Impact of climate change on olive growth suitability, water requirements and yield in Montenegro

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Abstract: *This study investigated the possible impact of climate change on the olive cultivation in Montenegro in terms of growth suitability, crop phenology, water requirements and yield. The elaborations were performed in GIS through the integration of climate, soil and crop data and successive application of the agro-ecological zoning methodology and a soil-water balance model. The analysis included the baseline climate (1961-1990) and the climate data projections from the coupled regional climate model EBU-POM corresponding to the three scenarios: i) A1B (2001-2030), ii) A1B (2071-2100) and iii) A2 (2071-2100). Reference evapotranspiration was calculated using a modified Penman-Monteith approach from the air temperature data, while crop evapotranspiration and irrigation requirements were estimated following the standard FAO methodology. The results revealed that the foreseen increase of air temperature would extend the potentially cultivable areas from the present 17% of the total land surface to 30.2% in the A2 scenario. The areas suitable for olive cultivation are expected to shift northwards, and to the higher altitudes. Global warming would anticipate the flowering period of olives up to 17 days under the A2 scenario. Crop water requirements would likely increase in the future up to 3%, while the crop evapotranspiration under rainfed is foreseen to decrease from 5.5% to 21.7%. Net irrigation requirements would increase from 29.5 mm in the A1B scenario to 103.4 mm in the A2 scenario. The highest relative yield loss of 16.2±7.6% is expected under the A2 scenario which does not preclude the rainfed cultivation of olives in the future.*
Keywords: *soil water balance; agro-ecological zoning; olive tree phenology; crop evapotranspiration; irrigation requirements; rainfed cultivation, relative yield.*

Riassunto: *In questo studio è stato valutato il possibile impatto dei cambiamenti climatici sulla coltivazione dell'olivo in Montenegro in termini di idoneità alla crescita, fenologia, fabbisogni idrici e resa. Le elaborazioni sono state eseguite in ambiente GIS integrando i dati climatici, del suolo e della coltura e successivamente sono stati applicati la metodologia di zonizzazione agro-ecologica e un modello di bilancio idrico del suolo. Le analisi hanno riguardato l'analisi dei dati di riferimento (1961-1990) e le proiezioni ottenute con il modello climatico regionale accoppiato EBU-POM corrispondente ai tre scenari: i) A1B (2001-2030), ii) A1B (2071-2100) e iii) A2 (2071-2100). L'evapotraspirazione di riferimento è stata calcolata utilizzando un approccio Penman-Monteith modificato a partire dai dati di temperatura dell'aria, mentre l'evapotraspirazione e il fabbisogno irriguo delle colture sono stati stimati in base alla metodologia standard utilizzata dalla FAO. I risultati hanno rivelato che l'aumento previsto della temperatura dell'aria potrebbe estendere le aree potenzialmente coltivabili dall'attuale 17% al 30,2% nello scenario A2. Le aree adatte alla coltivazione dell'olivo dovrebbero spostarsi verso nord e ad altitudini superiori. Il riscaldamento globale anticiperebbe il periodo di fioritura dell'olivo fino a 17 giorni con lo scenario A2. I fabbisogni idrici della coltura potrebbero aumentare fino al 3%, mentre è previsto che l'evapotraspirazione in condizioni di asciutta potrebbe passare dal 5,5% al 21,7%. I fabbisogni netti di irrigazione aumenterebbero da 29,5 mm nello scenario A1B a 103,4 mm nello scenario A2. La massima perdita in resa relativa si attesterebbe al 16,2 ± 7,6% nello scenario futuro A2 che non preclude la coltivazione in asciutta dell'olivo.*
Parole chiave: *bilancio idrico del suolo; zonizzazione agro-ecologica; fenologia dell'olivo; evapotraspirazione delle colture; fabbisogno idrico; colture non irrigue, resa relativa.*

1. INTRODUCTION

The Mediterranean Basin is considered as one of the most prominent "hot-spots" due to climate change. Temperatures are expected to exceed the global average, and a marked variability in precipitation and increase in its inter-annual variability are foreseen (Giorgi and Lionello 2008). Uneven reduction of agricultural production may be expected due to shorter growing seasons, increased heat and water stress and lack of water for irrigation (Fischer *et al.*, 2007; Garofalo and Rinaldi, 2013). Many studies have reported an increase in crop water requirements in the Mediterranean region (Doll 2002; Topcu *et al.*, 2008), as well as the augment of irrigation requirements (Fischer *et al.*, 2007, Giannakopoulos *et al.*, 2009, Villani *et al.*, 2011). However, other studies have reported a decrease in net irrigation requirements due to a more favourable rainfall distribution (Lovelli *et al.*,

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2010) and expected shortening of growing season (Saadi *et al.,* 2015). Therefore, the impact and the magnitude of variation could differ, depending on the latitude, altitude, crop and soil characteristics and water availability of the territory under examination.

Montenegro is located in south-eastern Europe spreading from the central-southern part of the eastern Adriatic coast to the mountain chains of the Balkan Peninsula. The climate of Montenegro changes from a typical Mediterranean on the coast to a temperate-continental, characterized by four seasons in the inlands, and a cold mountainous climate in the northern higher zones. Therefore, the country is marked by strong variation of agro-ecological zones and other environmental factors. Similarly, the soil characteristics are heterogeneous and the soil depth varies from very shallow soils in some mountainous and coastal regions to deep soils in alluvial plains.

The olive (*Olea europaea* L.) is one of the best adapted crops in the Mediterranean region. It is the oldest subtropical crop grown on the coastline of Montenegro, covering about one-third of the total area under fruit trees (Statistical yearbook of Montenegro, 2003). Approximately 70% of olive production in the country is attributed to traditional systems, while about 10% of trees belong to young orchards. Most of olive cultivation is rainfed due to favourable precipitation pattern. However, due to climate change, the rainfed cultivation could be questioned in the future.

In general, flowering is the critical phase for olive growth; it is a sensitive indicator of inter-annual variability of temperature, and it has a potential to be used in climate change studies (Osborne *et al.*, 2000; Orlandi *et al.*, 2005, 2010). In fact, several studies, using different methodologies (Galán *et al.*, 2005; Bonofiglio *et al.*, 2008), have emphasized the temperature requirements of olive trees before the start of the flowering period in Spain and Italy. Moreover, the results of some investigations have indicated that the flowering date for olives in the western Mediterranean could become significantly earlier by the end of this century (Osborne *et al.*, 2000). Hence, there are few logical scenarios that might describe the future of olive production: a) the predicted global warming and increased temperature require the introduction of new varieties with lower chilling requirements, b) areas formerly characterized by low temperature could became suitable for olive growth due to the increase of temperature, c) the predicted changes in climate could shift olive production northwards, and to higher altitudes (Bindi and Howden, 2004; Moriondo *et al.*, 2008; Tanasijevic *et al.*, 2014).

Although the olive is resistant to water shortage, it produces best with high rainfall or with irrigation (Iniesta *et al.*, 2009; Palese *et al.*, 2010; Martinez-Cob and Faci, 2010). In the future, olive intensive cultivation could increase water demand, while the water availability is likely to be reduced (García-Ruiz *et al.*, 2011; Milano *et al.*, 2012). The impact of climate change on olive growth in the Mediterranean region has been studied recently (Moriondo et al., 2009, Tanasijevic *et al.*, 2014). However, there is an uncertainty about the temporal and spatial variation of the above-mentioned impacts at the local and national scale and in Montenegro, specifically.

This study aims to analyse the impact of climate change on olive cultivation in Montenegro by comparing a baseline climate for the period 1961-1990 with three future climate scenarios. The study focused on the possible changes in the areas suitable for olive cultivation and the anticipation of the flowering dates (due to air temperature increase), the estimation of crop evapotranspiration, net irrigation requirements and relative yield losses under rainfed growing.

2. MATERIALS AND METHODS

2.1 Study area

The climate of Montenegro changes considerably over a relatively small area (13810 km^2). The climate is mostly dominated by the proximity of the Adriatic Sea, and the physiography is characterized by deep and narrow river valleys and mountain chains, amongst which narrow relief units, basins, and Karsts plateaus are located (Fig. 1). High altitudinal gradients have strong modification impacts on local climates, which include a wide set of transitional and local sub-climate types. Hence, a number of climatic zones may be singled out when considering the impact of climate on agricultural production. The first zone comprises the Montenegrin coastal area and the Zetsko-Bjelopavlicka Plain, including the surrounding hilly areas, which are characterized, according to the Köppen criteria (Burić *et al.*, 2014), by Mediterranean climate with hot summer (Csa). This is the main zone of olive cultivation in Montenegro. The second climatic zone comprises the continental part of Montenegro (Karstic region) characterized by transitional variant of etesian climate with warm summer (Csb) and humid temperate climate with warm summer (Cfb). The third climatic zone includes the pre-mountainous and mountainous areas on North-

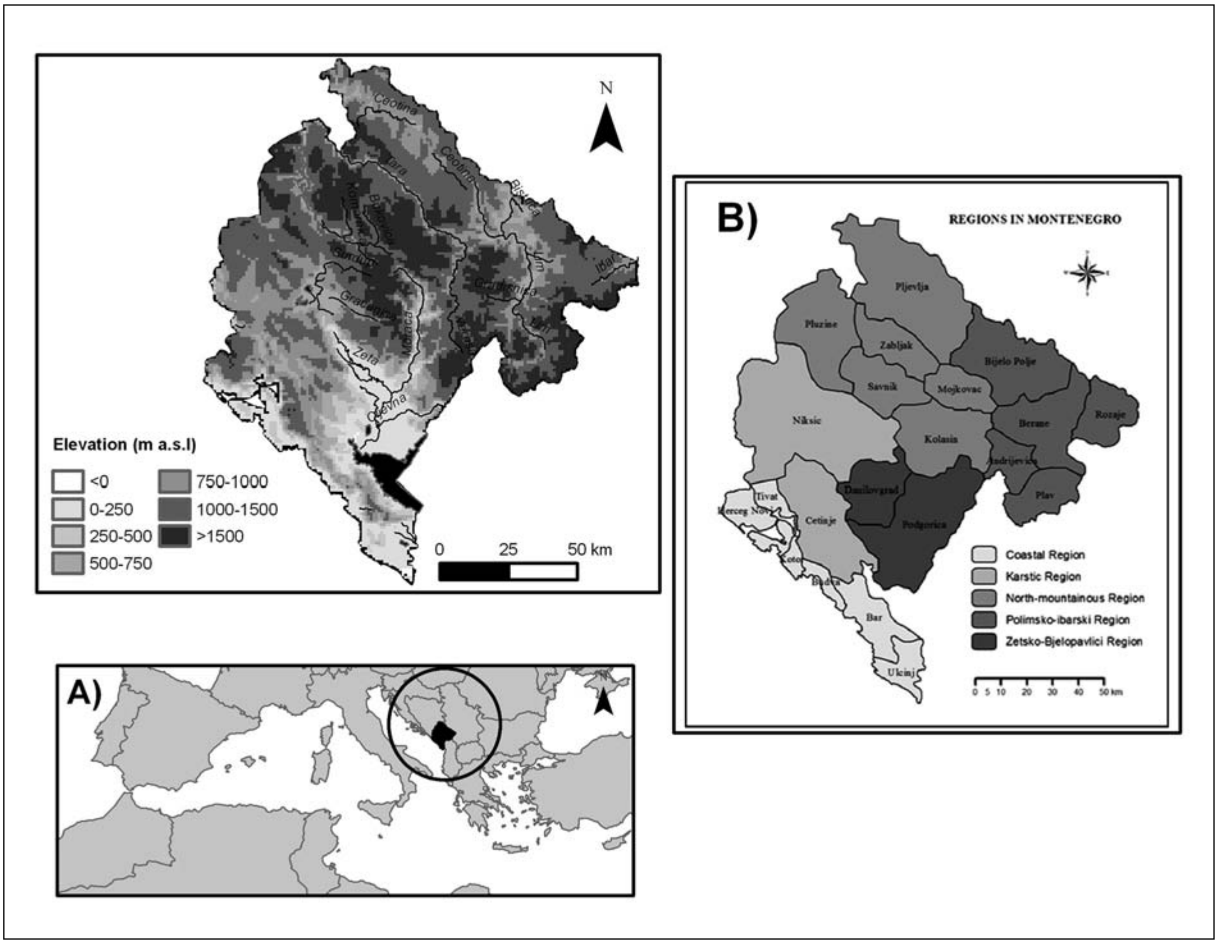

Fig. 1 - Geographic location of Montenegro (a) with the maps of elevation (b) and administrative regions (c).
Fig. 1 - Ubicazione geografica del Montenegro (a) con mappe di altitudine (b) e regioni amministrative (c).

West and East which have humid cold temperate climate with warm summer (Dfb) and humid boreal climate with cool summer (Dfc).. Olives are not grown in the latter two zones, due to climatic constraints. Accordingly, two different precipitation regimes are distinguished for the purposes of this study: Mediterranean and temperate–continental regimes. Soil characteristics of Montenegro are very heterogeneous, with many different soil types formed on various parent materials.

2.2 Climate change projections

The impact of climate change was assessed using the coupled regional climate model EBU-POM (Đurđević and Rajković, 2008; Gualdi *et al.*, 2008) with a resolution of about 30 km. The baseline scenario (period 1961-1990) was compared with SRES (Special Report on Emission Scenarios): i) referring to the on-going period 2001-2030 and A1B SRES and ii) referring to the period 2071-2100 and both A1B and A2 SRES. In relation to the concentration of greenhouse gasses, A1B and A2 scenarios are characterized as "mean" and "high" emission scenarios, respectively. According to A1B and A2 scenarios, the expected concentration of CO_2 at the end of the 21st century could be about 690 ppm and 850 ppm, respectively. The modelling results focused on the changes in air temperature and precipitation were presented in relation to the mean values of the baseline scenario.

A1B scenario, period 2001-2030: according to the results of the model, the biggest change occurred during the summer (JJA) season, with values ranging from +1.3 °C in the north to +1 °C in the coastal zone. For the winter season (DJF), the increase of air temperature was about 0.5 °C and 0.9 °C in the coastal area and the northern mountainous part of the country, respectively. For the spring season (MAM), the change of temperature was somewhat more significant compared to the winter season with values ranging from 0.8 °C in the south to 1.1 °C in the north.

The autumn season (SON) was characterized by almost homogenous temperature change of about 0.7 °C observed over the whole territory. The results of the model indicated both negative and positive changes in precipitation amounts, depending on the geographic location and the season. Specifically, an increase in precipitation during the summer months was observed in the central parts of Montenegro, while a similar increase occurred in the spring season in the northwest part of the country that borders with Bosnia and Herzegovina. These positive changes were very small and ranged up to 5% above the baseline scenario. In other parts of Montenegro, the results indicated a reduction of precipitation during the winter-spring season. Furthermore, the spring season was characterized by the highest reduction of precipitation, up to 20%, across almost the entire territory of Montenegro.

A1B scenario, period 2071-2100 (indicated as A1Bs): the spatial patterns of change similar to those noted for the period 2001-2030 were observed, but with a greater magnitude. The areas along the Adriatic Sea demonstrated lower change in temperature compared to the areas in the northern mountainous region. The biggest change in temperature occurred in the summer season. In the coastal zone, the increase of temperature was about 2.4 °C, and in the mountain region - in the northern part of the country - it was about 3.4 °C. During the winter season, the temperature gradient from the south towards the north of the country was observed, with an increase in temperature ranging from 1.6 °C in the coastal zone to 2.6 °C in the north. In the spring season, the changes of air temperature ranged from 1.6 °C to 2.6 °C, while in the autumn season they was approximately 1.6 °C in the coastal zone and 2.4 °C in the north, at the border with Serbia. For this scenario, a reduction of precipitation was observed everywhere and during all seasons up to 30% on the yearly basis in the northern and coastal zones. The spring season was characterized by a more uniform deficit of precipitation, and by the reduction of approximately -10% over the entire territory of the country. Similarly, a significant deficit during the summer season was observed in the coastal areas, while a negative trend ranged from -20% to -15% in the central and northern regions, respectively. In the autumn season, the projection results indicated a significant reduction of precipitation ranging from -30% to -50%.

A2 scenario, 2071-2100: the highest increase of air temperature occurred in the summer season in the mountainous region, with values above 4.8 °C. In the coastal zone, the temperature increased by 3.4 °C during the same season. In the winter season, the temperature changed by 2.6 °C along the Adriatic Coast and approximately 3.4 °C in the northern parts of the country. During the spring season, the temperature increase ranged from 2.8 °C to 3.6 °C, while the change of temperature in the autumn season was more uniform and ranged from 2.6 °C to 3° C. The A2 scenario demonstrated a negative anomaly of precipitation. In the winter season, a positive precipitation trend ranging from 5% to 10% was observed only the north-western parts of the country, while in the other parts of Montenegro the precipitation change was negative and ranged from -5% to -10%. The most significant change occurred along the coast in the summer season, with a precipitation decrease of -50%. In this season, the northern parts of the country experienced a precipitation anomaly of -10%. In the spring and autumn seasons, the spatial distribution of precipitation anomaly was uniform, with a mean value of -20%.

2.3 Methodology

The simulations and data elaborations were conducted for the baseline and three climate projection scenarios. The main methodological steps included: (a) determination of the temperature profiles and temperature regimes for 35 meteorological stations in Montenegro and bordering countries in terms of olive suitability; (b) determination of the areas suitable for olive cultivation; (c) computation of the reference evapotranspiration (ET_o); (d) estimation of the flowering dates; (e) estimation of crop evapotranspiration (ET_a), net irrigation requirements (NIR), and relative yield (RY) for rainfed cultivation and various irrigation scenarios using the CROPWAT model (Smith, 1992); (f) comparison of modelling results with the baseline scenario.

The temperature requirement approach (Fischer *et al.,* 2002), also known as the Agro Ecological Zoning (AEZ) method, was used to determine the areas suitable for olive cultivation. The analysis was conducted through a GIS interface using the geostatistical wizard and raster calculator. Temperature profiles, which provided quantification of temperature seasonality with regards to the year-round temperature regimes, were determined for each meteorological station. They were expressed through the number of days falling into pre-defined temperature intervals which consisted of 5 °C steps

Temperature interval (°C)	<-5	-5-0	0-5	5-10	10-15	15-20	20-25	25-30	>30
Number of days	L9	L8	L7	L6	L5	L4	L3	L2	L1

Acceptable (partially suitable)	Suitable
L8 = L9 = 0	L8 = L9 = 0
L7 + L6 + L5 + L4 > 0.400 x L	L7 + L6 + L5 + L4 > 0.400 x L
L4 + L3+ L2+ L1 > 0.333 x L	L4 + L3+ L2+ L1 > 0.333 x L
T_{sum} > 4000	T_{sum} > 5000

Tab. 1 - Temperature profiles (intervals with corresponding number of days) and crop temperature requirements for olives cultivation (L=365 days, T_{sum} - Temperature sum of the growing crop period) (adapted from Fischer et al., 2002).
Tab. 1 - Profili di temperatura (intervalli con numero corrispondente di giorni) e fabbisogni di temperatura per la coltivazione dell'olivo (L = 365 giorni, T_{sum} - Somma termica del periodo di coltivazione) (adattato da Fischer et al., 2002).

(Tab. 1). A complete account of the time periods of individual temperature intervals provided a year-round temperature profile. Each station was then evaluated following the specific criteria for olive cultivation and marked as either suitable or non-suitable.

The criteria used to specify the suitability for olive cultivation around a meteorological station include the temperature profile requirements and accumulated temperature requirements (T_{sum}) considering the areas where minimum monthly air temperature exceeded 0 °C (Tab. 1). The area around a station was considered suitable for cultivation when the temperature data matched both the temperature profile requirement and the accumulated temperature requirements. Otherwise, the area around a station was considered unsuitable for olive cultivation. Two climatic suitability conditions for olive growth were determined as suitable (full cultivation potential) and acceptable (limited cultivation potential) corresponding to T_{sum} greater than 5000 and 4000 °C, respectively (Tab. 1).

The temperature-driven growth was used to determine the dates of olive flowering. Growing degree days (GDD) were used to measure the heat energy accumulation that a specific crop can use for growth and development. GDD were calculated through the following equation (Ritchie, 1991):

$$GDD = \sum_{i=1}^{n} (T_{avg} - T_b) \quad (1)$$

where: T_{avg} is daily air temperature (°C) obtained as average of daily maximum and minimum temperatures, T_b is the base temperature, i.e. the lower temperature threshold below which the crop development is not possible, and n is the number of days under consideration. The impact of cut-off temperature (i.e. the upper temperature threshold) was neglected. GDD was zero for all days when T_{avg} was lower or equal to T_b.

The olive flowering dates were determined assuming the base temperature of 8.5 °C for olive development (De Melo-Abreu *et al.*, 2004) and 1st of March was the date marking the beginning of the season. It was further assumed that the flowering of olives occurred when GDD has reached 514 °C-days (De Melo-Abreu *et al.*, 2004).

Crop water requirements were calculated using the single crop coefficient methodology and reference evapotranspiration (ET_o) estimated by the Penman–Monteith temperature (PMT) method with limited weather parameters (Allen *et al.*, 1998). Net irrigation requirements (NIR) were computed as a difference between crop evapotranspiration (ET_c) and effective rainfall (P_{eff}), fixed as 80% of total precipitation. The CROPWAT 8.0 software (Smith, 1992) was used to compute crop water requirements, irrigation requirements and relative yield on the basis of climate, soil, crop and management input parameters. Crop input parameters for simulations were mainly adopted from the FAO 56 (Allen *et al.*, 1998). Rooting depth was assumed to be between 0.8 m and 1.0 m (depending on soil characteristics). The crop coefficient (K_c) values were those suggested by Er-Raki *et al.*, (2008) as average values for semi-intensive orchards and they were 0.6, 0.5 and 0.65 for the initial, mid-season and late-season stages, respectively. Soil water balance in the root zone run on a daily bases and the water stress occurred each time the soil moisture content was depleted below readily available water content, which was fixed as 65% of the total available water for all growing stages. Then, crop evapotranspiration under water stress (ET_a) was estimated as:

$$ET_a = K_s K_c ET_o \quad (2)$$

where K_s is a water stress coefficient ($0<K_s<1$), a fraction of soil moisture content in the root zone depleted below readily available level. The reduction of yield due to water stress was determined by the Stewart's form of water-yield model (Stewart *et al.*, 1977):

$$1-(\frac{Y_a}{Y_m}) = K_y 1-(\frac{ET_a}{ET_m}) \quad (3)$$

where K_y is the yield response factor fixed to 0.7 (Allen *et al.*, 1998), ET_a and ET_m refer to crop evapotranspiration under water stress (K_s<1) and optimal water supply (K_s=1), respectively, and Y_a and Y_m are yield corresponding to cultivation under non-optimal and optimal water supply, respectively. The analyses of future scenarios were completed using the 'damb-farmer approach' (Rosenberg 1992; Easterling *et al.*, 1993), meaning that the only variable factor in future production is climate. The other factors are assumed to remain constant. Spatial interpolation of data was performed in GIS using an exact interpolator in calculations. A completely regularized spline interpolation technique was applied for the spatial presentation of data. This method estimates values using a mathematical function that minimizes overall surface curvature, resulting in a smooth surface that passes exactly through the input points (Jeffrey *et al.*, 2001). The technique was applied in numerous studies, at different scales and included several climate and hydrological variables (El Kenawy *et al.*, 2010; Todorovic *et al.*, 2013). All the maps were created in ArcGIS 9.2 using the standard procedures and tools.

3. RESULTS

3.1 Areas suitable for olive cultivation

The areas suitable for olive cultivation in Montenegro are spatially presented in Fig. 2 for the baseline scenario and the three future scenarios considering minimum monthly air temperature of 0 °C and temperature sums above that temperature. An assessment of the present conditions indicated the Montenegrin coastline, the southern part of the Bjelopavlicka Plain and the area around Skadar Lake as the areas suitable for olive cultivation. The analysis conducted through the raster calculator indicated that 2,346.7 km² are in the zone suitable for olive cultivation, while an additional 91.5 km² are in the area partially acceptable for olive cultivation, which represents 17.0% and 17.7% of the total area of Montenegro, respectively. The results of the analysis for the A1B scenario indicated that an additional 335.3 km² of the territory is expected to be suitable for olive growth in the future. This area included the broader territory around Danilovgrad and Podgorica, shifting north-west through the Bjelopavlicka Plain. In the A1B scenario, the area where the temperature sums were more than 4000 °*C* covered a much wider portion of the country's territory. However, this area cannot be considered acceptable for olive cultivation because the criteria of minimum monthly air temperature were not satisfied. According to the A1B scenario, 19.4% and 19.9% of the territory of the country is expected be suitable or partially acceptable for olive cultivation, respectively, which represents an increase of 2.4% and 2.2% in respect to the baseline conditions.

The results obtained for the A1Bs scenario identified the Montenegrin coastline, the Bjelopavlicka Plain, the area around Skadar Lake and the Niksic Valley as the regions suitable for olive cultivation. The analysis indicated that an additional 1,821.9 km² are foreseen to be suitable for olive cultivation, while an additional 71.4 km² of the area is expected to be partially acceptable for olive cultivation in the future, which amounts to 30.2% and 30.7% of the total area of Montenegro, respectively. This presents a notable increase for the period 2071-2100. The results of the analysis for the A2 scenario indicated that an additional surface area of 2,574 km² is expected to be suitable for olive growth, compared to the present conditions. It consists of the same territories as in A1Bs scenario, including the south-western part of the high Karst region, shifting to the south-eastern Herzegovina. The result of the temperature sums (greater than 4000 °*C*) for A1Bs and A2 scenarios comprised a wide portion of territory. However, these areas were not deemed suitable for olive cultivation because the criteria of minimum monthly air temperature were not satisfied. According to the A2 scenario, 35.6% and 35.7% of the territory are foreseen to be suitable or partially acceptable for olive cultivation, respectively, a twofold increase in respect to the baseline conditions.

3.2 Olive tree flowering dates

The indicative dates of olive flowering, expressed in DOY, for the present conditions in Montenegro and the three projected scenarios are presented in Tab. 2. The start of flowering on the Montenegrin coastline was in the second week of May, while it occurs up to first week of June in the interior locations. The results of the analysis predicted the anticipation of flowering for 9.8±3.8 days for the A1B scenario, 14.5±9.2 days for the A1Bs scenario and 17.1±12.9 days for the A2 scenario. The longest anticipation of the flowering period (24 days) was

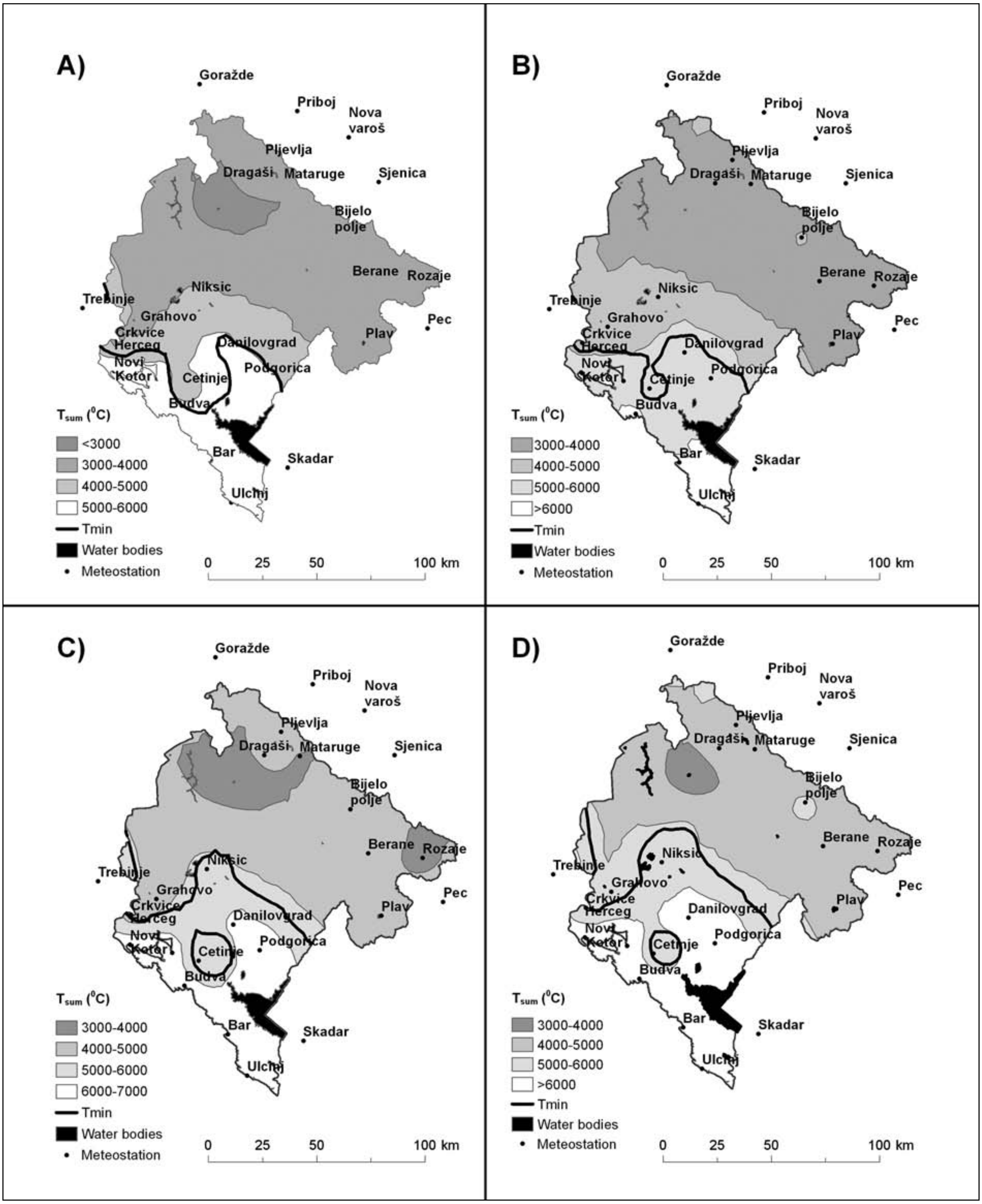

Fig. 2 - Mapping of the temperature sums variation and minimum air temperature (0 °C) describing the areas suitable for olive cultivation in Montenegro for: a) baseline (1961-1990), b) A1B (2000-2031), c) A1Bs (2071-2100) and d) A2 (2071-2100) scenarios. In Figg. 2a and 2b, the areas north from T_{min} line are not suitable for olive cultivation. In Figg. 2c and 2d, the areas north from T_{min} line and inside the closed lines east from Kotor and Budva are not suitable for olive cultivation.

Fig. 2 - Mappatura delle variazioni delle somme termiche e della temperatura minima dell'aria (0 ° C) che descrivono gli areali idonei alla coltivazione dell'olivo in Montenegro per gli scenari: a) di riferimento (1961-1990), b) A1B (2000-2031), c) A1B (2071 -2100) e d) A2 (2071-2100). Nelle Figure 2a e 2b, le zone a nord della linea di T_{min} non sono idonee alla coltivazione dell'olivo. Nelle Figure 2c e 2d, le zone a nord dalla linea T_{min} e all'interno delle linee chiuse ad est di Kotor e Budva non sono idonee alla coltivazione dell'olivo.

Station	Baseline	A1B	A1Bs	A2
Ulcinj	153	143	137	131
Bar	156	145	139	132
Herceg Novi	153	143	137	131
Budva	153	143	137	131
Podgorica	152	143	137	131
Kotor	154	144	138	131
Danilovgrad	159	150	134	136
Crkvice	-	-	-	169
Niksic	-	-	164	155

Tab. 2 - Flowering dates of olives (in DOY) in Montenegro for the baseline and future scenarios (considering the areas suitable for cultivation).
Tab. 2 - Date di fioritura dell'olivo (in DOY) in Montenegro per gli scenari di riferimento e futuri (considerando le aree idonee alla coltivazione).

observed for the location of Bar in the A2 scenario. These results are in agreement with those obtained by other authors for the olive's cultivation areas in Italy (Orlandi *et al.*, 2009, 2010; Bonofiglio *et al.*, 2008) and Greece (Osborne *et al.*, 2000).

3.3 Response of olive trees to water availability

The results of crop evapotranspiration for optimal (ET_m) and non-optional water supply (ET_a) conditions for four climate scenarios are given in Tab. 3. Maximum crop ET ranged from 495.5 mm in Bar to 565.2 mm in Danilovgrad. The average ET_m for all stations in the present climatic condition was 509.3±35.3 mm. The average actual crop evapotranspiration was 480.8±50.5 mm, and the highest values were observed for Danilovgrad, at 564.6 mm, while the lowest ET_a was in Ulcinj, at 438.4 mm. These results are quite similar to olive evapotranspiration reported for Benevento (Italy), which was 530 mm, (Tognetti et al., 2007).
Crop water requirements of olives under future climatic scenarios A1B, A1Bs and A2 were 1.6% 4.3%, and 5.8% higher than the baseline scenario, respectively. Nevertheless, water consumption under ET_a was lower under future climate scenarios, at 5.8±1.2%, 15.7±1.4% and 22.3±0.9% for A1B, A1Bs and A2 scenarios, respectively. Low values of standard deviation indicate a very low coefficient of variation among different locations. In fact, a uniform impact of climate change on ET was observed among the Montenegrin coastline and interior areas that are suitable for olive growth.
For the baseline scenario, the area around Danilovgrad and Herceg Novi did not require irrigation at all, while low irrigation input was required for other locations (Fig. 3 and Fig. 4a). Mean yield reduction was 4.0±3.2%. The highest reduction of only 9.7% was observed in Ulcinj (Fig. 4b), indicating that the Montenegrin Mediterranean climate is very suitable for olive production in respect to precipitation pattern.
Under the A1B scenario, mean yield reduction over the Montenegrin area was 8.6%±3.7, with

Station	Baseline		A1B		A1Bs		A2	
	ET_m (mm)	ET_a (mm)	ET_m (mm)	ET_a (mm)	ET_m (mm)	ET_a (mm)	ET_m (mm)	ET_a (mm)
Ulcinj	509.1	438.4	523.7	411.1	529.3	378.2	536.6	357.5
Bar	495.5	472.9	506.7	449.8	518	410.7	525.9	387.6
Herceg Novi	515.7	515.2	522.6	490.4	534.1	442.8	540.9	418.2
Budva	497.1	480.6	505.7	457.8	520.7	419.5	525.1	393.7
Podgorica	524.6	497.8	532.3	464.4	545.6	427.6	555	401.2
Kotor	522.4	503	515.4	470.1	545.1	435.1	552.8	411.4
Danilovgrad	565.2	564.6	578	546.5	590.9	494.8	603.8	467.7
Crkvice	-	-	-	-	-	-	480.9	469.8
Niksic	-	-	-	-	507.1	506.8	526.3	526.3
Average	518.5	496.1	526.3	470.0	540.5	429.8	548.6	405.3
Standard dev.	23.5	39.2	24.7	41.5	24.7	35.5	27.0	33.8

Tab. 3 - Crop evapotranspiration for optimal (ET_m) and non-optimal (rainfed) water supply (ET_a) for the baseline conditions and three future climate change scenarios.
Tab. 3 - Evapotraspirazione dell'olivo per l'approvvigionamento idrico ottimale (ET_m) e non ottimale (non irrigato) (ET_a) per le condizioni di riferimento e tre scenari futuri di cambiamento climatico.

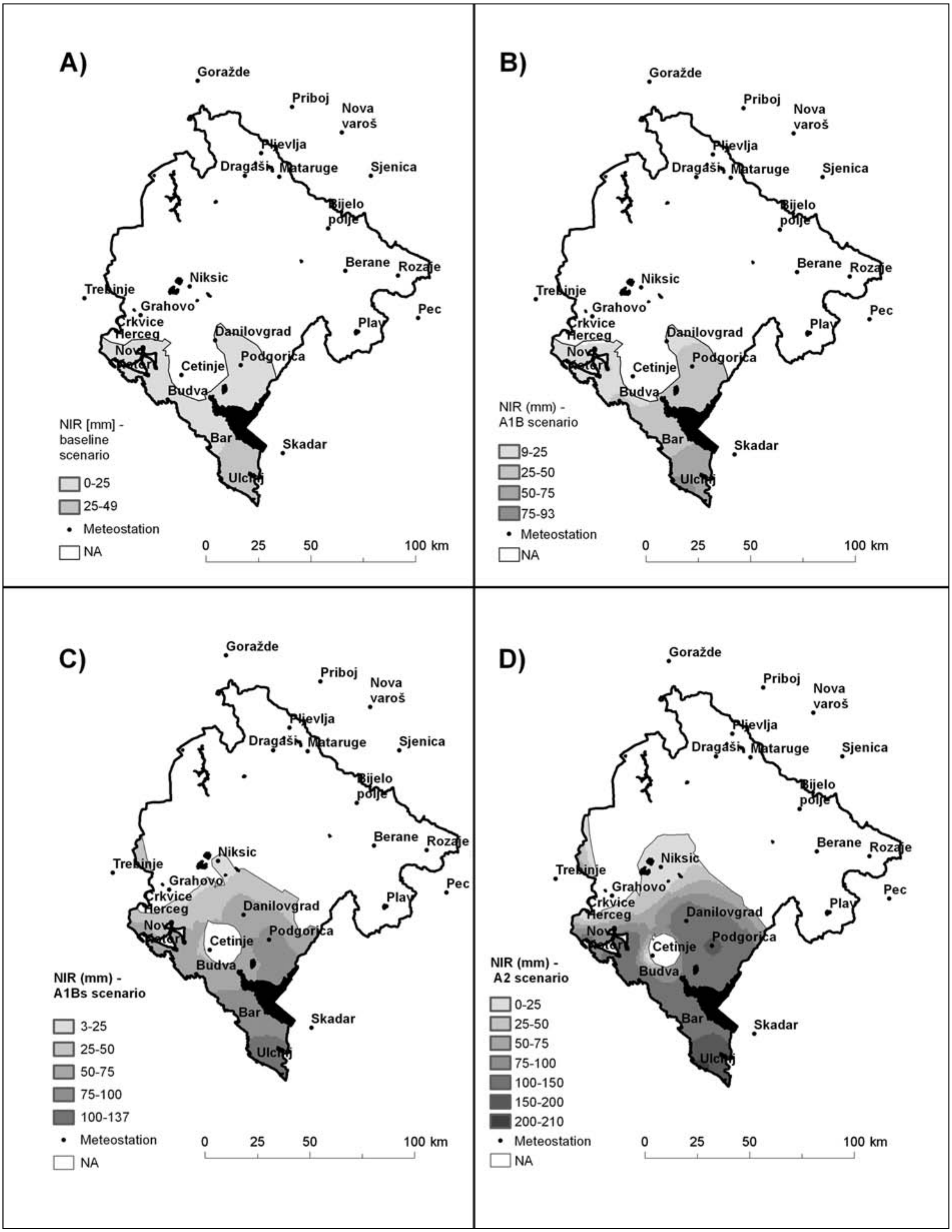

Fig. 3 - Spatial variation of net irrigation requirements (NIR) in Montenegro for: a) baseline conditions (1961-1990), b) A1B (2000-2031), c) A1Bs (2031-2070) and d) A2 (2031-2070) scenarios.

Fig. 3 - Variazione spaziale dei fabbisogni irrigui netti (NIR) in Montenegro per: a) condizioni di riferimento (1961-1990), e per gli scenari b) A1B (2000-2031), c) A1Bs (2031-2070) e d) A2 (2031-2070).

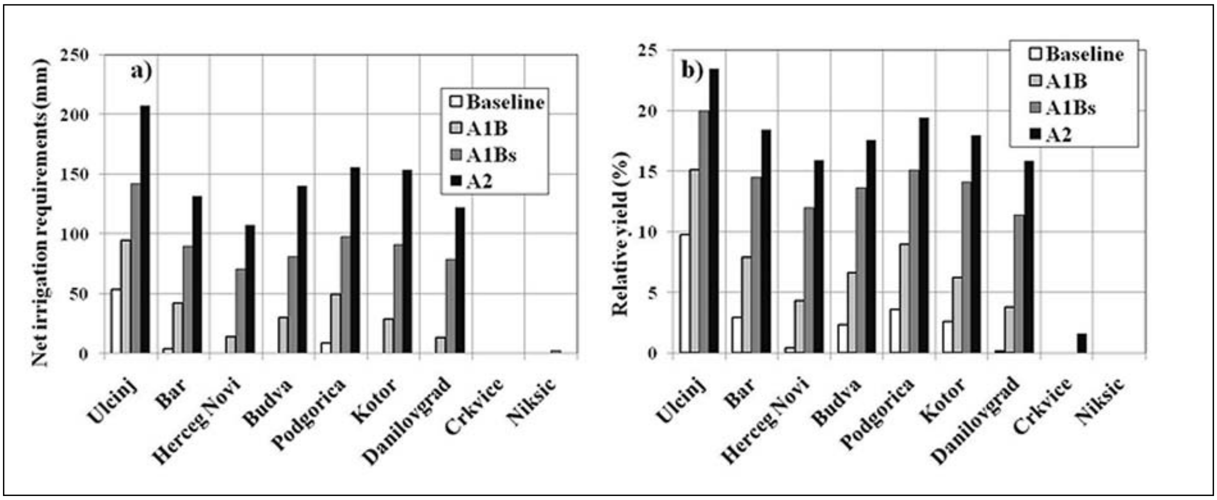

Fig. 4 - Net irrigation requirements (a) and relative yield loss under rainfed cultivation (b) of olive orchards for the baseline conditions and three SRES scenarios.
Fig. 4 - Fabbisogni netti di irrigazione (a) e perdita di resa relativa in oliveti non irrigati (b) per le condizioni di riferimento e i tre scenari SRES.

the highest in Ulcinj, 15.1%, and the lowest in Danilovgrad, at only 3.8%. Yield under this scenario was additionally reduced by 4.6% in respect to the baseline scenario (Fig. 4b). Compared to the baseline scenario, the NIR were around 80% greater, which, in terms of absolute value, means 34.0±12.1 mm. The highest irrigation demand was observed in Ulcinj, 94.7 mm, while in Herceg Novi and Danilovgrad it was approaching zero (lower than 15 mm).

Mean NIR under the A1Bs scenario were 96.7±44.3 mm. The high variability of NIR was due to the fact that the area suitable for cultivation was extended and one additional meteorological station (Niksic) was considered. Otherwise, the NIR would be 106.2±33.0 mm. Mean yield reduction for this scenario was 15.4±3.1%, with the highest yield loss in Ulcinj, 20%, and the lowest in Danilovgrad and Herceg Novi, at 11.4% and 12%, respectively. Relative yield was additionally reduced by 10.8% compared to the baseline scenario. The highest irrigation requirements were estimated for Ulcinj, where 141.7 mm of water were needed to gain the optimal level of production (Fig. 4a).

For the A2 scenario, the yield reduction under rainfed cultivation was 16.2±7.6%. The greatest losses of 23.4% and the highest net irrigation requirements of 207.1 mm were observed in Ulcinj on the coast, close to the Albania border. The lowest yield reduction of about 16% was found in Danilovgrad and Herceg Novi (Fig. 4b). The overall yield was reduced by 15.2±0.6% in respect to the baseline scenario.

4. DISCUSSION

The results of elaborations indicated that the impact of climate change on olive's cultivation in Montenegro could be very limited at least in terms of irrigation requirements, water stress and yield loss. It is expected that the foreseen increase in temperature will extend the potentially cultivable areas for growing olives from the present 17% of the total country area to almost 30.2% in the A2 scenario by the end of this Century. The new areas suitable for olive's cultivation are expected to shift northwards and to the higher altitudes which means that the olive's oil production would likely increase in the future. Accordingly, a new strategy for the olive cultivation in the country should be promoted to reinforce the participatory approach and to involve farmers, olive's oil producers and their associations since the beginning (Bonzanigo *et al.*, 2015). A potential adaptation option could be plant breeding (Fabbri *et al.*, 2009; León *et al.*, 2011), aiming to adopt new varieties that respond better to the foreseen changes in cultivation conditions, and to expected variations in air temperature, water availability and CO_2 concentration. Global warming is predicted to affect the anticipation of olive's flowering dates, which is in agreement with other studies (Moriondo and Bindi 2007; Orlandi *et al.*, 2009; Tanasijević *et al.*, 2014). Nevertheless, further investigations are needed to understand the impact of temperature variation during the winter and spring seasons because the flowering was mainly considered by the late spring temperatures.

A particular attention should be given to the frost risk during dormancy and in spring months.
Crop maximum evapotranspiration is foreseen to increase in the future by 5.8% in the most extreme scenario of air temperature rise (A2). However, the crop ET under rainfed conditions is expected to decrease by 5.8%, 15.7% and 22.3% in scenarios A1B, A1Bs and A2, respectively. Furthermore, NIR would increase more than crop ET due to the expected decrease in precipitation and expected larger impact of drought and dry spells. The expected increase of NIR was unevenly distributed and it was 34.0 mm in the A1B scenario, 81.2 mm in the AIBs scenario and 106 mm in the A2 scenario. Rainfed olive cultivation is expected to face mild to moderate stress, but not to the point that it would be excluded as a feasible method of cultivation. The future evapotranspiration and irrigation requirements of olive crops strongly depend on the type of cultivation (traditional, intensive or super-intensive), i.e., tree density and tree age, ground cover and pruning (Orgaz et al. 2006; Martinez-Cob and Faci 2010; Paço et al. 2014). Accordingly, crop water requirements could increase in respect to the values reported in this work if super-intensive olive groves are introduced (Orgaz et al. 2006; Paço et al., 2014). Therefore, potentially high water requirements and limited water availability could be the reasons for the introduction of a regulated deficit irrigation strategy, while terracing could be introduced as an adaptation measure for new suitable areas inside the Bjelopavlicka Plain and its surrounding hills.
Climate change will diversely affect the crop evapotranspiration with regards to crop behaviour and regional distribution of impact. Olive tree evapotranspiration will show similar behaviour in the Zeta and Coastal regions among various climate change scenarios. The increase of ET will be lower than 2% for scenario A1B, about 4.5% for scenario A1Bs, and approximately 6.2% for scenario A2. The actual ET of olive trees (rainfed cultivation) will experience almost the same decrease in the Zeta and Coastal regions. This reduction is due to the advance in phenology and will be approximately 5% for scenario A1B, 13.5% for scenario A1Bs, and 18% for scenario A2. Olive crops in the Zeta and Coastal regions will have additional yield reductions in the future of 1.9-3.6% under the A1B scenario, 6.4-8.0% under the A1Bs scenario, and 13.3-14.8% under the A2 scenario. The presented results indicated that olive cultivation is likely to expand to the interior parts of the country with a more favourable precipitation pattern. There is no risk of water excess in the root zone because the soils of Montenegro are dominantly shallow and gravelly in the areas of high precipitation. These soils are mainly formed on hard limestones in karstic landscape and have swallow holes and joints throughout which water easily percolates. Nevertheless, in the areas where olives are actually grown (Zeta and Coastal regions), the cultivation in the future is expected to face slightly greater water stress than nowadays with the corresponding increase of yield reduction.

5. CONCLUSION

The assessment of the expected impact of climate change on the olive trees growing in Montenegro relies on a simple methodology adapted to the national scale. The results obtained in this study underline the well-known ability of the olive trees to adjust to various environmental conditions. The extension of cultivation and its relocation "towards north and up" has been confirmed, especially for the northern areas of Bjelopavlićka and the Zeta Plain. However, a narrow part of this territory could be really used for olive growth, taking into consideration the high altitudinal gradients and shallow gravelly soils in the hilly-mountainous area of Karst zone. It appears that terracing is an option for olive cultivation in these areas, and that it might constitute one of the adaptive measures to be pursued in the future. Furthermore, the possible expansion of olive cultivation to other areas, like Niksic and Crkvice, under the A1Bs and A2 scenarios was observed.
The opportunity of growing olives further in the northern areas of Montenegro could lead to some changes in the approach to olive production which does not require to meet the criteria of traditional growing. This is due to the fact that the cultivation will be possible in the areas with greater precipitation and higher water availability. Therefore, the rainfed cultivation of olives could remain one of the viable solutions in the future. Certainly, it could represent an occasion and challenge to promote the sustainable olive growing in new regions by the introduction of intensive and super intensive cultivation with increased economic benefits in respect to the cultivation in semi-arid environments near to the coast. Nevertheless, a more detailed analysis of the frost risk during dormancy period and in spring is needed in order to justify eventual investments.
The results reported in the present study fit quite well with the current literature. Certainly, a more accurate assessment could be possible using local, site-specific soil characteristics and

crop phenological parameters, and more detailed weather databases. This is especially important due to the great heterogeneity of soil parameters in Montenegro, particularly in respect to soil depth. Consequently, the further research efforts should be devoted to the estimate of crop water use and productivity using comprehensive climate, soil and crop data which consider the different agronomic practices (i.e., orchard's density) and irrigation inputs. Accordingly, the accuracy of simulations should be enhanced using: (a) more complete climate data sets with weather parameters that enable the application of standard Penman-Montheith equation, (b) better characterization of olive orchards phenology, crop coefficients and yield response factor, (c) daily or decade-specific simulation option, (d) more complex soil-water balance models which include all water balance components in computation, (e) crop growth models and yield response to water functions that consider the impact of CO_2 and permit the estimation of yield in absolute terms, and (f) the establishment of a link between these models and GIS for the spatial presentation of data.

Finally, it is worthwhile to point out that the results presented in this study are limited by the format input climatic data and accuracy of the SRES used in the analysis. Recent observed global warming is significantly less than that simulated by climate models (Pielke, 2008 and 2013; Fyfe et al., 2013). For instance, Pielke (2008 and 2013) pointed out that, with reference to forecast up to 2012, the overestimation was of 53%, 9%, 20% and 20% for IPCC reports 1990, 1995, 2002 and 2007, respectively. The causes of this overestimation were analyzed and discussed by Fyfe et al (2013) and might be explained by some combination of errors in external forcing, model response and internal climate variability. New CLINO (30-year climate normal for 1991-2020 period) is now mostly finished and the measured climate data are available for the most of the period. Therefore, the presented approach could be applied to the current climate (since 1991) based on the real thermo-pluviometric data.

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