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Prediction of the European beech (*Fagus sylvatica* L.) xeric limit using a regional climate model: An example from southeast Europe

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ABSTRACT

Ellenberg's climate quotient (EQ), which is a simple biometeorological index, was used to predict the xeric limit of the European beech distribution and potential future changes in Serbia (southeast Europe). The general aim of this study was to evaluate EQ as a predictive tool of the xeric limit of the beech at the southern edge of its distribution and to predict future changes in the xeric limit. The novelty of this study is its assessment of EQ accuracy for Serbia, the beech populations of which were separated from Central European refugia during the last glacial period. Climate projections from the coupled regional climate model EBU-POM were used to predict the changes in the xeric limit in the 21st century. The computation of the area under the receiver operating characteristic curves showed that EQ had "good" and "fair" predictive ability for two samples. Using three threshold criteria and different samples, the beech xeric limit in Serbia for the reference period of 1961–1990 varied between EQ values of 20.1 and 29.5. Significant changes in the beech xeric limits were predicted for the 21st century. The EQ calculations for 2001–2030 (A1B scenario) predicted that more than 20% of the present-day beech forests will be located outside of the ideal bioclimatic niche characterised by EQ ≤ 30 that was proposed by Ellenberg. For 2071–2100 (A1B and A2 scenarios), up to 90% of the current beech forests are expected to be located outside of that niche, and approximately 50% will be located beyond the limit EQ = 40 for which beech mass mortalities have been observed. The results suggest an urgent need for the development of adaptive forest management strategies for beech in this region.

1. Introduction

European beech (*Fagus sylvatica* L.) is widely distributed across Europe and is the dominant natural tree species in Central Europe (Ellenberg, 1988). Numerous studies have examined the distribution and limits of European beech forests (Badeau et al., 2004; Peñuelas et al., 2007; Bolte et al., 2007; Fotelli et al., 2009; Mátyás et al., 2009; Kramer et al., 2010; Czúcz et al., 2011). These so-called trailing edge ("xeric limits"), which respect the distributional margins at low elevations and low latitudes, are more difficult to identify than leading edge ("upper limits"), which are determined by temperature conditions (Mátyás, 2010; Rasztovits, 2011). The xeric limits are determined by climatic aridity, which is affected by the local soil water conditions.

Several studies have drawn attention to the susceptibility of beech to drought in light of global warming (Fang and Lechowicz, 2006; Geßler et al., 2007; Granier et al., 2007), although the magnitude and significance of the topic requires further research. Ellenberg (1988) stated that the main limitation on the natural distribution of beech is the availability of water. In response, he developed a climate quotient (EQ) to characterise the climate conditions for beech in Central Europe. Although EQ was defined approximately half a century ago, it has recently gained importance with the development of regional climate models and advanced software that utilise spatial data (Thuiller, 2003; Phillips et al., 2006; Guo and Liu, 2010; Czúcz et al., 2011). Führer et al. (2011) proposed a new forest aridity index that was originally designed for yield assessment; it is based on the same principles as EQ (relationships between precipitation and mean monthly temperatures) and is calibrated to characterise beech, oak and forest-steep zones in Hungary. Comparative studies have shown that EQ is a more accurate than various climatic factors (Mátyás et al., 2010; Czúcz et al., 2011) to determine the xeric distributional limits of beech.

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The study had two main objectives:

1. To evaluate EQ as a predictive tool of the xeric limit of European beech at the southern edge of its distribution (Serbia); and
2. To predict future changes in the xeric limit due to climate change using regional climate projections and EQ.

The novelty of this study is the evaluation of the prediction accuracy of EQ for the region of Serbia, where the influences of continental and Mediterranean climates are combined. The fact that populations of beech from Serbia (Balkans) were separated from Central European refugia during the last glacial period and that they did not contribute to the colonisation of central and northern Europe (Magri et al., 2006; Magri, 2008) makes this study particularly interesting. The strength of the study is in its universal approach, which can be applied at the local scale and included in decision-making processes regarding forestry.

2. Materials and methods

2.1. Biometeorological index

To explore the impact of the past and future climate on European beech, we used a biometeorological index, Ellenberg's climate quotient (EQ; Ellenberg, 1988). EQ is defined by a simple equation in which the mean temperature of the warmest month (in °C) is divided by the annual precipitation (in mm) and multiplied by 1000 (1).

$$EQ = \left(\frac{T_{July}}{P_{annual}}\right) * 1000 \qquad (1)$$

Areas with lower EQ values (less than 30) are characterised by a humid climate and are dominated by beech, whereas higher EQ values (greater than 30) characterise dryer and warmer regions dominated by oak species (Ellenberg, 1988; Jahn, 1991; Fang and Lechowicz, 2006). An EQ value of 30 is considered to be the maximum under which natural beech forests are expected to appear in Central Europe (Ellenberg, 1988). In addition to EQ, other similar metrics have been developed (Führer et al., 2011).

2.2. Observed data and regional climate change projections

Data were gathered from a network of 69 meteorological stations across Serbia (Appendix A) for the period 1961–1990. Temperature and precipitation were interpolated by universal kriging (a statistical–topographic model for mapping climate data over mountainous terrain; Dingman et al., 1988) in SAGA-GIS at a resolution of 90 m. EQ was then calculated for every interpolated cell.

Regional climate change data, which were based on the SRES A1B and A2 scenarios for the periods 2001–2030 and 2071–2100, were obtained from the Eta Belgrade University – Princeton Ocean Model (EBU-POM). EBU-POM is a two-way coupled regional climate model that uses the Eta/NCEP limited area model as its atmospheric module and the Princeton Ocean Model (POM) as its oceanic module. The atmospheric module has been connected to a global model to make seasonal predictions (Fennessy and Shukla, 1999). In addition to a downscaling assessment in the Mediterranean and southern Europe (Djurdjević and Rajković, 2008), it has also been used for downscaling in the United States (Xue et al., 2007). To overcome the bias problem in addressing differences between the observed and modelled climate data, the so-called "delta change approach", was used (Graham et al., 2007; Ruml et al., 2012). The period 1961–1990 was considered as reference period. EQ values for the periods during the 21st century were obtained by adding the differences of temperature and precipitation (the difference between the modelled future periods and the modelled 1961–1990 reference period) to the observed climate values of the 1961–1990 reference period (Republic Hydrometeorological Service of Serbia; Kržič et al., 2011). EQ values were calculated for the two time periods: 2001–2030 and 2071–2100.

2.3. Spatial analysis

Beech was the dominant species in 1651 of the 19,371 2 × 2 km grid cells, of which 5852 were forest grid cells. The inventory data were provided from Serbia's national forest inventory (Banković et al., 2009). Using a map of interpolated EQ values for the period 1961–1990, we examined whether EQ was a good predictor of beech occurrence and determined the EQ value at the xeric limit of beech in Serbia. Finally, we predicted the changes inbeech distribution under climate scenario A1B for the periods 2001–2030 and 2071–2100 and under scenario A2 for the period 2071–2100.

To evaluate whether EQ had the ability to identify areas of beech occurrence, we computed the area under the receiver operating characteristic curve (AUC; Swets, 1988). To determine the xeric limit of beech in the reference period 1961–1990, we used different EQ thresholds, including one that maximises the kappa value (Huntley et al., 1995; Araújo et al., 2005), one that maximises the sum of sensitivity and specificity (Manel et al., 2001; Czúcz et al., 2011) and the threshold below which 95% of the beech-dominated stands were found. Calculations were performed for two samples: all inventory fields and fields that contained forests (Appendix B). All analyses were performed in the R statistical package (R Development Core Team, 2012).

Projections of the future limits of the beech distribution were then assessed for different periods and Ellenberg thresholds of 20, 30 and 40. First, index datasets were divided into two classes (above and below EQ = 30) and presented graphically. Then, datasets were partitioned into equal two unit classes and presented graphically, all using ArcGIS 9.3.1. Finally, the beech distribution was compared across the two unit index classes for the different time periods using a line chart.

3. Results and discussion

3.1. Determination of the predictive accuracy of EQ and the limits of beech occurrence

EQ had a "good" ability to discriminate beech occurrence for the case that used all of the inventory fields (AUC = 0.83) and a "fair" ability (AUC = 0.71) when using inventory fields for which land use was assigned only to forests (Appendix C). The xeric EQ limit for beech occurrence varied according to the threshold criteria and the sample selection (entire forest inventory or only the forest land) (Table 1). The EQ limit ranged from 20.1 for the criterion of maximising the kappa value to 29.5 for the criterion of 95% of all beech occurrences. The sum of sensitivity and specificity was lower than the threshold obtained using the same criterion in Hungary (EQ = 28.9) (Czúcz et al., 2011). All beech-dominated inventory stands were included at EQ ≤ 35.1. Fang and Lechowicz

Table 1
EQ threshold values for different criteria.

Criteria	All inventory fields	Inventory fields that contained forests
Maximising kappa	22.3	20.1
Maximising sensitivity + specificity	28.0	25.0
Including 95% of occurrences	29.3	29.5
Including all occurrences	35.1	35.1

Table 2
Proportions of European beech in four EQ classes (modified after Ellenberg (1988)) for the reference period 1961–1990 and the different SRES scenarios.

Time period	Beech (EQ < 20) (%)	Beech and oaks[a] (20 < EQ < 30) (%)	Mixed oaks (EQ > 30) (%)	Beech mortality and pest attack (EQ > 40) (%)
1961–1990 Normal climate	43.8	53.0	3.2	0.0
2001–2030 Scenario A1B	21.5	53.9	24.6	0.1
2071–2100 Scenario A1B	0.0	10.6	89.4	46.9
2071–2100 Scenario A2	0.0	9.0	91.0	49.1

[a] In Serbia, only Sessile oak and Turkey oak appear regularly with beech.

(2006) and Czúcz et al. (2011) suggested that the EQ limit should be approximately 29, and Ellenberg (1988) proposed an EQ limit of 30. However, our statistical analysis has shown that the lower limits provide better performance for two criteria, while the limit for the third criterion was similar to that found in previous studies. The use of different samples resulted in large differences in AUC values (and in thresholds) because all of the forests are located in wet areas with lower EQ values; thus, they are not a random subsample of the inventory. Histograms and 5%, median and 95% quantile data distributions are shown for both sample cases in Appendix D. The differences between the threshold values in the different studies highlight the need for a careful and detailed regional approach.

3.2. Analysis of the distribution of beech for the reference period 1961–1990

The distribution of beech according to forest zones for the reference period has shown that 43.8% of beech forests in Serbia were located in areas of pure beech climate (EQ < 20), and 53.0% of beech forests were located in the beech–oak climate (20 < EQ < 30; Ellenberg, 1988) (Table 2, Fig. 1A and Fig. 2A). The remaining 3.2% of beech forests were located in the mixed oak forest climate (EQ > 30), which are beyond Ellenberg's beech limit. Analysis of the beech inventory fields across the EQ ranges showed a nearly normal (Gaussian) distribution (Fig. 3). The majority of beech stands were located in the zone of 14 < EQ < 30, i.e. in the pure beech and beech–oak climate zones.

3.3. Projections for the period 2001–2030 – scenario A1B

The projected distribution of beech by EQ index classes for the period of 2001–2030 indicates that the current beech forests will experience a change of climate conditions (Fig. 1B, Fig. 2B and Fig. 3). Approximately 22% of the stands in a pure beech climate will shift to a beech–oak climate, and a similar number will change from a beech–oak climate to a pure oak climate (Table 2).

3.4. Projections for the period 2071–2100 – scenarios A1B and A2

As expected, the climate change predicted for the period 2071–2100 includes a severe increase of temperature that will bring significant changes in EQ values. According to the A1B and A2 scenarios, approximately 90% of the present-day beech forests will be in locations with EQ values greater than 30 (Table 2, Fig. 1C, D, Fig. 2C, D and Fig. 3). Mátyás et al. (2010) found that recurrent summer droughts for several consecutive years in which the EQ value was greater than 40 resulted in beech mortality and pest and disease attacks. Up to 47% of existing beech forests will experience mean climate EQ values greater than 40 under the A1B scenario, and approximately 49% of beech forests will experience EQ values greater than 40 under the A2 scenario (Table 2). Because Mátyás et al. (2010) observed only three to four consecutive dry years, it can be assumed that adverse consequences of drought on beech could occur well before the end of the 21st century. Thus, establishing long-term adaptation strategies for beech management is of critical importance.

3.5. Comparison and perspectives

The Intergovernmental Panel on Climate Change's Fourth Assessment Report (IPCC, 2007) foresees an increase in precipitation at higher latitudes and a decrease in precipitation in the Mediterranean region in the 21st century. The mean temperature for Serbia (central part of southeast Europe) for the 2001–2030 A1B scenario is projected to be approximately 1 °C higher than in the reference period 1961–1990. According to scenarios A1B and A2, the seasonal temperature is likely to increase by approximately 3 and 4 °C, respectively, by the end of the 21st century. On the other hand, annual precipitation will most likely increase slightly in the near future and decrease slightly at the end of the century, with corresponding changes in seasonal patterns (Božanić and Gasperič, 2010). The EBU-POM regional climate projections also show that the number of tropical days (with absolute maximum temperature above 30 °C) and the number of consecutive dry days will increase during the 21st century (Kržič et al., 2011). According to the National Republic Hydrometeorological Service of Serbia, a warming trend occurred over the last 12 years. Extreme droughts were recorded in this region in 2000, 2003, 2007, 2011 and 2012 (Table 3), and the highest temperature ever observed in Serbia (44.9 °C) was recorded in 2007.

Numerous studies have used various approaches to cope with growth of beech in relation to climate (Lindner et al., 2000; Lebourgeois et al., 2005; Čufar et al., 2008) and distribution (Fang and Lechowicz, 2006; Rasztovits, 2011). Because beech is the most abundant tree species in Serbia (Banković et al., 2009) and is also naturally abundant in many Mediterranean countries, such as Spain, France, Italy, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Albania and Greece (von Wuehlisch, 2008), dealing with its xeric limit is important for the forest industry and biodiversity conservation in the future. After the severely dry summer of 2003, Granier et al. (2007) found that beech shows a strong negative growth reaction to drought; this underlines the usefulness of Ellenberg's climate quotient (Ellenberg, 1988), which determines the suitability of beech habitats.

The results of this study predict a remarkable change of climate conditions for beech. Compared to the current distribution of beech

Table 3
Climate conditions in Serbia for several recent extremely dry years.

Year	Mean temperature April–October (°C)	Sum of precipitation April–October (mm)	Mean annual temperature (°C)	Sum of annual precipitation (mm)
2012	18.4	367.0	/	/
2011	17.1	300.5	10.8	469.8
2007	17.0	454.6	11.6	775.3
2003	17.1	421.5	10.8	606.3
2000	17.7	262.0	11.9	436.8
1961–1990	15.6	437.1	10.0	690.7

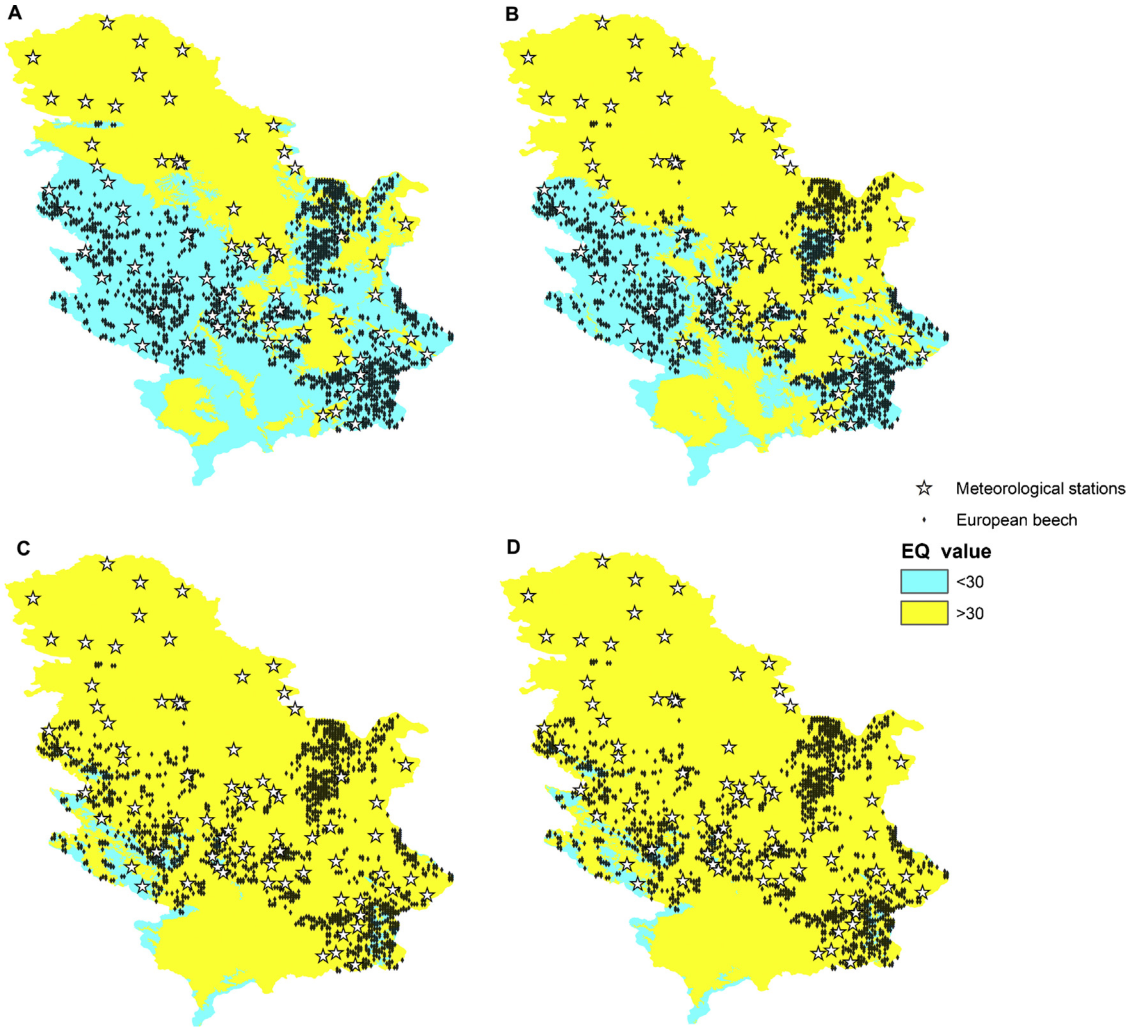


Fig. 1. Maps of interpolated Ellenberg's climate quotient (EQ) showing two classes: (i) beech-suitable climate with EQ values less than 30 (dark area); and (ii) oak-suitable climate with EQ values greater than 30 (light area).

in Serbia, up to 90% of the present-day forests may be located outside their 20th century bioclimatic conditions in the future, and almost 50% may be found in locations of EQ > 40 (for which mass mortality is expected) by 2100. The results agree with the results of Czúcz et al. (2011), who concluded from a bioclimatic distribution model that 56–99% of existing beech forests in Hungary might be outside their bioclimatic niche by 2050. The results obtained by Kramer et al. (2010), who applied state of the art statistical and process-based models to predict the beech distribution in Europe, are also consistent with our findings for the study region, but our study has a higher resolution that is applicable in forest management practice.

The occurrence of an extreme drought during the summer of 2003 led to broad disturbances in European forest ecosystems, which have been reviewed by several authors (Granier et al., 2007; Betsch et al., 2011) and which suggested that such events will most likely be more common in the near future. In Hungary, Lakatos and Molnar (2009) recorded mass beech mortality during the drought of 2000–2004. Raftoyannis and Radoglou (2002) observed changes in the appearance and vigour of beech in contrast to Sessile oak in natural mixed stands during the extremely dry summer of 1998 in Greece; these were due to decreased net photosynthesis and stomatal conductance, which were related to decreased leaf water potential. These results suggest that with increasing soil drought, oak may substitute beech in mixed beech–oak forests. Lebourgeois et al. (2005) studied the relationship between climate and tree growth using tree-ring data and concluded that beech is especially sensitive to drought conditions at the beginning of the growing season and that climate change may shift the competition ratio among species to the detriment of beech and to the benefit of less sensitive tree species such as oaks. Rennenberg et al. (2004) analysed climate data and suggested that beech may be threatened in the future in the southern part of Central Europe, but that research has been criticised by Ammer et al. (2005) due to methodological weaknesses. Jump et al. (2007) recognised temperature as a critical environmental factor for the successful regeneration of beech in the Mediterranean region. Despite the expectation that beech will adapt to new circumstances, evidence suggests the opposite. Huntley et al. (1989) compared the influence of climate on the distribution of beech (*Fagus spp.*) in Europe and North America during the Holocene and found that they were in the same climatic niche even though they had separated between 25 and 10 million years ago. This indicates that fundamental physiological limitations in the genus *Fagus* have not been affected by evolution for millions of years. On the other hand, there is evidence that marginal beech provenances may express better drought adaptation capabilities (Rose et al., 2009) and that southern beech populations show greater ecophysiological adaptive capacity to address

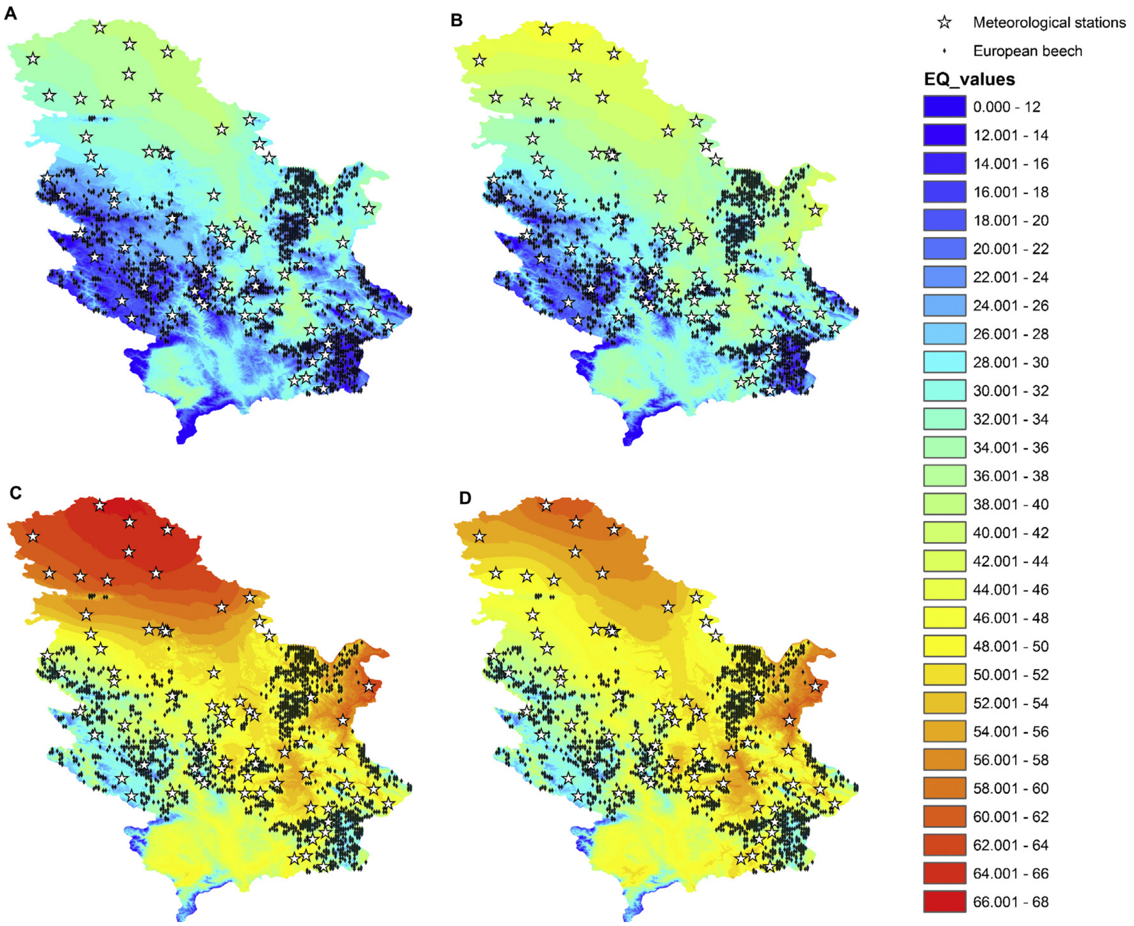
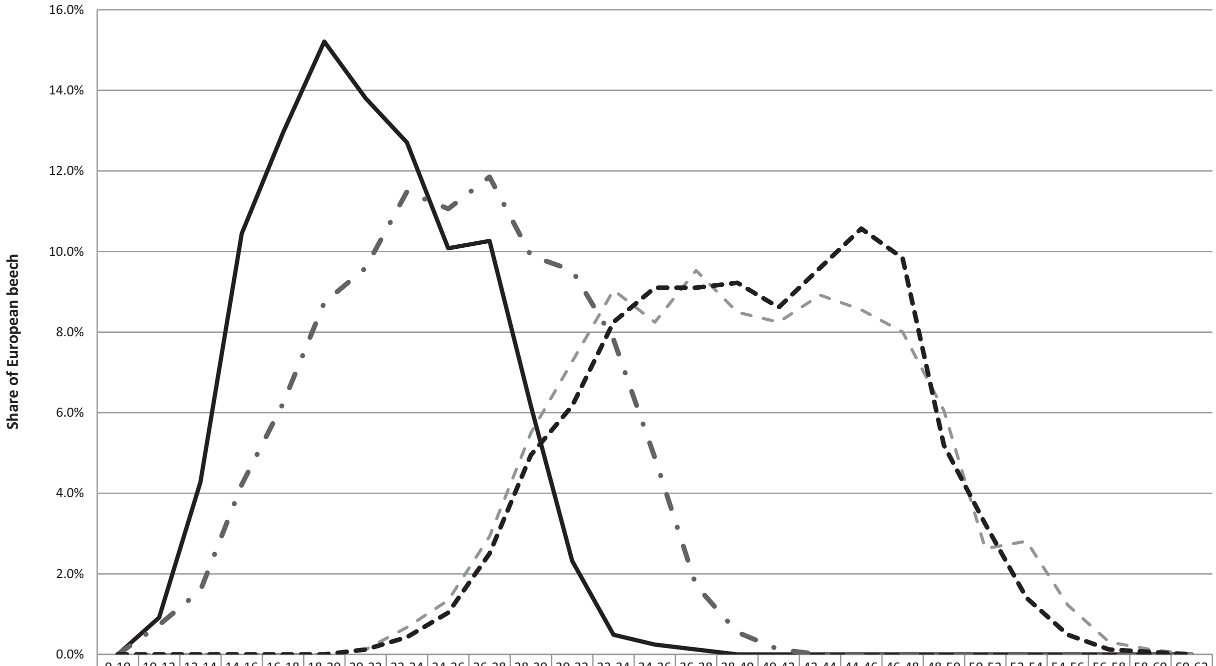


Fig. 2. Maps of interpolated Ellenberg's climate quotient with beech-dominated stands indicated. A – 1961–1990; B – 2001–2030 scenario A1B; C – 2071–2100 scenario A1B; D – 2071–2100 scenario A2.



	0-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30	30-32	32-34	34-36	36-38	38-40	40-42	42-44	44-46	46-48	48-50	50-52	52-54	54-56	56-58	58-60	60-62
EQ 1961-1990	0.0%	0.9%	4.3%	10.4%	13.0%	15.2%	13.8%	12.7%	10.1%	10.3%	6.2%	2.3%	0.5%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EQ 2001-2030 A1B	0.0%	0.7%	1.6%	4.2%	6.2%	8.7%	9.6%	11.5%	11.1%	11.9%	9.9%	9.5%	7.8%	4.9%	1.7%	0.5%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EQ 2071-2100 A1B	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.7%	1.3%	2.9%	5.5%	7.3%	9.0%	8.2%	9.5%	8.5%	8.2%	8.9%	8.6%	8.0%	6.0%	2.6%	2.8%	1.2%	0.3%	0.1%	0.0%
EQ 2071-2100 A2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	1.0%	2.5%	4.9%	6.2%	8.2%	9.1%	9.1%	9.2%	8.6%	9.6%	10.6%	9.8%	5.2%	3.2%	1.4%	0.5%	0.1%	0.1%	0.0%

Fig. 3. Distribution of beech stands by EQ classes for different scenarios.

drought conditions than populations in Central Europe (Fotelli et al., 2009). These results contradict the unfavourable predictions for beech in the future. Our research did not find a significant number of beech forests outside the EQ = 30 limit for the reference period 1961–1990, although no mass mortality of beech has been recorded in Serbia despite extreme weather over the last decade. The results of this study suggest the need for a critical review of possible adaptation strategies and regional and local approaches to the problems facing beech forests in the future.

4. Conclusions

Based on the results of our study, we conclude that:

1. A simple biometeorological index, Ellenberg’s climate quotient (EQ), has shown good predictive ability to determine the beech xeric limit in Serbia based on the AUC.
2. The calculated EQ xeric limit boundaries for European beech in Serbia (southeast Europe, Balkans) in this study were generally lower than those in previous similar studies of other regions.
3. By the end of the 21st century, approximately 90% of the current beech forests will be outside their 20th century bioclimatic niche, and approximately 50% of beech forests will be within a bioclimatic niche for which mass beech mortality has been recorded.
4. The difference between the EQ values that form the beech xeric limits in our study and those in previous studies suggests the need for strict regional and local approaches to beech forest management.

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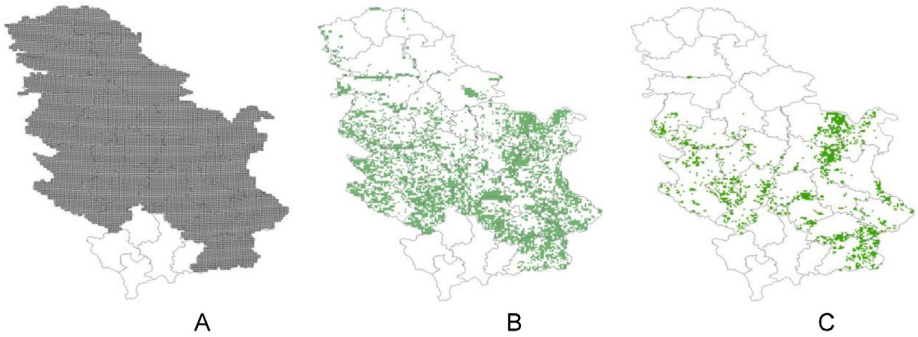
Appendix A. Meteorological stations in Serbia and their coordinates

	Latitude	Longitude	Name
1.	45.05	21.03	“Banatski Karlovac”
2.	45.62	20.07	“Becej”
3.	44.8	20.47	“Beograd”
4.	44.12	21.95	“Crni Vrh”
5.	43.93	21.37	“Cuprija”
6.	43.02	22.75	“Dimitrovgrad”
7.	45.85	20.47	“Kikinda”
8.	43.28	20.8	“Kopaonik”
9.	44.03	20.93	“Kragujevac”
10.	43.72	20.7	“Kraljevo”
11.	43.57	21.35	“Krusevac”
12.	43.13	21.27	“Kursumlija”
13.	42.98	21.95	“Leskovac”
14.	44.55	19.23	“Loznica”
15.	44.23	22.55	“Negotin”
16.	43.33	21.9	“Nis”
17.	46.1	19.77	“Palic”
18.	43.83	20.03	“Pozega”
19.	45.33	19.85	“Rimski Sancevi”
20.	43.28	20	“Sjenica”
21.	44.37	20.95	“Smederevska Palanka”
22.	45.78	19.08	“Sombor”
23.	44.97	19.63	“Sremska Mitrovica”
24.	44.82	20.28	“Surcin”
25.	44.28	19.92	“Valjevo”
26.	44.75	21.52	“Veliko Gradiste”
27.	42.48	21.9	“Vranje”
28.	45.15	21.32	“Vrsac”
29.	43.88	22.28	“Zajecar”
30.	43.73	19.72	“Zlatibor”
31.	45.4	20.35	“Zrenjanin”
32.	45.4	19.25	“Bac”
33.	45.37	19.57	“Backi Petrovac”
34.	45.93	20.08	“Senta”
35.	44.37	19.38	“Krupanj”
36.	44.77	19.68	“sabac”
37.	44.62	19.78	“Vladimirci”
38.	44.38	19.92	“RC Valjevo-Blizonski Vis
39.	44.13	20.52	“Rudnik”
40.	44.9	21.42	“Bela Crkva”
41.	43.97	19.57	“Bajina Basta”
42.	43.1	20.1	“Karajukica Bunari”
43.	43.42	20.23	“Ivanjica”
44.	43.72	20.42	“Kaona”
45.	43.13	20.52	“Novi Pazar”
46.	43.38	20.75	“Josanicka Banja”
47.	43.23	20.85	“Blazevo”
48.	43.62	20.9	“Vrnjacka Banja”
49.	43.55	20.85	“Goc”
50.	44	21.05	“RC Besnjaja”
51.	43.87	21.1	“Rekovac”
52.	43.92	21.02	“Ratkovic”
53.	43.45	21.07	“Aleksandrovac”
54.	43.38	21.03	“Brus”
55.	43.13	21.43	“Pacaradja”
56.	43.3	21.3	“Blace”
57.	43.43	21.38	“Jastrebac”
58.	43.98	21.32	“Jagodina”
59.	43.23	21.6	“Prokuplje”
60.	43.55	21.68	“Aleksinac”
61.	43.65	21.85	“Sokobanja”
62.	43.22	22.32	“Bela Palanka”
63.	43.57	22.27	“Knjazevac”
64.	43.07	22.43	“Babusnica”
65.	43.17	22.6	“Pirot”
66.	42.45	21.78	“Bujanovac”
67.	42.37	22.08	“Trgoviste”
68.	42.83	22.13	“Predejane”
69.	42.97	22.13	“Vlasotince”

Appendix B. Additional maps



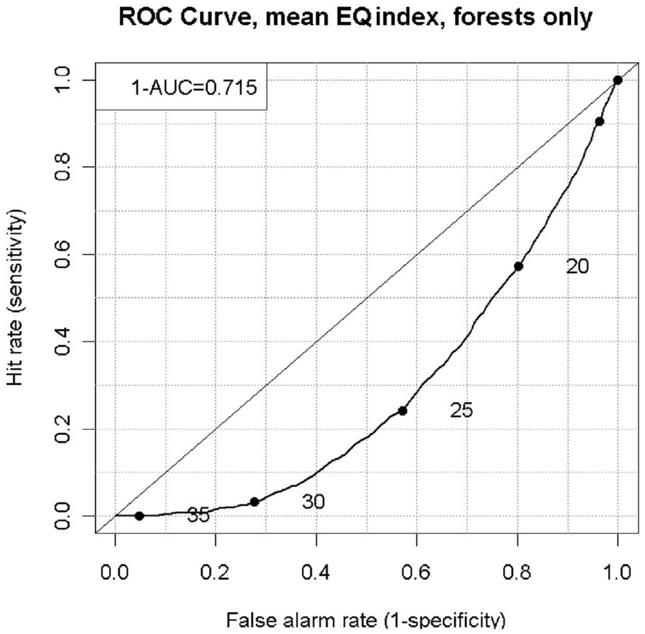
A – All inventory fields

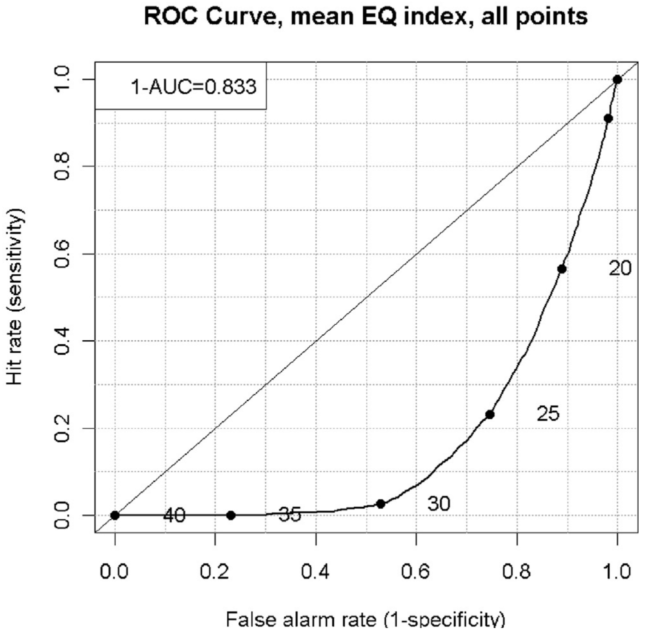
B – Inventory fields that contained forests

C – European beech inventory fields

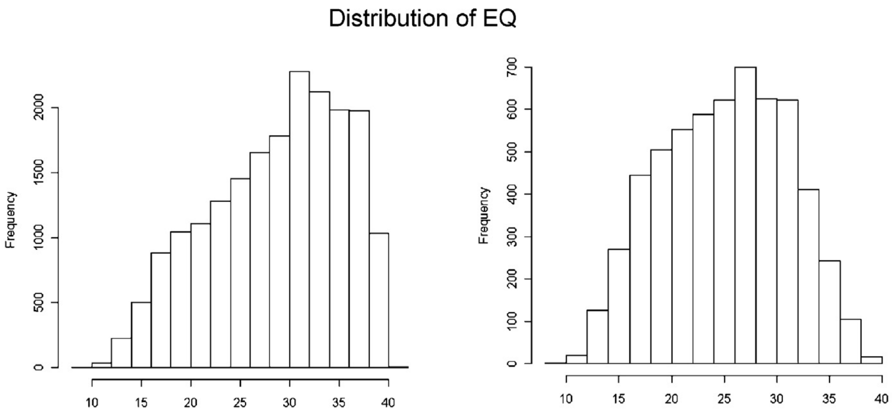
Appendix C.

ROC curves‡‡





Appendix D.



A – over all forest inventory fields B – over inventory fields that contained forests

	All forest inventory fields	Inventory fields that contained forests
5% Quantile	16.5	15.1
Median	29.8	25.4
95% Quantile	38.1	34.5

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