	30,09
IH5 - Warm	106,08	158,33	52,25	136,77	13,69

3. Discussion

Projections based on the RCP 4.5 scenario reveal major changes in climate suitability for viticulture in the Cotnari winegrowing region during 2005-2100, namely high temperatures and an intensified phenomenon of aridation. And it should be noted that this study was developed based on an intermediary and relatively optimistic scenario in relation to the current situation. Although

assessments based on climate models have a significant relativity, correlating the results of this research with the results of the research regarding the Cotnari winegrowing region's climate during the 1961-2013 (Irimia et al., 2018a), and also with results of the simulations on the evolution of viticulture in the context of climate change (Stock et al., 2005; Moriondo et al., 2013), indicates the occurrence of major changes in climate suitability for the wine production in the Cotnari area over the coming decades.

The increase in the annual average temperature in the Cotnari winegrowing region during the 2005-2100 period continues the increases during the previous time period 1981-2013 (Irimia et al., 2018a). The growth trends of thermal parameter for the 2005-2100 period, corresponding to the RCP 4.5 scenario, are lower than those recorded over the period 1981-2013. Temperature increases have already been observed in other European wine regions and have been related to increased sugar content and lower grape acidity (Duchêne and Schneider, 2005). In the case of the Cotnari wine area, beyond the overall increase of the thermal resources that will influence the composition of grapes, an increase of the TWM would be challenging for the quality of yields in the perspective of the 2080-2100 period. According to projections, after 2060 the TWM will exceed the limit of 24°C, which for Romania viticulture is the upper limit for the production of quality wines (Oşlobeanu et al., 1991). The Cotnari area will gain a higher thermal availability, leading to early phenological events and an extension of the growing season (Menzel and Fabian, 1999). These developments will firstly eliminate the early white winegrape varieties from the traditional assortment of the Cotnari area, such as *Fetesca albă*, whose chemical and organoleptic characteristics will cede first under the influence of climate change.

Between 1961 and 2013 the IH increased in the Cotnari wine region from 1714.1 units (*cool* class, IH2) to 1879.4 units (*temperate* class, IH3) (Irimia et al., 2018a). The current simulation shows further increase of the IH, to about 2200 units (*temperate-warm* class, IH4) after 2050, and finally to more than 2500 units (*warm* class, IH5) after 2080. It is the type of evolution found for the European wine regions climate for the same time-period by reference studies (Moriondo et al. 2013; Hannah et al., 2013). Also, it is the type evolution predicted for the climate of the French wine regions for the following decades, until 2100 (Quenol et al., 2017), or also for other European wine-growing regions (Eccel et al., 2016; Neumann and Matzarakis, 2011). This index, however, does not include the influence of sunshine duration which, according to our studies (Irimia et al., 2017), increased in the Cotnari region by 102 hours between 1961-2013. The increase of the sunshine duration may accentuate the aridity of the area and enforce more severe adaptation measures, namely the replacement of the winegrape varieties:

firstly the local white varieties *Fetească alba, Frâncuşă, Tămâioasă românească* with varieties such as *Cabernet Sauvignon, Merlot* and *Syrah*, and after 2080 replacement of these ones with some better adapted to warm climate, such as the Mediterranean varieties of *Carignan* and *Grenache*. According to AvGST, the time period suitable for producing quality wines of the *Cabernet Sauvignon* variety maintains until 2080. However, values exceeding the maximum threshold of 19.5°C for producing quality wines of this variety (Jones et al., 2005) are recorded starting before 2070.

The spatial shifts revealed by this study follow patterns foreseen for the Cotnari area in previous works (Irimia et al., 2018a, 2018b), respectively shifts of types of wine production at higher altitudes following the suitable climate. This evolution follows closely the scenario predicted for the Tuscany region by Moriondo et al. (2011), respectively changes in winegrape varieties and shifts on altitude of wine types. From this point of view, the Cotnari area has an acceptable potential to adapt to climate change due to its quite high altitudes (up to 380 m asl). But the altitude shifts are equivalent to the narrowing over time of the surface suitable for each category of winegrape varieties and wine type. This development is certain in terms of climate change. However, it worth mentioning that under the RCP 4.5 scenario in the 2100s perspective not even the valleys in the Cotnari will be in danger of losing their climate suitability for the wine production. But this somehow optimistic result is related to the fact that our projections follow the RCP 4.5 scenario. The next step will be to achieve the same analysis approach with other climate change scenarios (RCP2.5, RCP 6.0 and RCP8.5) as well as other climate models in order to integrate the uncertainty limits into results.

Conclusions

Climate projections based on the RCP4.5 scenario reveal the evolution of climate of the Cotnari winegrowing region towards an accentuated warmth and intensification of aridization. This condition will lead in the coming decades to replacement of climate suitability for white wines with climate suitability for red wines, a specialization which is not specific to the Cotnari area at present. These developments are caused by the increase in temperatures, both as an annual average and as increases during certain periods, namely the growing season and the July temperature. According to projections, the climate of the Cotnari winegrowing area will maintain suitable for both white and red wines until 2060-2070. After this period averages of bioclimatic indices indicate the setting of a climate suitable exclusively for the red wine production, first from varieties such as *Cabernet Sauvignon* and *Merlot*, then from some winegrape varieties adapted to the Mediterranean climate such as *Carignan* and *Grenache*. With climate change, the

climate suitability types shift to higher altitude until 315 m asl where those requiring lower temperatures will disappear successively and will be replaced in the low area by the ones that require higher temperatures. Surfaces characterized by climatic classes shifting on altitude will gradually diminish. The evolutions are in line with those predicted in recent decades by climatologists and require the development of strategies for adapting the viticulture of the Cotnari area to climate change.

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