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ORIGINAL PAPER

Mapping the impact of recent climate change on viticultural potential in Romania

Cristian Valeriu Patriche[1] · Liviu Mihai Irimia[2]

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Abstract

Climate change affects the viticulture sector worldwide in different ways, some countries reporting negative impacts, other positive effects, depending on the type of climate in which they are located. Romania is an important wine-producing European country, with a long viticultural tradition. Our study aims to map the ecological potential for viticulture at country scale, using a GIS-based multi-criteria methodology, which quantifies and integrates the influences of climate, soil and relief factors. The soil and relief factors are considered stable in the analysed time period, while the climate factors are dynamic, their influence being assessed for two periods of time: the reference climate period (1961–1990) and the more recent period (1991–2013), affected by climate warming. The results show that the area suitable for viticulture has expanded during the last decades, new regions in the plateau, hilly and lower mountain areas shifting from restrictive to suitable for wine grape cultivation (25,245 km^2, 10.6% of the country). On average, the upper limit vine growing has shifted from 612 m (1961–1990) to 860 m (1991–2013). As a consequence, the potential for white wines has migrated to higher elevations and latitudes, while the potential for red wine production has significantly increased at lower elevations. Overall, there is an increase in suitability for wine grape production for about one third of the country (76,833 km^2, 32.2%). Such changes are likely to modify the typicity of traditional winemaking regions, compelling the producers to adapt through introducing of new grape varieties and technological changes.

1 Introduction

The recent climate change has a significant impact on viticulture and wine production throughout the globe (Jones et al. 2005; Jones and Webb 2010). Research on climate change impacts on viticulture has significantly grown over the last decades (Kenny and Harrison 1992; Marx et al. 2017). Various studies point out changes in grapevine growth characteristics and wine quality (Nemani et al. 2001; Lebon 2002; Jones et al. 2005; Webb et al. 2008) as an effect of climate warming and of the increase in the frequency/intensity of extreme climatic events (droughts, hail, flooding). Higher temperatures affect grapevine phenology by shifting the phenological phases to earlier periods, including the shifting of ripening phase to warmer periods, which affects the grape composition, by increasing sugar content, diminishing total acidity and altering the aroma compounds (Fraga et al. 2016b; Van Leeuwen and Darriet 2016). Water deficit, as a consequence of increased evapotranspiration, already affects many viticultural regions of the world and impacts on vintage quality (Van Leeuwen and Darriet 2016) and reduces the yields because of the smaller berry size and reduced bud fertility (Ollat et al. 2002; Duchêne and Schneider 2005; Guilpart et al. 2014). Simulations of climate change impact show that the areas suitable for viticulture in the major wine-producing regions of the world will decrease by 19% to 62% in the lower RCP 4.5 concentration pathway scenario and by 25% to 73% in the higher RCP 8.5 scenario by 2050 (Hannah et al. 2013).

Europe has the largest vineyard area in the world (about 40%) (Fraga 2019), being home to world-renowned wine regions. Climate simulations have shown that mean annual temperatures are likely to increase in Europe by 3.2—3.6 °C until 2100, while annual precipitations are likely to decrease by 12% in the Mediterranean basin within the same timeline

✉ Cristian Valeriu Patriche
patriche.cristian@acadiasi.ro

Liviu Mihai Irimia
liviuirimia2005@yahoo.fr

1 Geographic Research Center, Romanian Academy, Iași Branch, 8 Carol I, 700505 Iași, Romania

2 Faculty of Horticulture, Iasi University of Life Sciences, 3 Mihail Sadoveanu Alley, 700490 Iași, Romania

(Christensen et al. 2007). In future climate scenarios, the traditional winemaking regions, especially those in southern Europe, are likely to experiment a decline in their viticultural suitability mainly due to severe dryness (Malheiro et al. 2010; Moriondo et al. 2013; Cardell et al. 2019; Santos et al. 2020). Countries like Spain, Portugal, Italy, Greece are likely to experience a decline of the viticultural sector due to increased temperatures and water deficit (Fraga et al. 2016a; Lazoglou et al. 2018; Teslić et al. 2019). On the other hand, areas favourable for vine growing are expected to migrate to higher elevations (Lazoglou et al. 2018). For Central and Western Europe, future warmer climates may have positive effects at some traditional wine regions like Burgundy, Champagne, Alsace, Loire Valley, Rheingau, Mosel, while other new regions suitable for winemaking may emerge (Cardell et al. 2019; Santos et al. 2020) as an effect of the migration of climate suitability for grapevine cultivation towards north up to the 55° N parallel (Fraga et al. 2016b). Climate change may impact the territorial identity of traditional wine-growing regions (Neethling et al. 2019), through quantitative and qualitative changes of grape properties and wines. Territorial shifts in viticulture potential may occur, determining changes in the boundaries of some geographical indications.

Within the Carpathian region, excepting Romania, Serbia and Hungary, where climate is fully suitable for grapevine growing, the rest of the region is characterized by less suitable climatic conditions. Against the background of global warming, suitable conditions for grapevine growing occur in northern areas of the Carpathian region from Poland or Czech Republic (Kryza et al. 2015), while in the established areas (Hungary, Romania, Serbia) the climatic suitability of the wine-growing regions increases (Mesterházy et al. 2014; Irimia et al. 2018a).

In Romania, changes in climate parameters as well as their effects on agricultural sector have been approached by several studies (Croitoru and Piticar 2013; Prăvălie et al. 2017, 2020). Significant warming trends were found for most of the Romanian wine regions, especially for spring and summer seasons (Dumitrescu et al. 2015; Bucur and Dejeu 2016; Irimia et al. 2018a). The actual sunshine duration has also increased, while precipitations do not display significant changes (Dumitrescu et al. 2015; Irimia et al. 2018a). As a consequence of temperature and sunshine duration changes, the areas suitable for viticulture have migrated upwards, towards higher elevations, and northwards, towards higher latitudes. Also, the climate suitability for white wines tends to reduce in favour of climate suitability for red wines (Irimia et al. 2018a, 2018c).

In this context, our study attempts to assess the ecological potential for viticulture in Romania and its spatial evolution induced by climate change in the 1961–2013 period. The assessment is carried out by application of a multi-criteria methodology (Irimia et al. 2014), including both climate and soil–relief factors, which was previously applied and validated in several studies (Irimia et al. 2014, 2015, 2018c; Sirnik et al. 2019). Such assessments, which take into account all three categories of environmental factors (soil, relief, climate) and analyse their distribution through the use of GIS, were initiated in 1990s in the USA to identify areas suitable for grapevine growing (Watkins 1997) and were subsequently used for wine zoning in many areas of the world (Carey et al. 2008; Anderson et al. 2012; Tomasi et al. 2013) including in Europe (Pythoud 2006; Herrera Nuñez et al. 2011).

A first assessment for the Romanian territory has already been carried out by Patriche and Irimia (2020). The present study corrects some soil assessment deficiencies of the first version and provides more insight into the Romanian viticultural potential. Our research considers the entire Romanian territory, not just the current viticultural regions, as we are interested to delineate the ecological potential for viticulture outside the traditional limits, in order to identify new areas suitable for viticulture. Moreover, our study seeks to reveal the qualitative changes in the wine production sector and to provide a basis for technological adaptation of wine producers to climate change.

2 Materials and methods

2.1 Study region

Romania is a medium-size European country (about 238,000 km^2), situated in the central–eastern part of Europe. Its relief is characterized by a balanced distribution of mountain, hill, plain areas, shaped on a variety of rocks, including hard, magmatic and metamorphic rocks in the mountain area, less consolidated or soft rock formations in the plateau and hilly areas (limestones, sandstones, clays, marls and sands) and loess and loess-like formations in the plain areas. The elevation ranges from 0 to 2544 m asl., with an average value of 398 m asl.

The climate of Romania is temperate continental, with mean annual temperatures ranging from > 11 °C, in the southern, south-eastern and western part of the country (southern Romanian Plain, Dobrogea Plateau, Danube Delta, part of the Western Plain), to 8–11 °C in the plateau and hilly areas, 0–5 °C in the high mountain area of the Carpathians and < 0 °C on the highest mountain peaks (Dumitrescu and Bîrsan 2015). The warmest month is July with average temperatures over 22 °C in the lower elevation areas, while the coldest month is January when the average temperatures are negative throughout the country, except for the Black Sea influence zone and southern Western Plain, where sub-Mediterranean climate influences are present. The Romanian

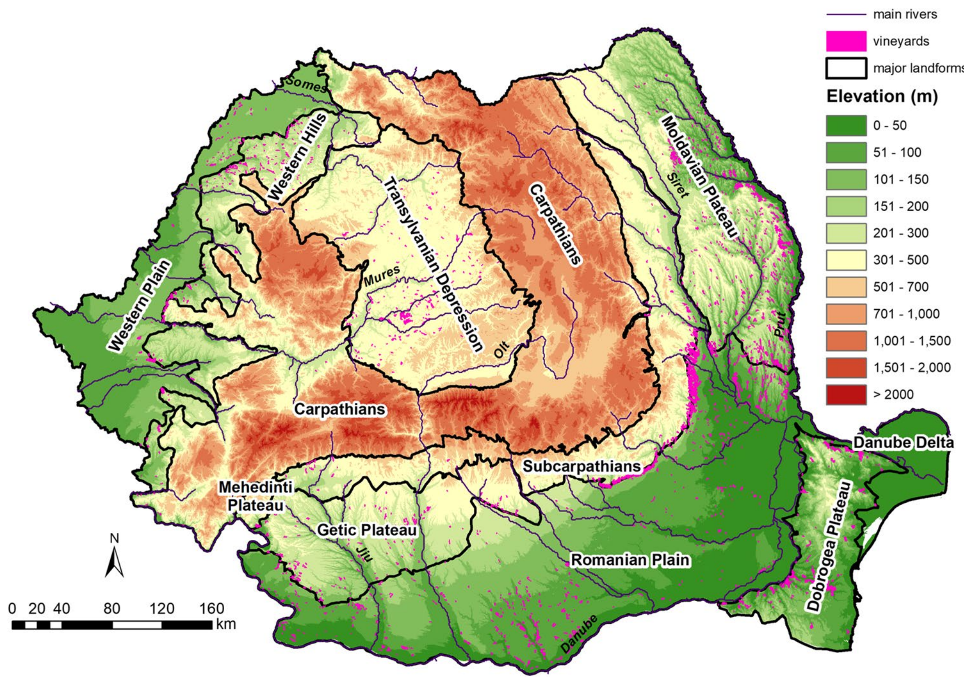

Fig. 1 Elevation map of Romania and spatial distribution of vineyards according to Corine Land Cover 2018 (EEA 2018)

climate is more humid in the western part of the country, due to the influences of Atlantic moist air masses, and more arid in the eastern and south-eastern part, because the Carpathians mountain chain retains moisture along west-facing slopes, while the large opening towards east and north-east allow the continental dry air masses to easily penetrate and influence the climate of this part of the country. As a consequence, the precipitations generally decrease from west to east, as the climate becomes more arid, the mean annual values varying from 500–600 mm yr^{-1} in the Western Plain to 300–500 mm yr^{-1} in the south-eastern part of the country (eastern Romanian Plain, Dobrogea Plateau and Danube Delta). The Subcarpathians, Transylvanian Depression and Western Hills receive an average of 600–700 mm yr^{-1} of precipitations, while in the mountain area the average quantities reach and exceed in some places 1000 mm yr^{-1}. In the south-western part of the country (southern Western Plain and Western Hills, western Getic Plateau and western Romanian Plain), there are sub-Mediterranean climate influences, while the Black Sea has a moderating influence on the climate along a narrow strip (about 20 km) along the coastline.

The soil cover[1] is dominated by Chernozems in the plain and lower plateau and hilly areas, while in the Dobrogea Plateau the Kastanozems are present. In the higher plateau and hilly areas and lower mountain areas, the Luvisols are dominant soil types, while in the mountain area the soil cover is diverse including Cambisols, Podzols, Regosols, Leptosols.

The land use is dominated by agriculture (about 57% of the country) mainly in the lower elevation areas, the main annual crops being maize, winter wheat and sunflower. Pastures also have an important extent (~ 10% of the country), but most of pastures on sloping terrain are overgrazed and therefore degraded. Regarding the viticulture, Romania is one of the main wine-producing countries in the world. Romanian viticulture is old, traditional, represented by 37 wine-growing regions totalling about 191,000 ha of vineyards (International Organisation of Vine and Wine 2019). The well-known international wine grape varieties (eg. *Sauvignon, Chardonnay, Cabernet Sauvignon, Merlot*) are mainly cultivated, while each Romanian wine-growing region also keeps in its assortment some local *vinifera* varieties. The total vineyard area, including table grape varieties and specific infrastructure, is 224670 ha according to Corine Land Cover (CLC) 2018 (EEA 2018).

The current spatial distribution of vineyards in Romania, according to CLC 2018 (Fig. 1), generally follows the contact areas between hilly and plain landform units. Most of the vineyards are situated in the Romanian Plain (841 km^2, 37.4% of the total vineyard area), the Moldavian Plateau (475 km^2, 21.1%), the Dobrogea Plateau (246 km^2, 10.9%) and the Subcarpathians (213 km^2, 9.5%). There are 1812 vineyard polygons with an average area of 1.23 km^2, varying between 0.02 and 42.21 km^2.

In the context of climate change, the Romanian viticulture seems to change in a positive way, with occurrences of new areas suitable for wine grape growing and diversification of local wine type production (Irimia et al. 2018a).

[1] Soil names according to WRB (FAO, 2015).

2.2 Input environmental data

The primary input data consisted in:

- *The digital elevation model (DEM)* of Romania with a spatial resolution of 25 × 25 m, extracted from EUDEM model (European Environment Agency, http://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem/eu-dem-v1.1/view);
- *ROCADA climate database* with a spatial resolution of 10 × 10 km and daily time resolution (Dumitrescu and Bîrsan 2015);
- *The soil map of Romania* at 1:200,000 scale, published by Florea et al. (1963–1993) and digitized by Vintilă et al. (2004);
- Soil data extracted from *SoilGrids* v0.5.3 platform (ISRIC, https://soilgrids.org/) for the Romanian territory at a spatial resolution of 250 × 250 m.

The digital elevation model was used to compute terrain slope and aspect at a resolution of 25 × 25 m. ROCADA database (Dumitrescu and Bîrsan 2015) was used to retrieve the climate information, namely the average monthly values of air temperature, precipitations and sunshine duration for the reference (1961–1990) and recent (1991–2013) time periods. The temperature and sunshine duration layers were downscaled at a resolution of 100 × 100 m using regression kriging method using elevation as predictor. We chose this approach for two main reasons: temperature and sunshine parameters are highly dependent on elevation, leading to high significance regression models; the regression kriging method is considered by numerous studies as superior to other spatial interpolation methods (Dobesch et al. 2007; Hengl 2007; Moral 2010; Meng et al. 2013), allowing both the integration of spatial information as predictor variables and the mapping of spatial anomalies of the dependent variable (Patriche 2011). The determination coefficients (R^2) of the elevation-based regression models are high for temperature (0.81–0.85) and sunshine duration (0.74–0.75) variables, ensuring that the interpolation errors are minimum.

For precipitation, we chose a simpler approach, that of ordinary kriging interpolation (Chen et al. 2010), because this variable is less dependent on terrain parameters (eg. elevation), while the density of the grid points is high enough for kriging to be able to render the general or local terrain influences on the spatial distribution of precipitations. The root mean square errors (RMSEs) for growing season precipitations, resulting from the cross-validation procedure, are small: 15.2 mm 1961–1990 and 14.7 mm for 1991–2013.

The potential (clear sky) global radiation and the potential sunshine duration were derived in SAGA-GIS software (Conrad et al. 2015) on the basis of DEM. We computed the sunshine fraction (actual/potential sunshine duration) and used it to derive the actual global radiation, according to a formula proposed by Entekhabi (1997):

$$GR_a = GR_p \times (1 - 0.65 \times N^2) \tag{1}$$

$$N = 1 - f \tag{2}$$

where:

- GR_a: actual global radiation (kcal cm^{-2});
- GR_p: potential global radiation (kcal cm^{-2});
- N: cloud cover fraction;
- f: sunshine fraction.

For the derivation of soil data layers for the upper 100 cm of soil, we used both the soil map of Romania at 1:200,000 scale (Florea et al. 1963–1993) and SoilGrids platform (ISRIC, https://soilgrids.org/). The clay data from SoilGrids platform is unfortunately inaccurate for the Romanian territory, most of the clay content values exceeding 40%, which is not in agreement with terrain reality. Therefore, we used the soil map of Romania to derive this parameter and estimated the clay content on the basis of soil texture: < 15% clay for sandy and loamy sand textures; 15–40% for sandy loam and loamy textures; > 40% clay for clay loam and clay textures. The gravel content was extracted from the previous (v0.5.3) SoilGrids version, because the current (v2) version displays unrealistically high gravel content almost all over the country. In addition, we corrected the SoilGrids gravel content data with the data retrieved from the soil map of Romania in order to produce the final gravel content map. Regarding organic matter content, we used the current SoilGrids data (v2) and derived the organic matter content by multiplying the soil organic carbon by 1.724 factor. The SoilGrids-derived data layers (gravel and organic matter contents) were downscaled from 250 × 250 m resolution to 100 × 100 m resolution using ordinary kriging interpolations. The clay content was also derived at a resolution of 100 × 100 m by conversion of the vector soil map into a raster map.

Finally, the spatial information was integrated at a common resolution of 100 × 100 m, because we thought it was an optimum resolution for a national-scale evaluation of the viticulture potential.

2.3 Methodology

The methodology used for the evaluation of ecological viticulture potential is the one proposed by Irimia et al. (2014) suitable especially for temperate climate conditions. This multicriteria methodology was applied and

Table 1 Ranking of ecological factors according to their suitability for wine grape growing (adapted from Irimia et al. 2014)

Ecological category	Factors	Suitability ranking scores			
		0	5	8	10
Relief	Slope (%)	-	< 8	> 15	8–15
	Aspect	-	NW, N, NE, horizontal	E, W	SE, S, SW
Climate*	Average annual temperature (°C)	< 8.5	8.5–9.3	9.4–10.0	10.1–11.2
	Average temperature of the warmest month (°C)	< 18.0	18.1–19.7	19.8–21.0	21.1–22.0
	Actual global radiation (kcal cm^{-2})	< 80.0	80–83.9	84.0–86.9	87.0–92.0
	Actual sunshine duration (hours)	< 1280	1280–1450	1451–1550	1551–1610
	Average precipitations (mm)	-	> 390	< 250	251–390
	Sum of effective temperatures (°C)	< 1045	1045–1200	1201–1400	1401–1675
	Length of growing season (days)	< 160	160–175	176–190	> 190
	Actual heliothermal index	< 1.36	1.36–1.70	1.71–2.20	2.21–2.66
	Bioclimatic index	< 3.9	3.9–5.0	5.1–8.0	8.1–13.0
	Oenoclimate aptitude index	< 3793	3793–4300	4301–4600	> 4600
Soil**	Clay content (%)	> 40.0	< 15	25–40	15–25
	Organic matter content (%)	-	3.1–4.0	2.1–3.0	1.5–2.0
	Gravel content (%)	> 40.0	< 10	30–40	10–30

* Except for average annual temperature, warmest month temperature and length of growing season, the other climate parameters are computed for the standard growing season, from April, 1st to September, 30th

** Soil parameters are computed as averages for the upper 100 cm of the soil profile

validated in several previous studies, conducted both in Romania (Irimia et al. 2013a, b, 2014, 2015, 2018a, 2018b) and in other regions of Europe (Sirnik et al. 2019).

The methodology considers and quantifies the influences of 15 factors from three ecological categories: relief, soil and climate factors. The influence of each factor is ranked by means of 0, 5, 8 and 10 scores (Table 1), with the following significance:

- 0: unsuitable or restrictive for vine growing;
- 5: suitable for white table wines, sparkling wines and wines for distillates;
- 8: suitable for quality white wines and red table wines;
- 10: suitable for quality red wines and secondary for white wines.

The influence of relief is expressed by means of two factors: terrain aspect and slope, while the influence of soil is quantified by means of three factors: soil clay, organic matter and gravel contents. The climate ecological category is the most consistent one, comprising 10 factors, of which nine were used in our study (the length of the growing season was not computed in this study due to the absence of daily temperature data). The climate factors include both basic parameters (mean annual temperature, warmest month temperature, actual sunshine duration and precipitations) and derived more complex indices (actual global solar radiation, sum of effective temperatures, actual heliothermal index, bioclimatic index, oenoclimate aptitude index). The actual global solar radiation was computed using formula (1), while the other bioclimatic indices were calculated according to the following formulas:

- *Sum of effective temperatures* (°C):

$$\Sigma t_u = \sum_{01.IV}^{30.IX} (t_d - 10) = \sum_{IV}^{IX} (t_m - 10) \times N_m \tag{3}$$

- *Actual heliothermal index* (Oşlobeanu et al. 1991):

$$IH_a = \Sigma t_u \times ASD \times 10^{-6} \tag{4}$$

- *Bioclimatic index* (Constantinescu 1967):

$$Ibcv = \frac{ASD \times \Sigma t_a}{10 \times PP \times N_d} \tag{5}$$

- *Oenoclimate aptitude index* (Teodorescu et al. 1987):

$$IAOe = ASD + \Sigma t_a - (PP - 250) \tag{6}$$

- t_d: average daily temperature (°C);
- t_m: average monthly temperature (°C);
- N_m: number of days in the month.
- Σt_u: sum of effective temperatures (°C);
- ASD: actual sunshine duration (hours) from April, 1st to September, 30th;

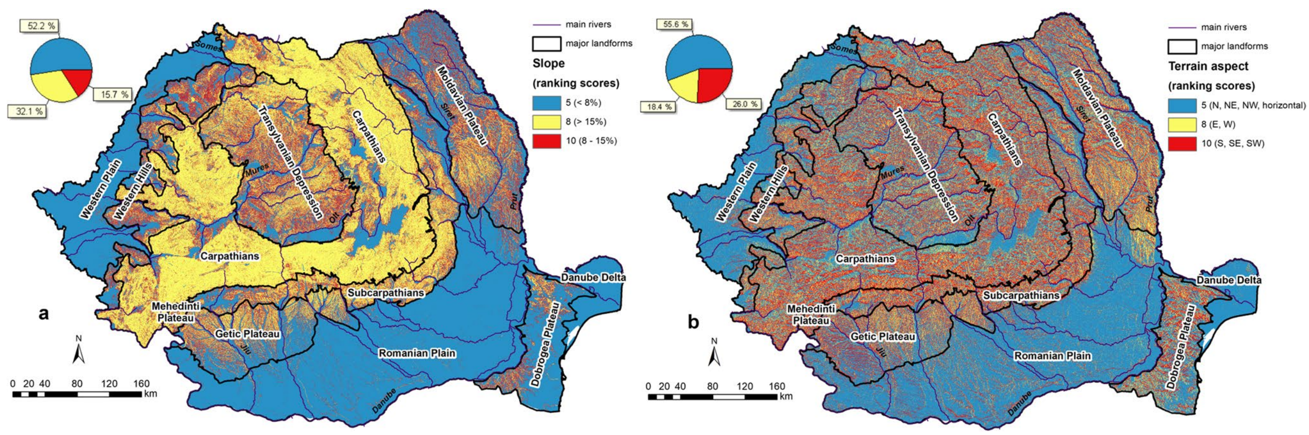

Fig. 2 Suitability of relief parameters for wine grape growing: a – slope; b – aspect

– Σt_a: sum of active temperatures (sum of daily temperatures > 10 °C from April, 1st to September, 30th, °C);
– N_d: number of days in the growing season.
– PP: precipitation sum from April, 1st to 30 September, 30th (mm); in formula 6, if precipitations are < 250 mm, the difference (PP – 250) is set to zero.

Most of the heliothermal factors (average annual temperature, average temperature of the warmest month, actual global radiation, actual sunshine duration, sum of effective temperatures, actual heliothermal index, bioclimatic index) have delimited maximum intervals (Table 1), the upper limits of which represent the maximum average values identified within Romanian vineyards for different time periods between 1900 and1985 (Irimia et al. 2014). Due to climate change, the maximum values have grown in Romania, but so far they did not negatively influenced the production quality of the wine grape varieties. For this reason, the factor values exceeding the maximum threshold were considered favourable and assigned 10 ranking scores.

The averages of suitability ranking scores were computed separately for each group of factors (relief, soil and climate), resulting the suitability maps of relief, soil and climate. Then, these 3 maps were averaged in order to achieve the viticultural ecological potential map. If one or more factors were restrictive for wine grape growing and therefore received a score of 0, the final suitability was also considered 0. Where no factor was restrictive for vine growing, the average suitability ranges from 5 to 10, with the following significance (Irimia et al. 2014):

- 5: viticultural potential for white table wines, sparkling wines and wines for distillates;
- 6: viticultural potential for white table wines, sparkling wines and wines for distillates as well as for quality white wines in very suitable years, in terms of climate;
- 7: viticultural potential for quality white wines;
- 8: viticultural potential primarily for quality white wines and secondarily for red table wines;
- 9: viticultural potential primarily for quality red wines and secondarily for quality white wines;
- 10: viticultural potential for quality red wines.

The relief and soil suitability were considered constant during 1961–2013 period, while the climate suitability was considered variable and therefore analysed for 2 periods of time (1961–1990 and 1991–2013) in order to assess the modifications of the viticulture potential induced by climate change.

3 Results

3.1 Relief suitability

According to relief parameters, the suitability for wine grape varieties is higher in plateau and mountain areas, where steeper slopes are encountered and various expositions are present, including southern, western and eastern aspects, which are favourable for vine growing (Fig. 2). Suitability is lower in plain areas due to the dominance of flat (horizontal) terrain. Overall, slope has moderate and high suitability for vine growing for 32% and 16%, respectively, of the Romanian territory, while terrain aspect present moderate and high suitability for 18% and 26%, respectively. More than half of the country presents lower slope and aspect suitability for vine.

Integrating the influence of slope and aspect parameters, it is found that the relief of Romania is mostly suited for white wine varieties, the 5, 6 and 7 ranking scores being assigned for 70% of the country (Table 2). Most of this area corresponds to plains, which have a dominant

Table 2 Percentages of relief suitability ranking scores for the major landform units and the entire Romanian territory

Landform unit	Area (km^2)	Suitability ranking scores (%)					
		5	6	7	8	9	10
Carpathians	66,286	7.6	29.8	8.0	18.4	31.3	4.9
Subcarpathians	16,589	20.7	20.8	17.8	9.9	21.1	9.7
Transylvanian Depression	25,297	20.0	19.2	19.7	8.7	22.3	10.1
Western Hills	12,834	29.7	16.5	21.2	5.6	16.4	10.6
Mehedinti Plateau	802	6.0	23.0	14.3	13.4	30.3	13
Getic Plateau	13,824	33.0	17.0	20.6	6.3	14.8	8.3
Moldavian Plateau	22,955	25.2	18.2	26.4	5.7	14.2	10.3
Western Plain	16,195	86.1	5.5	7.0	0.1	0.6	0.7
Romanian Plain	48,968	81.7	6.4	10	0.2	0.9	0.8
Dobrogea Plateau	10,160	43.0	17.6	26.5	2.1	6.3	4.5
Danube Delta	4470	95.0	2.1	2.7	0.0	0.1	0.1
Total	238,380	37.8	18.0	14.2	8.1	16.3	5.6

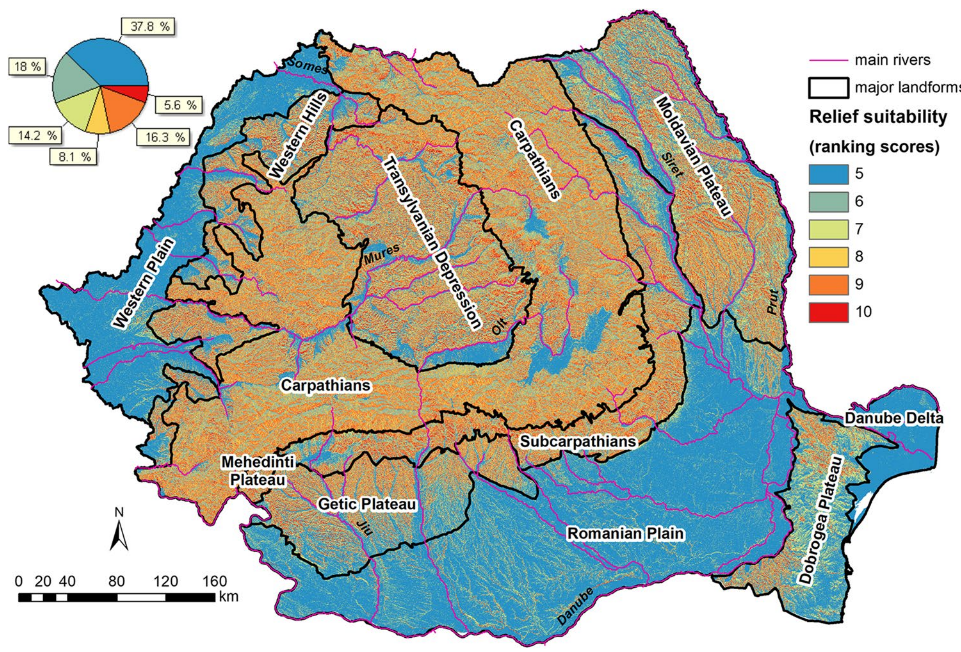

Fig. 3 Relief suitability for wine grape growing in Romania

ranking score of 5 (Fig. 3). The potential for red wines, from the relief point of view, is present on 30% of the country (the ranking scores 8, 9 and 10) and corresponds to hilly, plateau and mountain areas. However, this potential is downgraded by the restrictive climate of mountain zones.

According to the major landform units of Romania, the highest potential of relief for red wine varieties (ranking scores of 8, 9 and 10) is present in the Mehedinti Plateau (56.7%, 455 km^2), Carpathians (54.5%, 36,149 km^2), Transylvanian Depression (41,1%, 10,408 km^2) and Subcarpathians (40,7%, 6760 km^2). The potential for white wine varieties (ranking scores of 5, 6 and 7) is especially high in the Western Plain (98,7%, 15,984 km^2) and the Romanian Plain (98,1%, 48,030 km^2).

3.2 Soil suitability

From the viewpoint of clay content, most of the Romanian territory is highly suitable for grapevine (66,6%) (Fig. 4a), due to the dominance of average clay values (15–25%). The gravel content is highly suitable only in mountain areas and part of the Curvature Subcarpathians, while most of the Romanian territory has low suitability (75%), because of the low gravel content of soils (Fig. 4b). The suitability of organic matter content is more balanced, most of the country having moderate suitability (41%), while the low and high shares of suitability scores are similar (about 29%) (Fig. 4c).

The joint influence of these parameters show that the soils of Romania are mostly suitable for quality white wines, 40% of the country presenting a ranking score of 7 (Fig. 5).

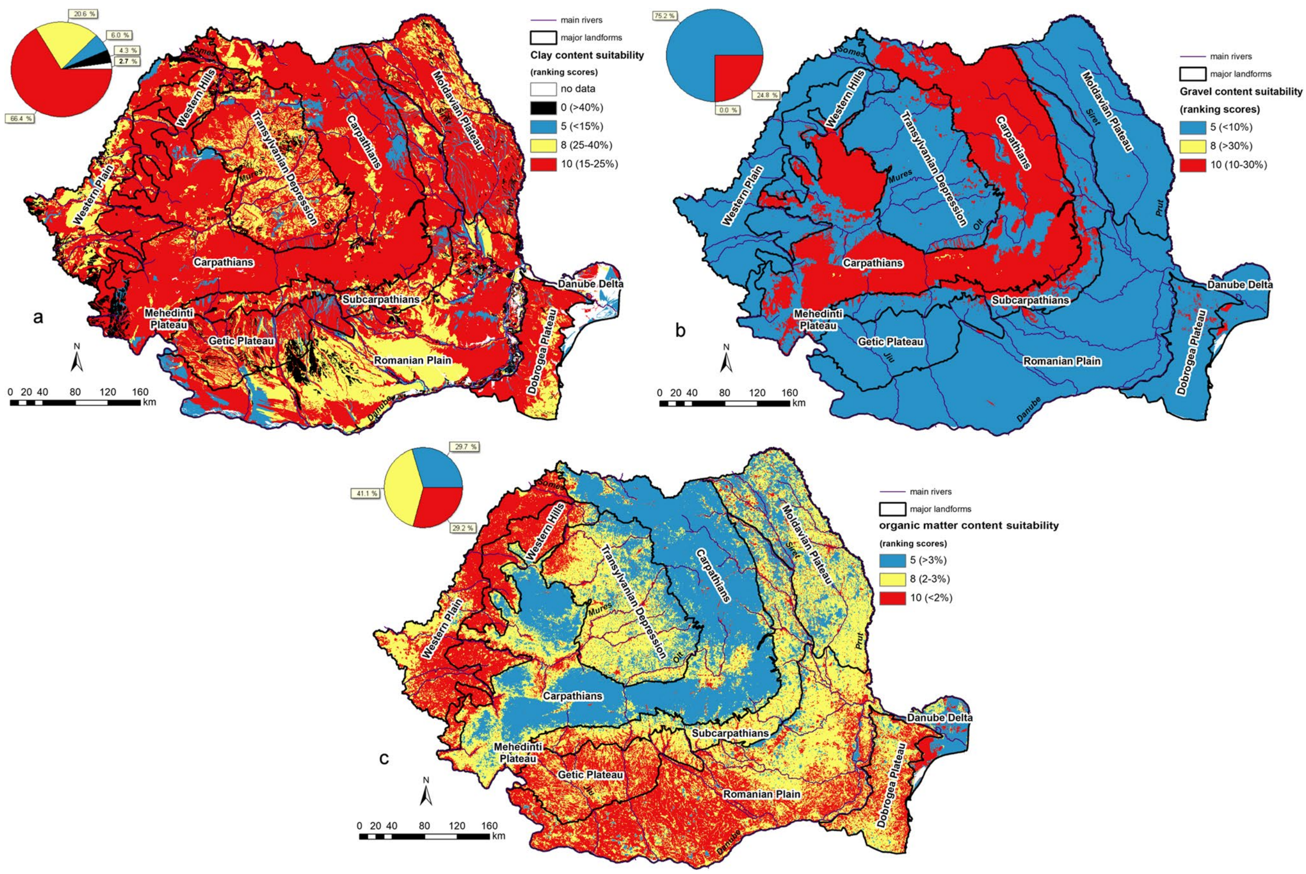

Fig. 4 Suitability of soil parameters for wine grape growing: a – clay content; b – gravel content; c – organic matter content

Fig. 5 Soil suitability for wine grape growing in Romania

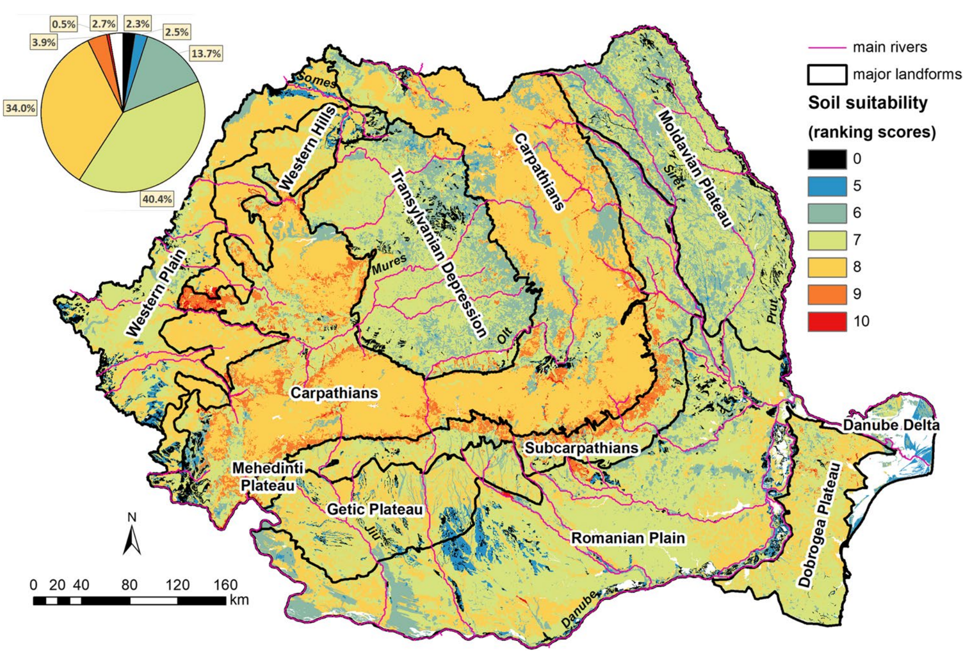

Table 3 Percentages of soil suitability ranking scores for the major landform units and the entire Romanian territory

Landform unit	Area (km^2)	Suitability ranking scores (%)							No data*
		0	5	6	7	8	9	10	
Carpathians	66,286	1.3	0.6	9.3	15.9	61.8	9.5	1.1	0.5
Subcarpathians	16,589	1.2	1.6	17.3	47.9	18.8	11.8	1.1	0.3
Transylvanian Depression	25,297	3.0	0.7	24.9	59.6	10.3	1.2	0.2	0.1
Western Hills	12,834	2.3	2.6	1.9	25.2	65.4	1.3	1.0	0.3
Mehedinti Plateau	802	0.0	0.5	1.5	54.5	28.1	12.3	1.6	1.5
Getic Plateau	13,824	2.4	5.1	7.2	47.6	37.2	0.2	0.0	0.3
Moldavian Plateau	22,955	3.1	1.5	33.9	54.2	5.7	0.3	0.0	1.3
Western Plain	16,195	4.2	5.7	3.9	42.1	42.2	0.1	0.0	1.8
Romanian Plain	48,968	3.3	4.6	13.4	55	18.6	0.2	0.2	4.7
Dobrogea Plateau	10,160	0.5	0.3	4.5	58.1	31.9	1.3	0.3	3.1
Danube Delta	4470	1.2	12.5	16.2	5.9	3	0.1	0.1	61
Total	238,380	2.3	2.5	13.7	40.4	34	3.9	0.5	2.7

* no data include water bodies and marshes

Moreover, 34% of the territory is suitable for both quality white wines and red table wines, having a ranking score of 8 (Table 3). The potential for quality red wines from the soil viewpoint is present on 4.5% of the territory (10,727 km^2).

The distribution of soil suitability according to the major landform units of Romania (Table 3) shows that the highest potential of soils for red wine varieties (ranking scores of 8, 9 and 10) is present in the Carpathians (72.3%, 47,930 km^2) and Western Hills (67.7%, 8695 km^2) areas. As in the case of relief suitability, we have to stress that this potential is significantly downgraded by climate restrictions in the mountain area. The soil potential for white wine varieties (ranking scores of 5, 6 and 7) is present within the Moldavian Plateau (89.5%, 20,550 km^2), Transylvanian Depression (85.3%, 21,571 km^2) and Romanian Plain (73%, 35,729 km^2). We also notice that 2.3% (5566 km^2) of the country is restrictive for grapevine growing due to the high clay content of soils (> 40%).

3.3 Climate suitability for the 1961–1990 and 1991–2013 time periods

The climate of the 1961–1990 period, unaffected by climate change, is considered representative to the one which determined, over the centuries, the specificity of the Romanian viticulture. It began to change significantly in the 1990s with the first manifestations of climate change on the Romanian territory, represented mainly by rising temperatures (Dumitrescu et al. 2015; Prăvălie et al. 2017; Irimia et al. 2018a, b, c). Figure 6 shows that the most important temperature change happened during the growing season. Thus, the temperature increase of the warmest month (July) has led to the expansion of high suitability areas (having a rank score of 10) from south to north, on about 23% of the Romanian territory, especially in the Western Plain, Western Hills and the Moldavian Plateau. The sum of effective temperatures during the growing season is also characterized by a significant expansion of the high suitability areas towards north (on about 23% of the country), from southern Romanian Plain, during 1961–1990 period, to the entire Romanian Plain, southern part of the Western plain and southern and eastern part of the Moldavian Plateau. The average annual temperatures show less spatial variation between the two time periods. However, it can be noticed the increase in suitability for vine in the central and southern part of the Moldavian Plateau (from low to moderate and from moderate to high suitability) and in the northern part of the Western Plain and Hills (from moderate to high suitability).

From the viewpoint of radiation factors, the most important changes between the two time periods occur in the case of sunshine duration (Fig. 7). The suitability of this factor has significantly increased. During the 1961–1990 period, 23% of the Romanian territory was restrictive for vine growing, while in the more recent period these restrictive areas have diminished to 12%. The most important dynamics is related to the expansion of the high suitability areas from only 4%, during 1961–1990 period, to 28%, during 1991–2013 period. The actual global solar radiation shows little spatial dynamics between the two periods, being highly suitable for most of the Romanian territory, more than 80% having a ranking score of 10.

The spatial dynamics of growing season precipitations between the two time periods is reduced (Fig. 8). There are, however, some important changes: the expansion of the low suitability area in the northern Moldavian Plateau and central Transylvanian Depression, as a consequence of precipitation increase, the restrictive areas replacing high suitability areas; and the expansion of the high suitability area in the western Dobrogea Plateau, by replacing moderate suitability areas.

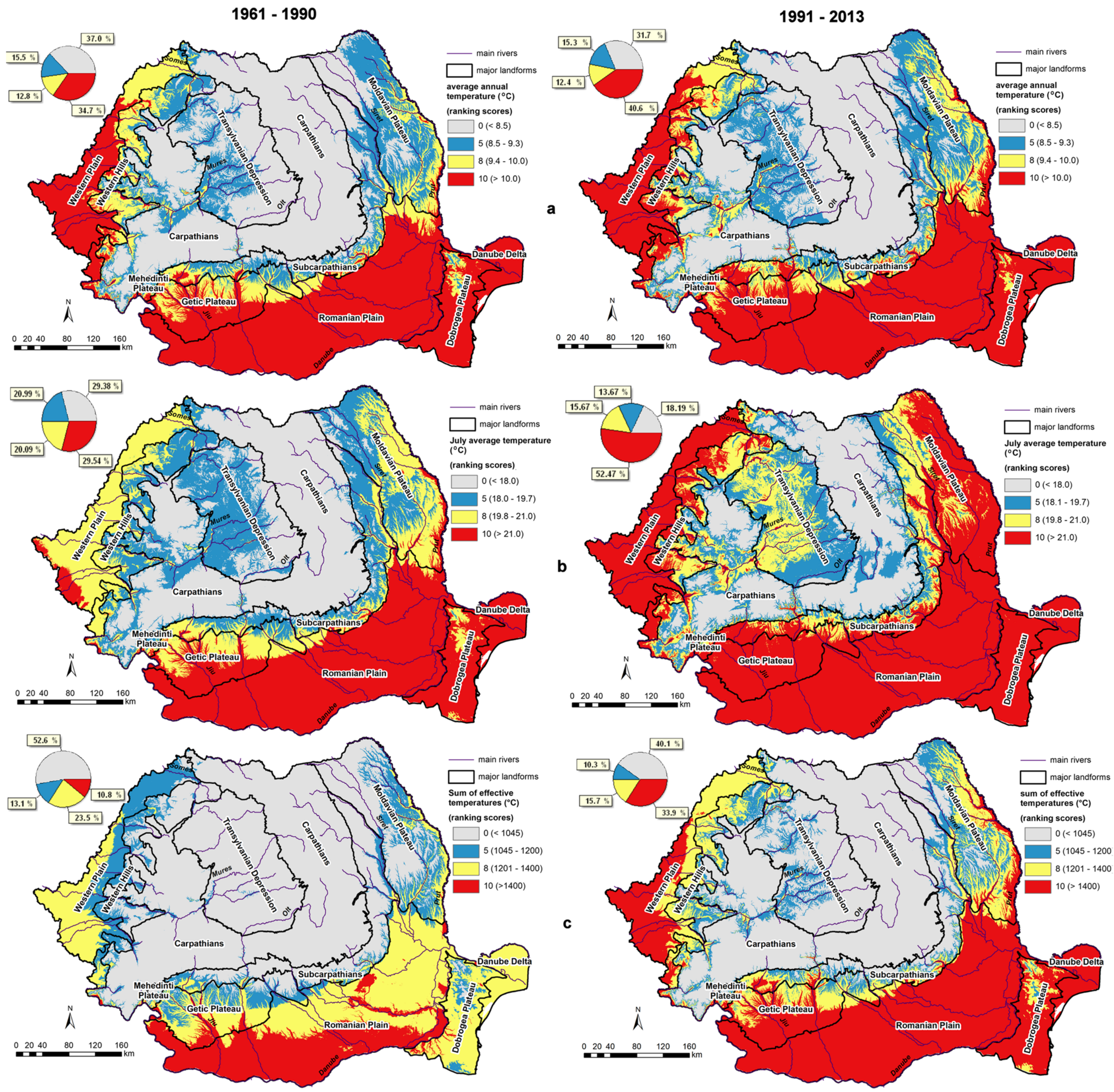

Fig. 6 Suitability of temperature factors for wine grape growing during 1961 – 1990 and 1991 – 2013 time periods: a – average annual temperatures; b – average July temperatures; c – sum of effective temperatures

The spatial distribution and dynamics of bioclimatic indices reflect the joint effect of temperature, sunshine duration and precipitations (Fig. 9). We may notice that the general evolution pattern is towards reduction of areas restrictive to vine growing, expansion of the high suitability areas from south to north and from lower to higher altitudes. This pattern has been previously reported at country level by Irimia et al. (2018a) and local level by Irimia et al. (2018b, 2018c). Among the bioclimatic indices, the greatest changes were identified for the heliothermal index, in which case the areas restrictive for vine withdrew on 12% of the country from lower to higher altitudes, while the high suitability areas expanded from south to north on 25% of the Romanian territory.

The integration of the nine climate factors led to the computation of climate suitability for wine grape growing for the two time periods (Fig. 10). Overall, as an effect of climate warming, the upper altitude limit for vine cultivation has increased, leading to a diminution of the areas restrictive for vine growing in Romania, from 45.7% (108,551 km^2)

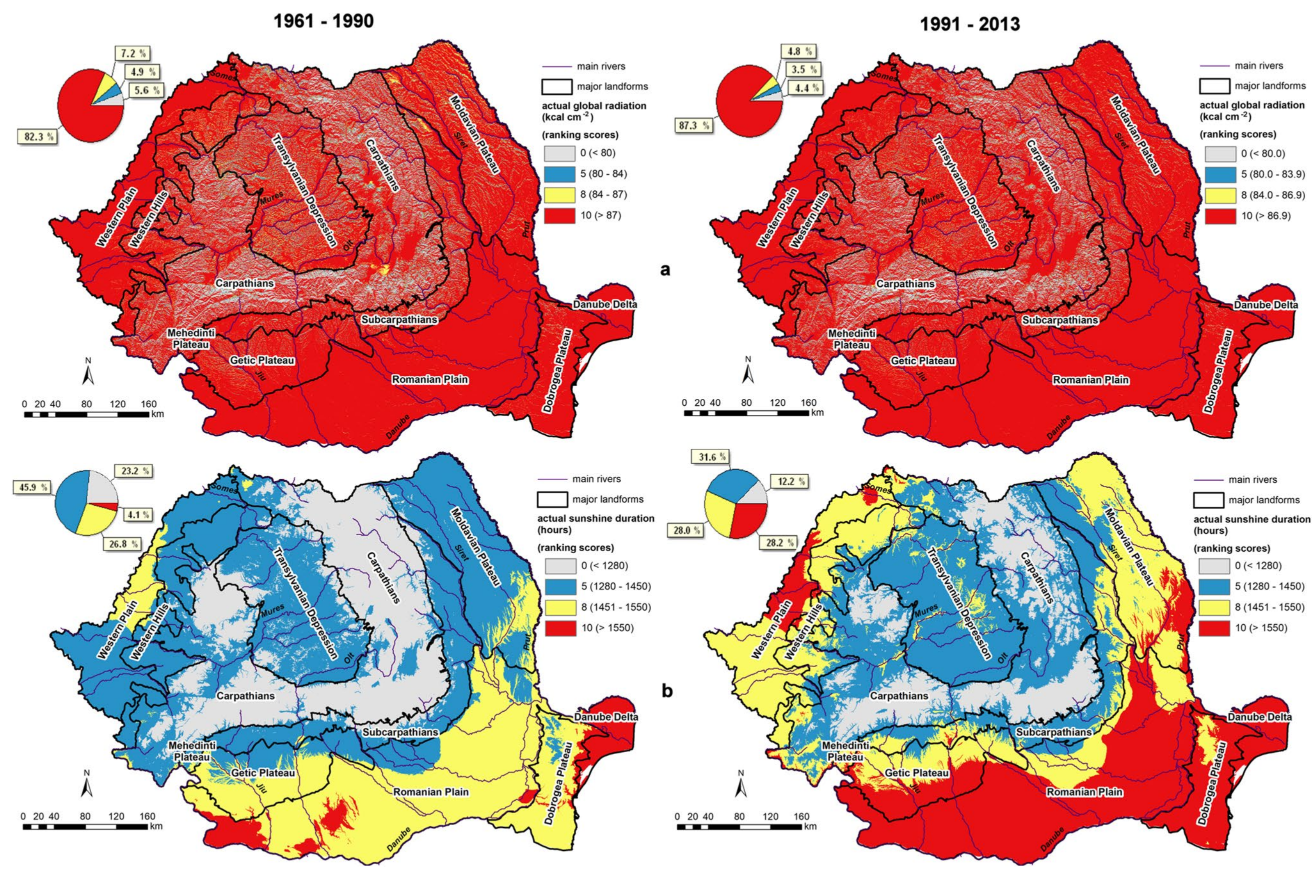

Fig. 7 Suitability of solar radiation factors for wine grape growing during 1961 – 1990 and 1991 – 2013 time periods: a – actual global radiation; b – average sunshine duration

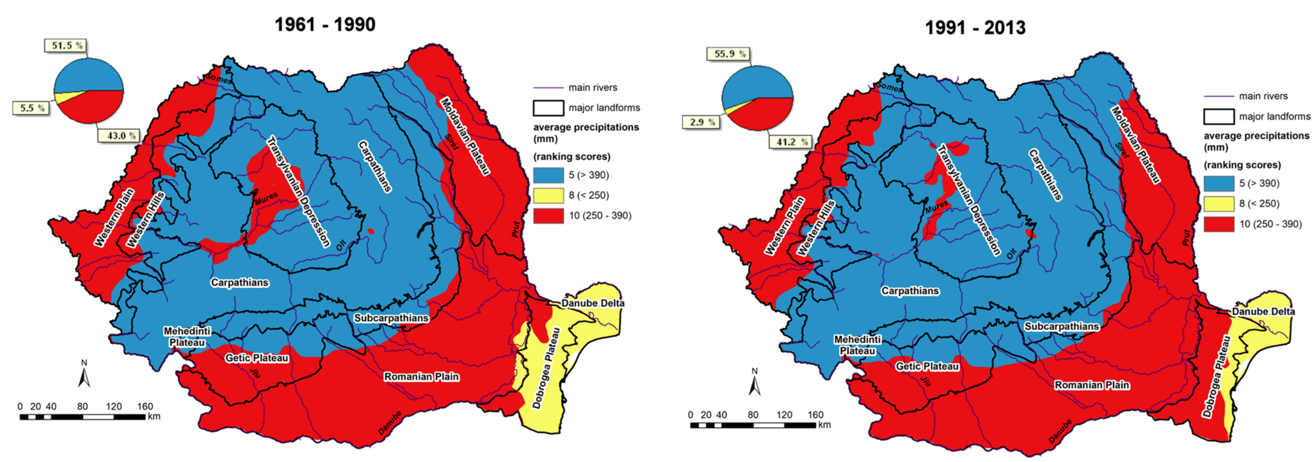

Fig. 8 Suitability of growing season precipitations for wine grape growing during 1961 – 1990 and 1991 – 2013 time periods

during 1961–1990 period to 34.8% (82,567 km^2) during 1991–2013 period. The suitability for white wine varieties, resulting from the cumulated shares of 5, 6 and 7 ranking scores, has decreased from 18% (1961–1990) to 14.3% (1991–2013). On the other hand, the potential for quality red wines (ranking score 10) has significantly increased, from 8.9% (21,217 km^2) to 30.8% (73,385 km^2) between the two time periods. The decrease of the share of ranking score 9 is due to the area increase of ranking score 10, which expanded and replaced most of the regions associated with rank 9 (Fig. 10). As a general feature, climate suitability for white wines has migrated towards north and to higher

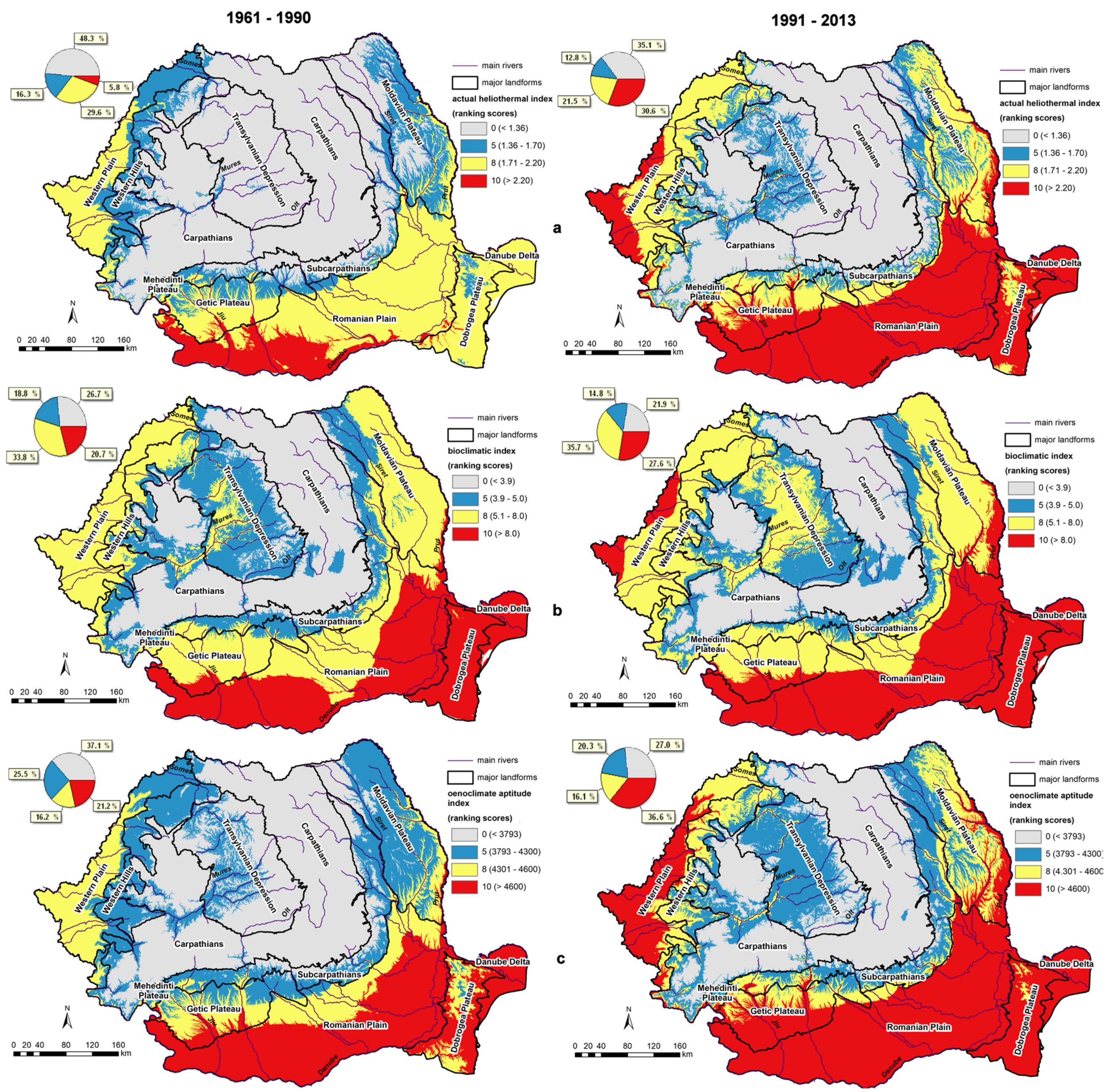

Fig. 9 Suitability of bioclimatic indices for wine grape growing during 1961 – 1990 and 1991 – 2013 time periods: a – actual heliothermal index; b – bioclimatic index; c – oenoclimate aptitude index

altitudes, being replaced by climate suitability for red wines at lower altitudes. This finding is in agreement with previous results (Irimia et al. 2018a).

Regarding the major landform units, we notice that significant areas from the hilly and plateau regions, especially in Mehedinți Plateau (40.1% of its territory), Subcarpathians (31.6%), Western Hills (28.8%) and Transylvanian Depression (28.0%), have become suitable for vine growing during the more recent time period (Tables 4 and 5). The most important changes in the structure of climate suitability for wine varieties have occurred in the Romanian Plain where 53.3% (26,099 km^2) of its area changed from a rank score of 9, during 1961–1990 period, to a rank score of 10, during 1991–2013 period. This change happened also in the Dobrogea Plateau and the Danube Delta, on 89.3% (8665 km^2) and 99.9% (4469 km^2) of their areas, respectively. In the Western Hills and the Moldavian Plateau, the dynamics of ecological potential for vine growing is characterized by the replacement of areas suitable for white wine production (1961–1990) by areas suitable for red table wines and quality red wines (1991–2013),

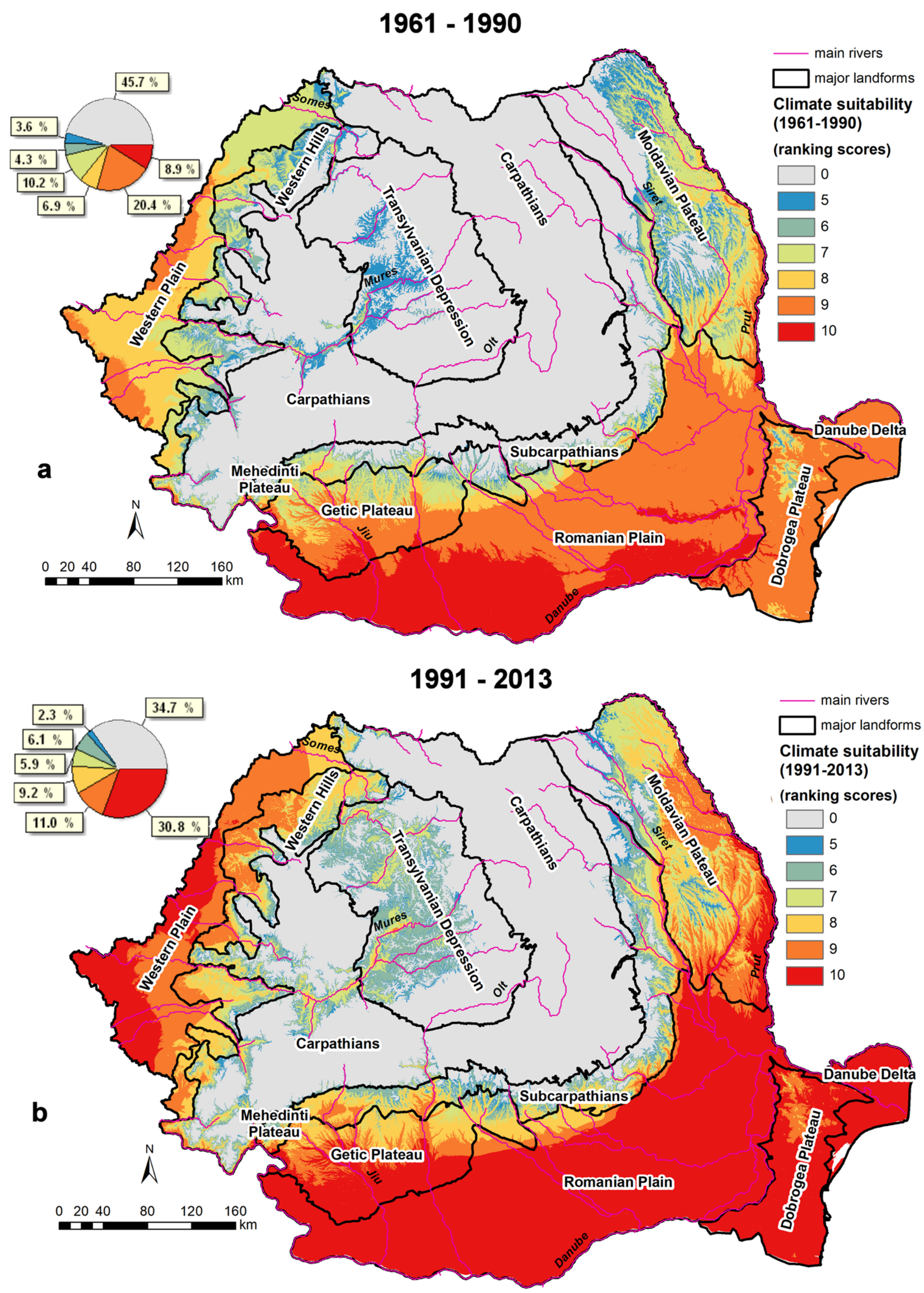

Fig. 10 Climate suitability for vine growing during 1961–1990 (a) and 1991–2013 (b) time periods

especially in the northern parts of these landform units. The Transylvanian Depression has lower dynamics, characterized by an expansion of areas suitable for white table wines, sparkling wines and wines for distillates and secondary for quality white wines (ranking score of 6) on 22,4% of its territory (5670 km^2).

3.4 Ecological potential for vine growing for the 1961–1990 and 1991–2013 time periods

The *ecological potential* for wine grape growing in Romania, as it results from the integration of the relief, soil and climate suitability, has changed between the two time

Table 4 Percentages of climate suitability ranking scores for the major landform units and the entire Romanian territory during 1961–1990 period

Landform unit	Area (km^2)	Suitability ranking scores (%)						
		0	5	6	7	8	9	10
Carpathians	66,286	95.2	1.6	1.7	1.0	0.3	0.2	0.0
Subcarpathians	16,589	63.0	4.2	8.5	18.0	5.4	0.9	0.0
Transylvanian Depression	25,297	87.9	10.3	1.1	0.7	0.0	0.0	0.0
Western Hills	12,834	35.0	10.0	18.0	32.2	4.8	0.0	0.0
Mehedinti Plateau	802	54.2	4.3	9.4	14.9	9.6	7.4	0.3
Getic Plateau	13,824	7.8	2.1	6.4	23.1	15.2	37.5	7.9
Moldavian Plateau	22,955	29.1	10.7	14.8	30.4	10.2	4.6	0.2
Western Plain	16,195	0.1	1.1	2.3	29.2	47.0	20.3	0.0
Romanian Plain	48,968	0.0	0.0	0.2	2.1	3.5	53.8	40.4
Dobrogea Plateau	10,160	0.1	0.3	1.7	3.1	9.0	82.2	3.6
Danube Delta	4470	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Total	238,380	45.7	3.6	4.3	10.2	6.9	20.4	8.9

Table 5 Percentages of climate suitability ranking scores for the major landform units and the entire Romanian territory during 1991—2013 period

Landform unit	Area (km^2)	Suitability ranking scores (%)						
		0	5	6	7	8	9	10
Carpathians	66,286	88.0	1.9	3.7	3.5	2.3	0.6	0.0
Subcarpathians	16,589	31.4	6.9	17.9	13.7	20.7	9.1	0.3
Transylvanian Depression	25,297	59.9	6.7	23.5	8.2	1.6	0.1	0.0
Western Hills	12,834	6.2	2.5	9.3	18.8	35	28.2	0.0
Mehedinti Plateau	802	14.0	7.4	19	21.8	18.4	13.0	6.4
Getic Plateau	13,824	0.7	1.0	2.6	4.5	26.4	22.3	42.5
Moldavian Plateau	22,955	12.6	3.8	5.7	17.3	23.1	28.7	8.8
Western Plain	16,195	0.0	0.0	0.0	0.1	11.3	48.9	39.7
Romanian Plain	48,968	0.0	0.0	0.0	0.1	2.1	4.1	93.7
Dobrogea Plateau	10,160	0.0	0.0	0.0	0.1	0.8	10.2	88.9
Danube Delta	4470	0.0	0.0	0.0	0.0	0.0	0.0	100
Total	238,380	34.7	2.3	6.1	5.9	9.2	11	30.8

periods mainly due to climate warming (Fig. 11). The restrictive areas for vine growing have decreased from 46.9% (1961–1990) to 36.4% (1991–2013), mainly by the migration of vine restrictive limit towards higher elevations. The potential for white wine varieties has decreased, the cumulated shares of ranking scores 5, 6 and 7 being 45.4% in 1961–1990 (Table 6) and 38.2% in 1991–2013 (Table 7). It is to be noted that these areas have migrated to higher elevations and also expanded in the Transylvanian Depression. The potential for red wine varieties (ranking scores 8, 9 and 10) has increased from 4.8% (1961–1990) to 22.6% (1991–2013) and that of quality red wines (ranking scores 9 and 10) from 0.28% to 2.52%, which represents an area of about 6013 km^2. Figure 11 shows that the potential for red wines has expanded towards North and at higher altitudes in the Moldavian Plateau, Western Hills, Getic Plateau and Dobrogea Plateau.

Significant areas have become suitable for vine growing due to climate warming, especially in the Transylvanian Depression (6770 km^2, 26.7%), Subcarpathians (5180 km^2, 31.2%,), Moldavian Plateau (3716 km^2, 16.2%), Western Hills (3563 km^2, 27.7%). Also, in the lower Carpathians, 4642 km^2 (7%) have turned from restrictive to suitable for vine growing. The potential for white table wines, sparkling wines and wines for distillates (ranking scores 5 and 6) has generally decreased throughout the landform units. However, the potential for quality white wines (ranking score 7) has increased, excepting the Getic Plateau, the Dobrogea Plateau and the Romanian Plain. The largest such expansion is noted for the Western Plain, where 5195 km^2 (32.0% of its area) has become suitable for quality white wines. Important expansions of quality white wine potential are also found in the Transylvanian Depression (4659 km^2, 18.4%) and the Subcarpathians (3274 km^2, 19.7%). The potential for red wine production (ranking scores 8, 9 and 10) has increased in all landform units. The most significant such expansion is noted for the Romanian Plain, where 11,393 km^2 (23.2%) have become suitable for the production of red

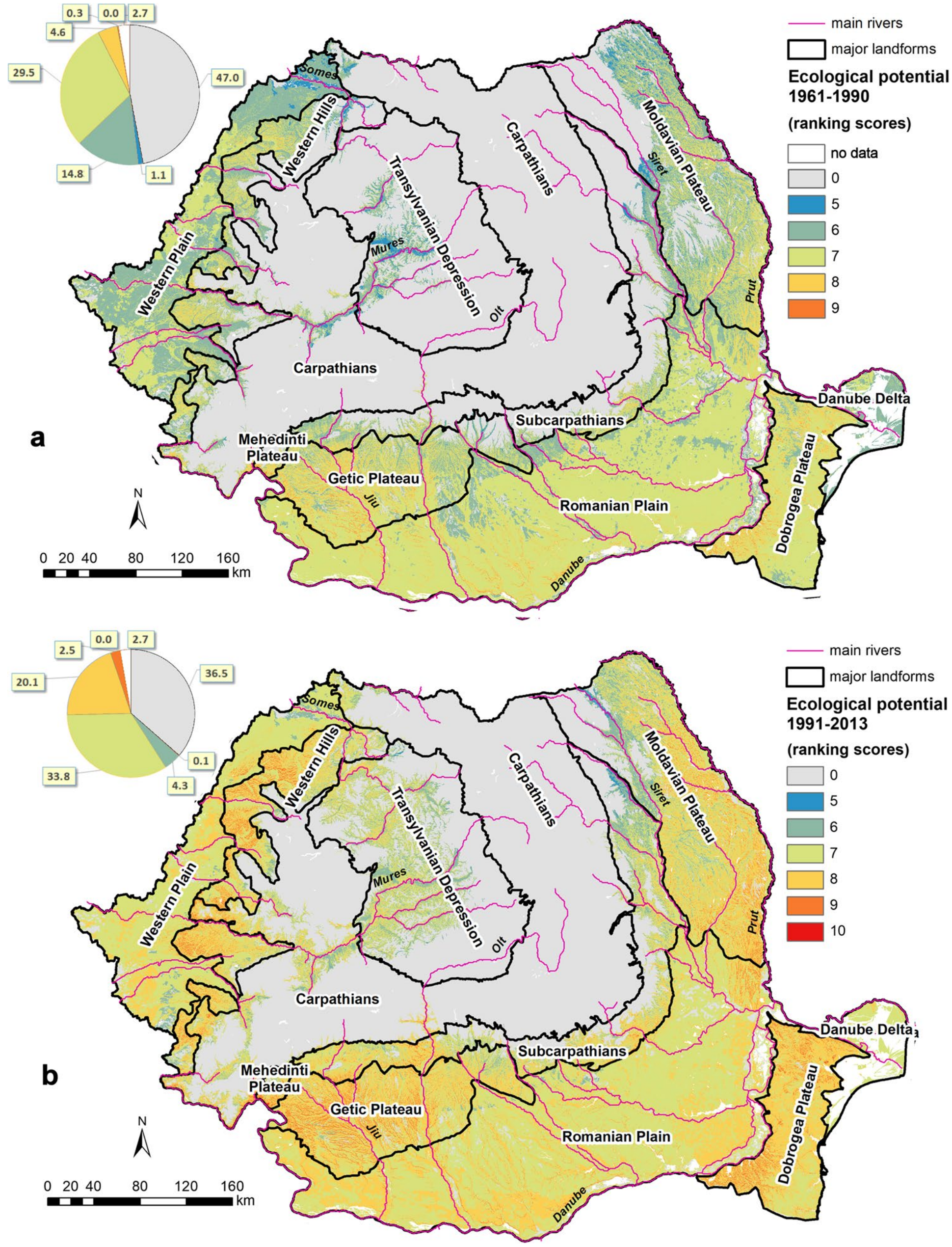

Fig. 11 Ecological potential for wine grape growing in Romania during 1961–1990 (a) and 1991–2013 (b) time periods

wines in the recent period (1991–2013), which replaced the previously suitable areas (1961–1990) for the production of white wines. Important expansions of the ecological potential for red wine production are noticed also in the Moldavian Plateau (6508 km^2, 28.3%), Getic Plateau (5034 km^2, 36.4%), Dobrogea Plateau (4692 km^2, 46.2%) and Western Hills (4562 km^2, 35.5%). The most significant expansions of the ecological potential for quality red wine production are found in the Getic Plateau and the Western Hills, where 1336 km^2 (9.67%) and 1098 km^2 (8.56%), respectively, have become suitable for quality red wines in the more recent period (1991–2013) compared to the reference period (1961–1990).

3.5 Shifts in ecological potential for vine growing between 1961–1990 and 1991–2013 time periods

A comparative analysis of the ecological potential for viticulture derived for the two time periods (1961–1990 and 1991–2013) shows that there are significant areas (25,245 km^2, 10.6% of the country) which became suitable for wine grape growing in the Subcarpathians, at the mountain area periphery, in the Transylvanian Depression, Moldavian Plateau and Western Hills (Fig. 12). Most of these shifts are from restrictive to 7 and 6 suitability scores,

Table 6 Percentages of ranking scores of ecological viticultural potential for the major landform units and the entire Romanian territory during 1961–1990 period

Landform unit	Area (km^2)	Suitability ranking scores (%)							No data*
		0	5	6	7	8	9	10	
Carpathians	66,286	95.0	0.3	1.8	1.8	0.6	0.0	0.0	0.5
Subcarpathians	16,589	63.8	1.3	16.9	14.3	3.4	0.0	0.0	0.3
Transylvanian Depression	25,297	88.1	2.9	6.0	2.9	0.0	0.0	0.0	0.1
Western Hills	12,834	36.1	1.3	28.9	24.9	8.5	0.0	0.0	0.3
Mehedinti Plateau	802	53.3	0.1	7.1	20.3	15.6	2.1	0.0	1.5
Getic Plateau	13,824	10.1	0.7	17.8	50.5	19.0	1.6	0.0	0.3
Moldavian Plateau	22,955	31.6	4.0	31.2	26.8	5.1	0.0	0.0	1.3
Western Plain	16,195	4.3	2.0	53.5	37.2	1.2	0.0	0.0	1.8
Romanian Plain	48,968	3.3	0.0	12.1	73.7	5.7	0.5	0.0	4.7
Dobrogea Plateau	10,160	0.6	0.1	6.0	69.3	19.1	1.7	0.0	3.2
Danube Delta	4470	1.2	0.0	26.9	10.2	0.6	0.0	0.0	61.1
Total	238,380	47.0	1.1	14.8	29.5	4.6	0.3	0.0	2.7

* no data include water bodies and marshes

Table 7 Percentages of ranking scores of ecological viticultural potential for the major landform units and the entire Romanian territory during 1991–2013 period

Landform unit	Area (km^2)	Suitability ranking scores (%)							No data*
		0	5	6	7	8	9	10	
Carpathians	66,286	88.0	0.0	1.6	5.7	3.7	0.5	0.0	0.5
Subcarpathians	16,589	32.6	0.8	11.1	34.0	19.6	1.6	0.0	0.3
Transylvanian Depression	25,297	61.4	0.2	12.2	21.3	4.8	0.0	0.0	0.1
Western Hills	12,834	8.4	0.0	5.1	42.1	35.5	8.6	0.0	0.3
Mehedinti Plateau	802	13.9	0.0	6.8	30.0	36.7	10.4	0.7	1.5
Getic Plateau	13,824	3.1	0.0	2.6	37.0	45.7	11.3	0.0	0.3
Moldavian Plateau	22,955	15.4	0.6	10.8	38.4	29.7	3.8	0.0	1.3
Western Plain	16,195	4.2	0.0	3.6	69.1	20.4	0.9	0.0	1.8
Romanian Plain	48,968	3.3	0.0	0.4	62.1	28.1	1.4	0.0	4.7
Dobrogea Plateau	10,160	0.5	0.0	0.0	29.4	57.2	9.6	0.1	3.2
Danube Delta	4470	1.2	0.0	0.0	33.1	4.3	0.2	0.0	61.2
Total	238,380	36.5	0.1	4.3	33.8	20.1	2.5	0.0	2.7

* no data include water bodies and marshes

indicating that these areas became suitable for white wines, including quality white wines.

Moreover, there is an increase in suitability for about one third of the country (76,833 km^2, 32.2%) especially in the plateau areas (Moldavian, Getic, Dobrogea Plateaus), as well as in the Western Plain and Hills by improving the pre-existing viticultural potential. This improvement is characterized by shifts mostly from 7 to 8 and from 6 to 7 of the suitability scores, indicating that areas previously suitable for quality white wines have gained characteristics favourable also for red table wine production, while areas suitable for white table wines, sparkling wines and wines for distillates have gained suitability for quality white wines.

These transitions are consequences of climate warming which have caused the shift of the climate suitability limits towards higher elevations and higher latitudes. On average, our study reveals that the upper limit for white wine production (5, 6 and 7 suitability scores) has shifted from about 612 m a.s.l. during the 1961–1990 period to about 860 m a.s.l. during the 1991–2013 period.

For more than half of the territory, there is no change in suitability (129,799 km^2, 54.4%) between the two periods. These areas are mainly found in the Carpathians, where terrain remans mostly restrictive for vine cultivation, as well as in the western and southern Transylvanian Depression and the Romanian Plain. Areas where suitability has decreased are negligible (0.02% of the country).

4 Discussions

The impact of climate change on European viticulture is widely studied in recent decades, due to the economic importance that this sector has for many countries, including

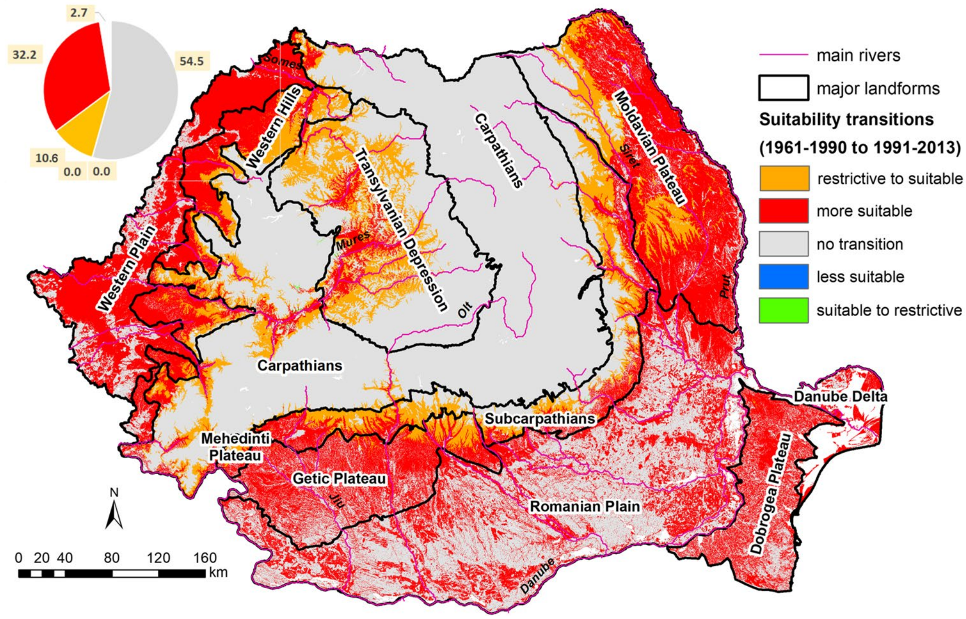

Fig. 12 Shifts in ecological suitability for wine grape vine between 1961–1990 and 1991–2013

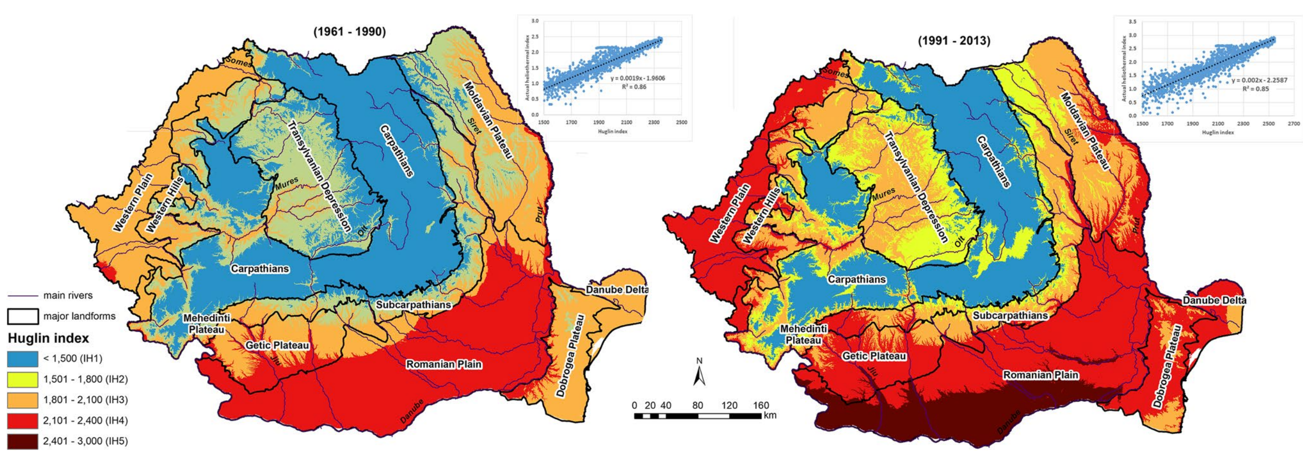

Fig. 13 Huglin index maps for 1961–1990 and 1991–2013 time periods

Romania. Climate change massively influences the viticultural potential of geographical areas, this conclusion also emerging from the results of our study, which shows both the significant increase of the suitable area for vine cultivation in Romania within the 1961 – 2013 period and the improvement of the current ecological potential for wine grape growing.

For a correct and full representation of the viticultural potential, our study used a GIS-based methodology that takes into account all three categories of ecological factors from the vineyard area: soil, relief and climate. The methodology reveals the viticultural potential of any area by relating the suitability of its specific ecological factors for the wine production, to the suitability of the ecological factors that generated vineyards grapevine varieties assortments and the specific types of wine production of the Romanian wine regions (Irimia et al. 2014). In order to increase the accuracy of the assessment of climate suitability, the methodology also includes some bioclimatic indices that integrate the influence of several factors, such as temperature, sunshine duration and precipitation. These bioclimatic indices (actual heliothermal, bioclimatic and oenoclimate aptitude indices) were developed through long-term research of climate influence on grape varieties in Romania (Constantinescu 1967; Teodorescu et al. 1987; Oşlobeanu et al. 1991). Their use, in the context of our study, is more appropriate than the established widely used international indices such as Huglin (1978), composite index (Malheiro et al. 2010) or dryness index (Riou 1994), because they were validated for the climate conditions of Romania and also because they are highly relevant for the fine-scale evaluation of the vineyard climate (Irimia et al. 2013a). They are also valid outside Romania, in any region with similar climate characteristics (Sirnik et al. 2019). In order to allow a comparison, we computed the Huglin index for the two time periods, we analysed and correlated the values showing climate suitability for grapevine (HI > 1500) with the actual heliothermal index values (Fig. 13). The correlations are strong ($R^2 = 0.85 - 0.86$) proving the capability of the actual heliothermal index to correctly assess the quality of the temperature resources. However, it should be noted that while Huglin is a heat summation index intended for regional assessments in relation to geographical latitude, some indices used in our methodology, such as the *oenoclimate aptitude index*, reveal the combined influence of temperature, precipitation and insolation on the spatial variation of the viticultural potential even at the fine scale of the vineyard. The relevance of the oenoclimate aptitude index compared to the Huglin index has been shown in previous studies (Irimia et al. 2013a).

Our findings are in agreement with other similar studies carried out both worldwide (Jones et al. 2005; Hannah et al. 2013; Moriondo et al. 2013) and within the European continent. In central and western Europe, projected climate changes may lead to improvement of wine quality and to identification of new potential areas suitable for viticulture (Malheiro et al. 2010; Cardell et al. 2019). Vigl et al. (2018), studying a mountainous region of the Central Alps, found that the increasing temperatures induced by climate change create new opportunities for wine grape cultivation, at higher elevations, in areas that were previously unsuitable. For Germany, one of the most northern wine-producing countries, Neumann and Matzarakis (2014) estimate that the effects of climate change may be either positive or negative, depending on the local conditions and the measures adopted by the viticulturalists. Flat terrains, which are easier to work and therefore more cost-effective, may become suitable for vine growing, but traditional German wines may lose their typicity because of changes in organoleptic properties. In Hungary, Mesterházy et al. (2014) show that the red wine grapes are likely to spread and dominate in the next few decades, replacing the white wine grapes. Kovacs et al. (2017) found positive effects of climate change for vine suitability in the western part of the country, which became warmer and therefore more suitable for a wider range, more quality grape varieties. Similar findings are reported by in Poland, where the area suitable for vine growing is likely to increase as an effect of climate warming (Maciejczak and Mikiciuk 2019). For the region of Upper Austria, Eitzinger et al. (2009) estimate that the potential growing areas for wine grapes is likely to double by the end of the century. In the UK, Nesbitt et al. (2016) relate the rapid growth of the viticultural sector in the twenty-first century to climate warming, as new areas of England and Wales have become suitable for cool climate viticulture. However, they suggest that the increasing inter-annual variability of climate factors may continue to threaten productivity.

Southern Europe is likely to experience a decline of viticulture sector because of thermal stress and dryness increase (Lereboullet et al. 2014; Lazoglou et al. 2018; Cardell et al. 2019). In Portugal, Fraga et al. (2016a, 2017) found a generalized warming and drying trend of the grapevine growing season, which affects vine phenology, suggesting that a reshape of the optimal environments for viticulture is needed throughout the country. Climate change projections show wine quality is likely to be negatively affected in central and southern Spain, while positive effects may occur in the north-western part of the country (Lorenzo et al. 2016). Lazoglou et al. (2018) found that the impact of climate change in Greece is negative in the islands and coastal regions and positive in mountain areas. In Italy, Teslić et al. (2019) found different effects of climate change in the Emilia-Romagna region, according to the representative concentration pathways (RCP) scenario.

For the Romanian territory, the climate predictions made so far (Malheiro et al. 2010; Hannah et al. 2013; Moriondo et al. 2013) reveal for the next decades an increase of the existing viticultural potential, but also the increase of seasonal drought and thermal stress frequency, which will impact the annual quality of wine grape production. The 2019 study on the Cotnari wine region (Irimia et al. 2019), an area with a cool climate, located at 47° north latitude, towards the northern limit of vine cultivation, reveals that by 2070 the viticultural potential for white wines of this area will be completely replaced by the potential for red wines, and after 2070, the viticultural potential will gradually disappear due to rising temperatures and aridity.

In order to ensure the resilience of traditional vineyards, adaptations may include changing the vine material with a more drought resistant one, changing the viticultural techniques, the pest and disease control measures, application of irrigation or selection of soils with higher water holding capacity (Keller 2010; van Leeuwen et al. 2019; Santos et al. 2020). Under severe climate warming conditions, vineyard relocation to cooler sites (at higher elevations, latitudes, on north-facing slopes or coastal zones) may be a long-term adaptation measure (Santos et al. 2020).

In Romania, the generalized warming trend is ongoing and it was demonstrated by our previous research based only on climate factors (Irimia et al. 2018a). Between 1960 and 2013, the area with suitable climate for viticulture has grown with about 2.4 million hectares, by expanding towards north with 0.036° and to higher elevations with 180 m. To increase the accuracy of determinations compared to previous studies (Irimia et al. 2018a), this study uses a more complex methodology, integrating also the relief and soil influences on the ecological viticulture potential. The methodology was previously used for fine (farm)-scale assessments of viticultural potential (Irimia et al. 2013b, 2014, 2018c), having common elements with both methodologies used for identification of new suitable areas for vine in recent viticultural countries (Olsen et al. 2011; Anderson et al. 2012) and methodologies used for viticultural potential zoning in traditional wine-growing areas (Herrera Nuñez et al. 2011; Tomasi et al. 2013). Regarding the study area, the present research includes the mountain area, which is mostly unsuitable for wine grape growing (95% in 1961–1990 and 88% in 1991–2013), in order to identify the areas which have gained ecological suitability during the last decades. Our previous study (Irimia et al. 2018a) revealed the extension of climate suitability for viticulture up to about 800 m as an effect of climate change.

Our results indicate that the Romanian viticulture potential is, on the one hand, maintained in traditional areas, and on the other hand, it is extending outside traditional areas and changing structure compared to 1961–1990 reference period. The spatial distribution shows that the most favourable regions for viticulture in Romania are still the hilly regions from the mountain area periphery. In the context of climate change, their viticultural potential is enhanced because of the favourable influences that this landform type and its specific soils exert on wine quality.

The research also reveals a higher suitability of soil and relief in the mountain area, which is mostly cancelled by the unsuitable climate. However, the comparative analysis of the viticultural potential for the two time periods reveals its extension towards the lower mountain area, especially along the main river valleys. Future studies will demonstrate whether this suitability can indeed be exploited, because on lower river valleys, especially in the mountain area, the temperatures may drop below the frost resistance limit of vine (-20 to -24 °C) during winter and also may drop during spring when frosts can damage vine shoots. Being conceived for viticultural potential assessment in traditional winemaking areas, where such limitations are generally missing, our study does not quantify the impact of frosts, which may diminish the viticultural potential achieved due to climate change. Therefore, further studies may be necessary to analyse the degree exposure to frosts in these areas, including the grape varieties which could be cultivated.

5 Conclusions

Our research, based on relief, soil and climate characteristics, has produced the map of the viticultural ecological potential in Romania, providing essential information on its transformations due to climate change during the last decades. Relief and soils of Romania are suitable for wine grape growing especially in the hilly and plateau areas. The relief is mostly suited for white wine varieties, 70% of the country presenting ranking scores of 5, 6 and 7. Although the mountain area displays high suitability, most of it is cancelled by the restrictive climate of this landform unit. The soils of Romania are also mostly suitable for white wine varieties, 74% of the country being assigned ranking scores of 7 and 8, specific for quality white wines and secondary for red table wines. The climate is suitable for viticulture especially in the lower elevation regions (plains, hills and plateaus) and its suitability has significantly grown during the last decades. The potential for quality red wines (ranking score of 10) has increased significantly, from 8.9% (21,217 km^2) to 30.8% (73,385 km^2) between the 1961–1990 and 1991–2013 periods. Overall, the integrated ecological potential for wine grape growing has undergone significant changes in Romania. The restrictive areas for vine growing have decreased from 46.9% (1961–1990) to 36.4% (1991–2013), mainly by the migration of vine restrictive limit towards higher elevations. The potential for white wine varieties has decreased from 45.4% (1961–1990) to 38.2% (1991–2013) and has migrated to higher elevations, while the potential for red wine varieties has increased from 4.8% (1961–1990) to 22.6% (1991–2013), by the expansion of suitable areas towards North and to higher elevations in the hilly and plateau areas. Important new areas of the country have become suitable for viticulture as an effect of climate change. Shifts from restrictive to 7 and 6 suitability scores (suitability for white wines) occurred in the Subcarpathians, at the mountain area periphery, in the Transylvanian Depression, Moldavian Plateau and Western Hills, cumulating 10.6% of the country. Moreover, part of the existing suitable areas for white wine production has gained suitability also for red wine production. This explains why several wine regions, traditionally focused on white wine production, such as Cotnari or Averesti (from the Moldavian Plateau) have recently introduced successfully red wine varieties. Our study supports previous assessments on climate suitability (Irimia et al. 2018a, 2018b, 2018c), revealing shifts of suitability zones towards higher elevations and latitudes, which leads to qualitative changes in wine production within traditional winemaking regions. In this context, wine producers need to adapt their plant material and technologies to cope with these changes, which may affect the typicity of traditional wine regions.

A future study should focus on the new areas which gained suitability for wine grape growing in the recent period due to climate change. The analysis should narrow the identified areas by extracting forests, settlements, human infrastructure. Also, a deepening of soil influence, through integration of limiting factors like pH, soil salinity, water logging etc., may improve the evaluation at fine scale.

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Code availability Not applicable.

Declarations

Ethics approval Not applicable.

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