

The potential impact of climate change on the distribution of key tree species in Serbia under RCP4.5 and RCP 8.5 scenarios

Mögliche Auswirkungen des Klimawandels auf die Verteilung der wichtigsten Baumarten in Serbien bei RCP 4.5 und RCP 8.5 Szenarien

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Schlüsselbegriffe: Operationscharakteristik eines Beobachters, Ellenberg-Klimaquotient, Forestry Aridity Index

Abstract

The survival of forest tree species within certain areas of their distributions is in question due to the increasing occurrence of disturbances and degradation processes in forest ecosystems due to climate change. The aim of this paper is to predict changes in the spatial distribution of the ten most important tree species in Serbia (European beech, Pedunculate oak, Austrian oak, Hungarian oak, Sessile oak, Narrow-leafed ash, Silver fir, Norway spruce, Black and Scots pine) using climate indices (Forestry Aridity Index, FAI and Ellenberg Quotient, EQ) with up-to-date climate observations (E-OBS, covering the time period 1990-2019) and projections of future climate conditions (RCP 4.5 and RCP 8.5 scenarios, split into two time periods 2041-2070, 2071-2100). The computation of the area under the receiver operating characteristic (ROC) curves

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has shown that both FAI and EQ have a “fair” to “excellent” ability to predict the occurrence of five out of ten species (European beech, Silver fir, Norway spruce, Black and Scots pine), with EQ having a slightly better predicting ability. EQ-based projections from mid (2041-2070) to late 21st century (2071-2100) under RCP 4.5 predict that reduction rates will not exceed 25%. Similar reduction rates are given by FAI-based projections until 2070, while rates increase to approximately 35% towards the end of this century. For RCP 8.5, FAI-based projections are significantly worse than EQ-based projections. Irrespective of the used index, projections until 2070 suggest that 55-75% of existing habitats will remain intact. Towards the end of the century, however, our analysis indicate that 75-85% (EQ) to 90-100% (FAI) of the five analyzed species habitats, will be found outside of their current climate space.

Zusammenfassung

Durch das zunehmende Auftreten von Störungen und Degradationsprozessen in Waldökosystemen aufgrund des Klimawandels ist das Überleben einiger Baumarten in bestimmten Gebieten Serbiens unklar. Das Ziel dieser Arbeit ist es, Veränderungen in der räumlichen Verteilung der zehn wichtigsten Waldbaumarten (Rotbuche, Stieleiche, Zerreiche, Ungarische Eiche, Traubeneiche, Schmalblättrige Esche, Weißtanne, Gemeine Fichte, Schwarzkiefer/Waldkiefer) in Serbien mittels Klimaindices (Forestry Aridity Index, FAI und Ellenberg-Klimaquotient, EQ) mit aktuellen Klimamessdaten (E-OBS, Zeitraum 1990-2019) und Prognosen der zukünftige Klimabedingungen (RCP 4.5 und RCP 8.5, in zwei Zeiträume geteilt, 2041-2070, 2071-2100) vorherzusagen. Die Berechnungen mittels ROC-Kurve (Operationscharakteristik eines Beobachters) zeigt, dass sowohl FAI als auch EQ "gut" bis "ausgezeichnet" geeignet sind, das Auftreten von fünf von zehn Baumarten (Rotbuche, Weißtanne, Gemeine Fichte, Schwarzkiefer/Waldkiefer) wiederzugeben, wobei EQ etwas besser geeignet war. Es zeigte sich, dass auf Basis von EQ und dem RCP 4.5 Szenario von der Mitte des 21. Jahrhunderts (2041-2070) bis zum Ende des Jahrhunderts (2071-2100) keine Reduktionsraten geeigneter Lebensräume zu erwarten sind, die 28% überschreiten. Ähnliche Reduktionsraten zeigen Prognosen des FAI bis zur Mitte des Jahrhunderts, während gegen Ende des Jahrhunderts diese auf etwa 35% steigen. Bei RCP 8.5 sind die auf FAI basierenden Projektionen im Vergleich zu EQ deutlich schlechter. Während in beiden Fällen (EQ und FAI) die Prognosen für die Mitte des Jahrhunderts vorhersagen, dass etwa 55% bis 75% der vorhandenen Lebensräume intakt bleiben wird, sind die Prognosen zum Ende des Jahrhunderts wesentlich beunruhigender. Unsere Ergebnisse zeigen, dass 75-85% (EQ) bis 90-100% (FAI) der fünf analysierten Artenlebensräume bis zum Ende des 21. Jahrhunderts außerhalb der derzeitigen klimatischen Zonen liegen werden.

1. Introduction

Climate change and its associated impacts on all aspects of life represents an enormous challenge to present and future environmental, economic, and social well-being. Forests covering 31% of the global land area (FAO and UNEP, 2020) have great

social-economic and ecological importance and are particularly endangered by climate change due to their inability to adapt quickly to rapidly changing conditions. Trees are sensitive to climate change, as an increase of just 1 °C in mean annual air temperature is sufficient to cause significant changes in the growth and regeneration capacity of many tree species (Kirschbaum and Fischlin, 1996). The consequences of this relatively minor change have been contributed across forests in Europe in recent years to more frequent dieback, pest outbreaks, reduced productivity or loss of vitality (Spathelf *et al.* 2013).

Climate indices such as the Forestry Aridity Index (FAI), the Ellenberg Quotient (EQ) (Führer *et al.* 2011, Vlăduț *et al.* 2017, Salamon-Albert *et al.* 2016, Nedelcov *et al.* 2019, Mellert *et al.* 2015, Trombik *et al.* 2013, Garamszegi and Kern, 2014, Jović *et al.* 2018, Móricz *et al.* 2018, Mátyás *et al.* 2018), the Standardized Precipitation Evapotranspiration Index, the Palmer Drought Severity Index, the Standardized Precipitation Index (Stojanović *et al.* 2015b, Boczoń *et al.* 2018), the Pálfaí Drought Index (Ladányi and Blanka 2015, Mátyás *et al.* 2018), and others can be used to investigate the effects of climate on forest growth. Some of these climate indices, like FAI and EQ, as well as many bioclimatic variables, have been used in species distribution modelling (SDM) as predictors to predict future tree species occurrence on continental European scale (Lindner *et al.* 2014, Falk & Hempelmann 2013, Thurm *et al.* 2018, Buras & Menzel 2019, Noce *et al.* 2017, Goberville *et al.* 2016, Ruosch *et al.* 2016) and regional scales including Serbia (Pavlović *et al.* 2019, Stojanović *et al.* 2013, Stojanović *et al.* 2014), Montenegro (Matović, 2013), Hungary (Czúcz *et al.* 2011, Mátyás *et al.* 2018, Móricz *et al.* 2013), Germany (Falk & Mellert 2011, Walentowski *et al.* 2017), Italy (Pecchi *et al.* 2020, Marchi *et al.* 2016), Slovenia (Kutnar & Kobler, 2011), and Iran (Taleshi *et al.* 2019). The common denominator in each of these studies is the prediction of shifts toward higher elevations and severe reductions in climate-suitable areas of mesophilous or hygrophilous species (*e.g.*, Scots pine, Norway spruce, Silver fir, Grand fir, European beech, Oriental beech, etc.). Some of the studies listed above, especially those on European scale, predict the sustainability of existing or expansion of climatically-suitable areas for xerophilous tree species such as Sessile oak and Black pine under climate change. Analyses conducted by Walentowski *et al.* (2017), Friedrichs *et al.* (2009), and Eilmann & Rigling (2012) suggest that there is a real threat to the survival of deciduous and coniferous species that are characterized as mesophilous and/or hygrophilous due to their poor tolerance of extreme climate events. Over the past two decades, such events have been increasingly reported for European beech (Štajner *et al.* 2017), Norway spruce (Matović *et al.* 2018, Karadžić *et al.* 2017), Pedunculate oak, and Austrian oak forests (Stojanović *et al.* 2015a, Stojanović *et al.* 2015b). Given that such events can be expected to occur with greater frequency in the future, SDMs can be useful for identifying indicators of degradation processes.

The aim of this study is to predict the distributions of ten tree species (Silver fir, Norway spruce, European beech, Austrian oak, Sessile oak, Pedunculate oak, Hungarian oak, Narrow-leafed ash, black and Scots pine) in Serbia using EQ and FAI indices with

climate observations (E-OBS: 1990-2019) and emission scenarios (RCP 4.5 and 8.5: 2041-2070, 2071-2100).

This study represents the first attempt to model the distribution of different tree species in Serbia. The novelty in this research is the use of the most recent climate data (1990-2019), which is a significant improvement in comparison to previous studies. This study also takes advantage of the most recent climate change projection data (Representative Concentration Pathway – RCP).

2. Material and methods

2.1 Climatic data

To evaluate past and future climate characteristics, we used:

1. The forest aridity index (FAI) of Führer *et al.* (2011), which takes into account the average temperature of the critical months (July and August; °C) and precipitation during the main growth cycle (May to July), as well as precipitation during the critical months (July and August; mm) (1).

$$FAI = \frac{100 * \frac{T_{VII} + T_{VIII}}{2}}{P_V + P_{VI} + 2 * P_{VII} + P_{VIII}} \quad (1)$$

2. Ellenberg's (1988) climate quotient (EQ), which takes into account the average temperature of the warmest month (July; °C) and annual precipitation (P_{annual}) (2).

$$EQ = \left(\frac{T_{VII}}{P_{annual}} \right) * 1000 \quad (2)$$

From the E-OBS v21.0 gridded dataset (Cornes *et al.* 2018), we extracted climatic data to calculate the FAI and EQ indices for the reference period (1990-2019) and for the past climatic sequence (1961-1990). For future projections, we used the Representative Concentration Pathway (RCP) 4.5 and 8.5 for mid- (2041-2070) and late- (2071-2100) 21st century scenarios (Marchi *et al.* 2020).

2.2 Spatial data analysis

Data regarding the spatial distribution of forest species were obtained from Serbia's National Forest Inventory (NFI). The inventory is based on a systematic sampling process that uses a 4x4 km network of sampling clusters (Banković *et al.* 2009). NFI clusters that fall outside afforested area were removed from the dataset based on satellite images. The NFI considered all inventory plots to be forested if they have an area of more than 0.5 ha and are overgrown with forest trees whose crowns cover or should reach a coverage of more than 10% of the area, where the trees must be able to reach a minimum height of 5 m at felling age. For our research, it is especially important

that all trees in an inventory unit are identified and the stand affiliations estimated. Accordingly, we used rasters of stand affiliation from the NFI, due to the higher representative value of such data in terms of reading the conditionality of the occurrence of a certain species with different habitat characteristics. The selection of species for this analysis is based on the list of main tree species managed by two state enterprises for forest management – "Srbijašume" and "Vojvodinašume" (SE "Srbijašume", 2021 & SE "Vojvodinašume", 2021). Special emphasis is placed on species whose stands are predominantly of natural origin (Silver fir, Norway spruce, European beech, Austrian oak, Sessile oak, Pedunculate oak, Hungarian oak, Narrow-leaved ash, and Black and Scots pine). This eliminates possible errors that may occur due to the analysis of species whose occurrence in certain areas is the result of anthropogenic activity, such as acacia and selected black poplar and willow varieties. It is important to note that, despite their different ecological requirements, the NFI methodology registers Black and Scots pine under a single category, "pine forests". Using the R statistical environment (R Core Team, 2020) and its "base" package coupled with the "raster" package (Hijmans, 2020), the spatial distribution of forest species is converted to a binary type raster. Using packages "base" (R Core Team, 2020), "ncdf4" (Pierce, 2019), and "raster" (Hijmans, 2020), climate data are processed, converted to raster (E-OBS), resampled, cropped to match resolution and extent of the binary type raster, and exported to an ArcMap 10.5 (ESRI, 2016) supported format. Maps of elevation and total forest cover were created within ArcMap 10.5 using the European Digital Elevation Model (EU-DEM) version 1.1. and Corine Land Cover (CLC) 2018 data from the European Environment Agency (EEA).

To examine whether FAI and EQ indices can predict the occurrence of the analyzed species, we computed the area under the receiver operating characteristic (AUC), a widely used statistic for assessing the discriminatory capacity of species distribution models (Jiménez-Valverde, 2011), using the R package "pROC" (Robin *et al.* 2020). Accuracy classification of AUC has been carried out using a scale where: 0.50–0.60 = fail; 0.60–0.70 = poor; 0.70–0.80 = fair; 0.80–0.90 = good; 0.90–1 = excellent (Swets 1988, as cited in Rasztovits 2011). Bearing in mind that algorithms with low AUC values produce very inconsistent spatial predictions (Aguirre-Gutiérrez *et al.* 2013), we have omitted species with "poor" accuracy from the prediction analysis. To determine best-fitting FAI and EQ values that describe the occurrence of the analyzed species, we used a threshold that maximizes the sum of sensitivity and specificity (Cantor *et al.* 1999, as cited in Liu *et al.* 2005, Czúcz *et al.* 2011, as cited in Stojanović *et al.* 2013).

With the help of the extract function from the "raster" package (Hijmans, 2020), we determined the minimum, maximum, mean, and standard deviation of FAI and EQ indices for the distribution of each current forest type (excluding the autonomous province of Kosovo and Metohija) in the reference and past climate sequences. We also calculated the differences between the mean values of the FAI and EQ indices of both climate sequences. Based on the previously calculated thresholds for each species, the FAI and EQ rasters for the reference and projected periods were reclassified

to consist of two classes using the “base” (R Core Team, 2020) and “raster” (Hijmans, 2020) packages. The first class contains all raster pixels whose values are equal to or less than the specified threshold; all other pixels make up the second class. The relative share of the total number of raster pixels in the first class represents the relative share of climatically-suitable habitats in the observed and projected periods. These calculations were performed separately for the area of current-day forests (Table 3) and the total area of Serbia (Table 4). The relative difference (Δ) between the values for the observed and projected periods represents a gain or loss of climatically-suitable habitats depending on whether the difference is positive or negative. It is important to note that the relative share of climatically-suitable habitats within areas of current-day forests in the reference period also represents an indicator of threshold spatial precision (Table 3, column E-OBS). The final map visualization was completed using ArcGIS 10.5 software (ESRI, 2016).

3. Results and Discussion

According to FAI and EQ values (Table 1), Hungarian oak forests and floodplain forests of Narrow-leaved ash and Pedunculate oak occur in the most “arid” zone. Other oaks also occupy more arid habitats, whereas Silver fir and Norway spruce grow in the most humid climates. European beech and Black and Scots pine are found in areas characterized by a moderately humid climate. In accordance with their growth and development capabilities, Austrian oak, Sessile oak, Hungarian oak, European beech, and Black and Scots pines are found in a wide range of climatic conditions (Table 1). As expected, species referred to as “azonal” (Narrow-leaved ash and Pedunculate oak) and “climax” (Silver fir and Norway spruce) have the narrowest ecological niches (Table 1). Many such species constitute a significant areas of forests, especially European beech in hilly and mountainous areas (Pavlović *et al.* 2019) and pedunculate oak and narrow-leaved ash in lowlands (Ivanišević and Knežević, 2008, as cited in Bobinac *et al.* 2010).

Table 1: Minimum, maximum, mean, and standard deviations of FAI and EQ values in current forest distribution.

Tabelle 1: Minimale, maximale, mittlere und Standardabweichung der FAI- und EQ-Werte in der aktuellen Waldverteilung.

Stand type	1990 – 2019								1961-1990	
	MEAN		MIN		MAX		SD		Δ MEAN	
	FAI	EQ	FAI	EQ	FAI	EQ	FAI	EQ	FAI	EQ
Silver fir	4.438	20.773	3.570	15.430	5.323	24.921	0.528	2.887	0.526	1.207
Norway spruce	4.828	22.190	3.620	16.065	7.895	33.804	1.136	4.892	0.644	1.370
Black and Scots pine	5.836	26.496	4.080	18.979	9.594	38.260	1.325	5.034	0.886	1.919
European beech	5.882	27.061	3.620	16.065	8.902	38.369	1.119	4.642	0.932	2.108
Austrian oak	6.529	29.780	4.257	19.850	9.288	39.585	1.216	4.702	1.827	2.130
Sessile oak	6.699	30.237	4.412	20.867	9.198	39.417	1.125	4.456	1.036	2.342
Pedunculate oak	7.119	35.834	6.684	32.822	7.885	42.310	0.394	2.861	0.561	1.361
Narrow-leaved ash	6.835	34.132	5.758	29.493	7.348	36.865	1.064	2.887	0.759	2.109
Hungarian oak	6.938	31.443	4.733	21.824	9.557	40.339	1.277	4.271	1.032	2.353

Compared to the previous climate sequence (1961-1990), the trend of increasing FAI values in the more recent sequence is least pronounced in areas where Silver fir and Norway spruce are present (Table 1). This is expected due to their dominance at higher elevations (Figure 1), where warmer temperatures are more likely to benefit growth. Interestingly, lowland forests of Pedunculate oak and Narrow-leaved ash also exhibit minor FAI trends. In the context of this study, increase of FAI values in areas where the most widespread tree species is present - European beech, can be described as moderate. Almost the same trend is observed in the areas populated by oaks (except for Austrian oak) and pines (Table 1). These extreme results for the widespread Austrian oak are not surprising (Table 1), as it inhabits predominantly xerophilous habitats at lower elevations (Figure 1). These habitats are especially vulnerable to climate change. In the case of the EQ index, the differences between the two climate series are fairly uniform among all species, except for areas inhabited by Silver fir, Norway spruce and Pedunculate oak, where the differences are the least pronounced (Table 1). Nevertheless, their narrow ecological niche makes them highly vulnerable to climate change. Interestingly, our results (Table 1) show that some European beech stands (Figure 1) are found close to the marking value (EQ=40) for its disappearance (Budeanu *et al.* 2016, as cited in Vlăduț *et al.* 2017). Given to the observed climatic trend, the number of stands that will be close to this value will only increase in the coming years.

3.1 Determination of the predictive accuracy of FAI and EQ

According to our analysis, the FAI index has a “fair” to “excellent” ability to discriminate the occurrence of four out of ten analyzed species, with AUC ranging from 0.739 to 0.927 (Table 2). In contrast, the EQ index has a “poor” to “excellent” ability to discriminate the occurrence of six out of nine analyzed species, with AUC ranging from 0.665

to 0.932 (Table 1). The lowest AUC values in both indices are mainly found in azonal species (e.g., Pedunculate oak and Narrowed-leafed ash) and species with wide ecological niches (e.g., oaks). For this reason, they are omitted from further analysis. As expected, the highest AUC values are found in climax species (e.g., Silver fir and Norway spruce). FAI thresholds show different spatial precision (Table 4) that is usually highly correlated with AUC accuracy (Table 2). This is not the case with Norway spruce, however. Although the accuracy of its AUC value is classified as “good”, the Norway spruce threshold describes only two-thirds (78.08%) of its spatial distribution (Table 3 and Figure 1.). Similar results are obtained for Black and Scots pine, but to a lesser extent. Norway spruce has a “fair” AUC classification and its EQ threshold describes 65.89% of its current-day distribution. Such results should not be surprising. According to Tomić *et al.* (2011), forest plantations of Norway spruce, and Black and Scots pine were mass-produced between the 1950s and the 1970s in areas with inadequate habitat characteristics. The low precision of the pine AUCs can also be explained by the different ecological needs of Black and Scots pine, which are lumped together in the NFI classification. However, the spatial precision of the EQ thresholds are quite similar to those of the FAIs, with one exception (Table 3 and Figure 1). The EQ threshold explains almost all (90.23%) of the spatial distribution of European beech, in contrast to its FAI analogue (75.99%).

Table 2: Statistical parameters for FAI and EQ index based on E-OBS observed climate dataset (1990 – 2019).

Tabelle 2: Statistische Parameter für FAI- und EQ-Index basierend auf dem von E-OBS beobachteten Klimaangaben (1990 – 2019).

Tree species	Threshold		AUC		Accuracy		Sensitivity		Specificity	
	FAI	EQ	FAI	EQ	FAI	EQ	FAI	EQ	FAI	EQ
Silver fir	5.334	24.953	0.927	0.932	excellent	excellent	0.917	0.917	0.853	0.859
Norway spruce	5.510	25.556	0.879	0.904	good	excellent	0.780	0.789	0.841	0.856
European beech	6.758	32.910	0.756	0.823	fair	good	0.757	0.902	0.700	0.667
Black and Scots pine	6.333	28.084	0.739	0.771	fair	fair	0.717	0.660	0.726	0.783
Austrian oak	6.880	35.127	0.591	0.680	fail	poor	0.599	0.897	0.613	0.467
Sessile oak	6.713	35.144	0.572	0.665	fail	poor	0.563	0.885	0.641	0.437
Pedunculate oak	6.482	31.505	0.491	0.581	fail	fail	0.937	0.959	0.329	0.369
Narrow-leafed ash	6.325	31.356	0.513	0.581	fail	fail	0.966	0.966	0.293	0.363
Hungarian oak	7.040	35.067	0.484	0.593	fail	fail	0.557	0.819	0.531	0.437

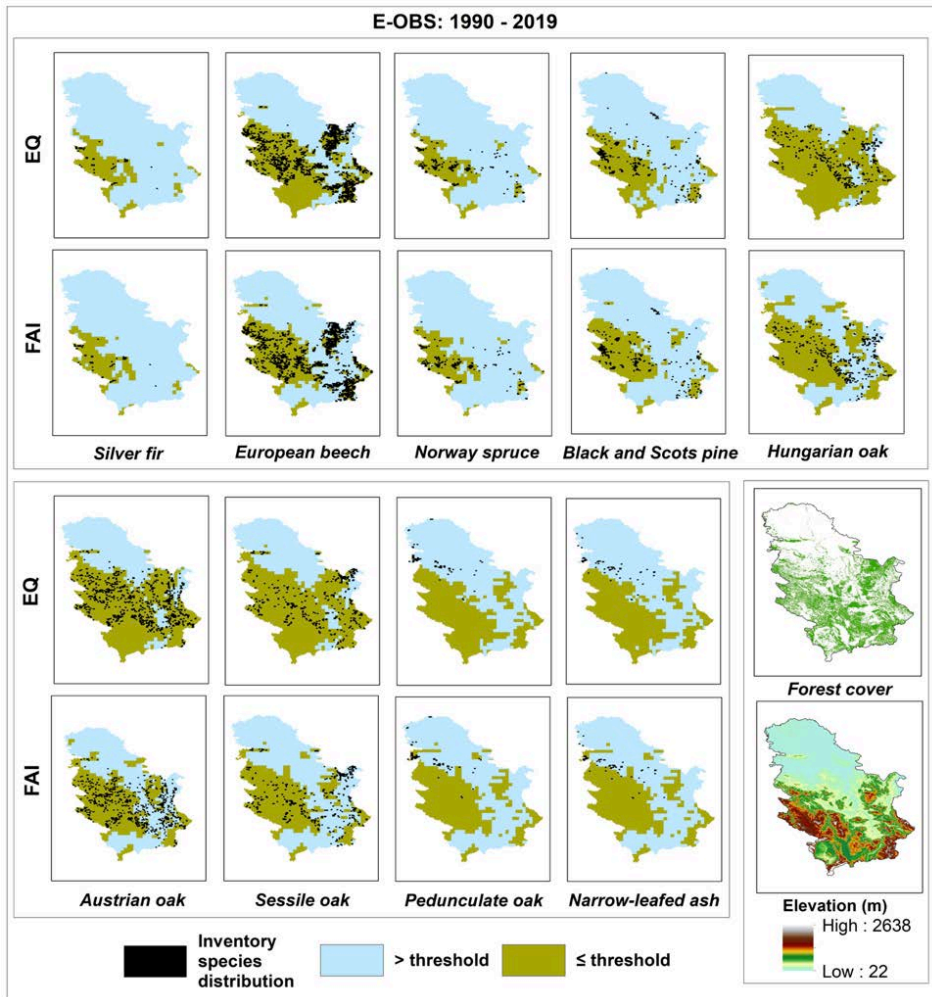


Figure 1: Map of the current forest trees distribution with indicated FAI and EQ index thresholds for observed climate (E-OBS, 1990-2019) with the display of elevations and overall forest cover in Serbia.

Abbildung 1: Karte der aktuellen Waldbaumverteilung mit den angegebenen FAI- und EQ-Indexschwennenwerten für das untersuchte Klima (E-OBS, 1990-2019) mit Anzeige der Höhen und der gesamten Waldbedeckung in Serbien.

3.2 FAI- and EQ-based projections

The increased FAI and EQ values shown in Figures 2 and 3 indicate that parts of Serbia, especially the southern and southeastern parts, are likely to be severely impacted by climate change. However, local and international studies indicate that the reactions of forests to climate change are likely to differ depending on the overall ecological needs and provenance characteristics of their species (Stojanović *et al.* 2015a, Mikac *et al.* 2018, Horváth and Mátyás 2016, Matović *et al.* 2018, Rybníček *et al.* 2012, Čermák *et al.* 2017, Castagneri *et al.* 2015, Tikvić *et al.* 2008, Jović *et al.* 2018, Gavrillov *et al.* 2019, Horák *et al.* 2014, Stjepanović *et al.* 2017, Carrer *et al.* 2012, Spathelf *et al.* 2013, Führer *et al.* 2016, Isaac-Renton *et al.* 2018, George *et al.* 2015, Taeger *et al.* 2013, Arend *et al.* 2011, Robson *et al.* 2012, Rose *et al.* 2009, Matías *et al.* 2016). This should be kept in mind because increasing aridity levels do not explicitly mean the disappearance of species. Further investigation into the impacts of climate change could tell us much more about current and future environmental processes.

Table 3: Percent of climatically-suitable areas and relative difference between observed and projected climate conditions within current NFI trees distribution based on FAI and EQ index and their threshold.

Tabelle 3: Prozentsatz klimatisch geeigneter Gebiete und relativer Unterschied zwischen beobachteten und projizierten Klimabedingungen innerhalb der aktuellen Baumverteilung basierend auf FAI- und EQ-Index und deren Schwellenwert.

Tree species	E-OBS (%)		RCP 4.5 – E-OBS (%)				RCP 8.5 – E-OBS (%)			
	1990-2019		2041-2070		2071-2100		2041-2070		2071-2100	
	FAI	EQ	Δ FAI	Δ EQ	Δ FAI	Δ EQ	Δ FAI	Δ EQ	Δ FAI	Δ EQ
Silver fir	93.10	93.10	-12.80	-7.83	-23.79	-11.38	-39.74	-19.89	-100.00	-70.93
Norway spruce	78.08	78.45	-15.43	-10.72	-24.10	-14.85	-37.30	-20.57	-99.76	-65.33
European beech	75.99	90.23	-11.44	-15.07	-28.35	-23.72	-41.89	-38.30	-93.85	-69.79
Black and Scots pine	71.39	65.89	-18.33	-15.67	-31.49	-20.96	-44.21	-31.63	-97.91	-75.73

Table 4: Percent of climatically-suitable areas and relative difference between observed and projected climate conditions within whole territory of Serbia based on FAI and EQ index and their threshold.

Tabelle 4: Prozentsatz klimatisch geeigneter Gebiete und relativer Unterschied zwischen beobachteten und projizierten Klimabedingungen innerhalb des gesamten Territoriums Serbiens basierend auf FAI- und EQ-Index und deren Schwellenwert.

Tree species	E-OBS		RCP 4.5 – E-OBS				RCP 8.5– E-OBS			
	1990-2019		2041-2070		2071-2100		2041-2070		2071-2100	
	FAI	EQ	Δ FAI	Δ EQ	Δ FAI	Δ EQ	Δ FAI	Δ EQ	Δ FAI	Δ EQ
Silver fir	15.38	16.39	-37.49	-13.96	-60.23	-26.02	-77.57	-41.97	-99.84	-85.93
Norway spruce	17.65	17.94	-34.12	-13.41	-56.55	-24.93	-72.19	-41.09	-99.68	-82.84
European beech	38.52	49.93	-23.84	-17.39	-42.47	-27.14	-55.06	-41.40	-94.16	-71.45
Black and Scots pine	29.16	27.48	-23.10	-16.13	-43.54	-27.29	-57.02	-42.96	-97.38	-75.21

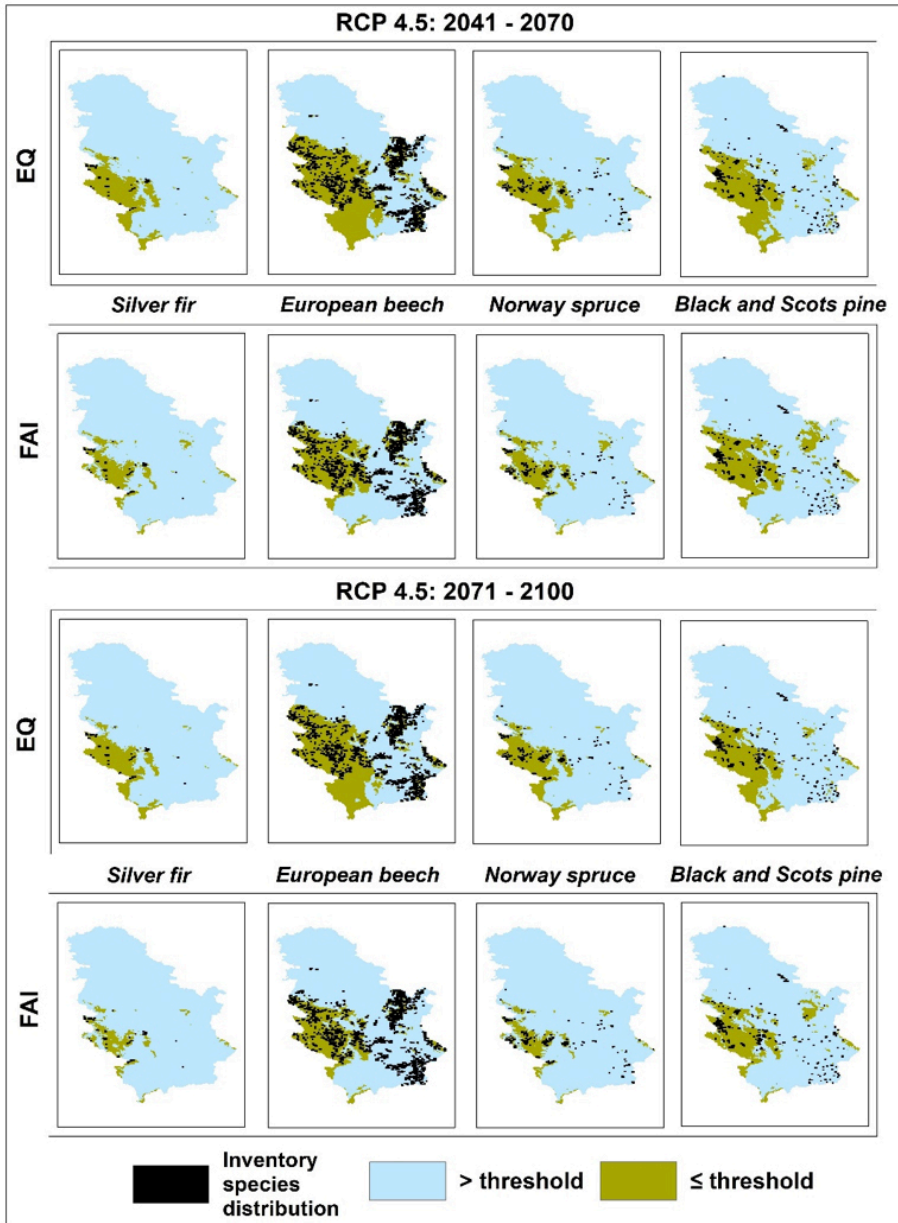


Figure 2: Map of the current forest tree species distribution over FAI and EQ maps for projected climate (RCP 4.5 for periods 2041-2070 and 2071-2100).

Abbildung 2: Karte der aktuellen Verteilung der Waldbaumarten über FAI- und EQ-Karten für das projizierte Klima (RCP 4.5 für die Zeiträume 2041-2070 und 2071-2100).

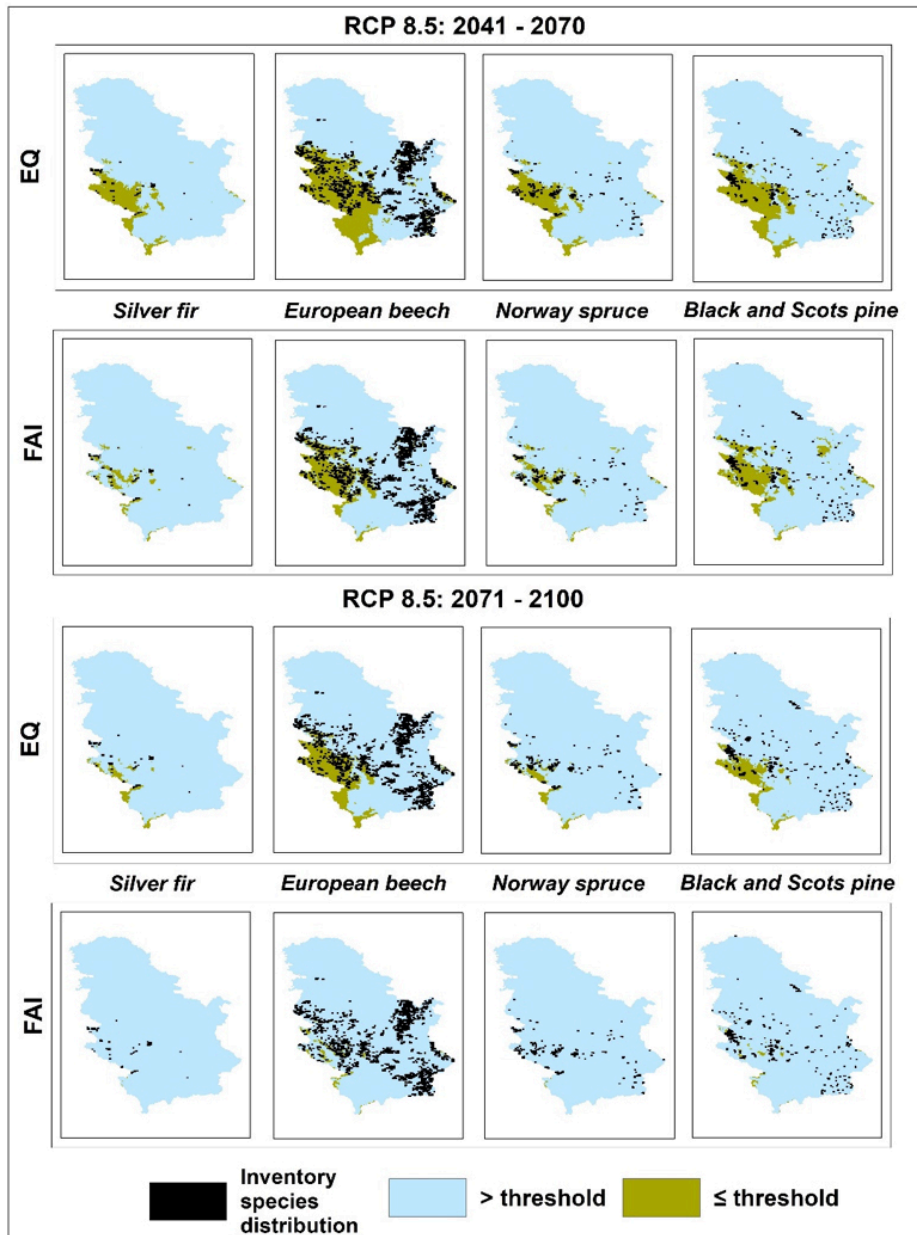


Figure 3: Map of the current forest tree species distribution over FAI- and EQ-maps for projected climate (RCP 8.5 for periods 2041-2070 and 2071-2100).

Abbildung 3: Karte der aktuellen Verteilung der Waldbaumarten über FAI- und EQ-Karten für das projizierte Klima (RCP 8.5 für die Zeiträume 2041-2070 und 2071-2100).

3.2.1 Silver fir and Norway spruce

According to FAI- and EQ-based RCP 4.5 projections, climatically-suitable areas throughout Serbia, where the presence of Silver fir and Norway spruce is not recorded, will partially withdraw from their eastern and southern "borders" towards higher elevations in the western part of Serbia by mid-century (2041-2070). Late-century (2071-2100) projections predict an intensification of these changes (spatially and value-wise). Up to 2.5 times higher reduction rates under FAI-based projections than those under EQ-based projections (Table 4) results in the narrowing of climate-friendly areas around existing spruce and fir habitats (Figure 1 and 2). Since FAI provides more extreme predictions, it may be worth stressing that it has stronger focus on climate data during growing season. Thus, Silver fir and Norway spruce may not be particularly endangered, as both EQ- and FAI-based projections give similar reduction rates that are relatively small and constant from mid to late century (around 20%) (Table 3). According to these projections, existing Norway spruce sites in the southeast and few sites of Silver fir in the east will be found under the impact of climate change (Figure 1 and 2).

FAI- and EQ-based mid-century projections under RCP 8.5 predict spatial changes similar to those under the RCP 4.5 scenario, but with almost twice the reduction rate of suitable habitats (Table 4). In this case, the withdrawal of suitable habitats is most pronounced from the northeast to the southwest. (Figures 1, 2, and 3). Such changes will increase the reduction rates of suitable habitats for Silver fir and Norway spruce by 20.96% (EQ) to 31.49% (FAI) (Table 3). Late-century FAI- and EQ-based projections under RCP 8.5 are even less promising, as they predict the severe to complete reduction of suitable habitats. The same is seen for the entire territory of Serbia (Table 4). Only the EQ-based projections leave some room for the survival of Silver fir and Norway spruce at higher elevations in west Serbia (Table 3, Figures 1 and 3).

3.2.2 European beech

In the case of European beech, all of the FAI index projections are quite uniform (Tables 3 and 4). From the mid to late century, they all predict an increasing reduction of climatically-suitable habitats (Table 4) toward the west, especially at lower elevations where the presence of European beech is not currently recorded (Figures 1, 2, and 3). In contrast, all major changes under EQ-based projections are those affecting the spatial distribution of European beech (Figures 1, 2, and 3). These predictions are to be expected as the threshold obtained from the ROC analysis almost perfectly outlines the distribution of European beech in Serbia. With regard to the distribution of European beech, FAI- and EQ-based projections under RCP 4.5 give almost identical results, predicting a slight reduction of suitable habitats at mid-century (not exceeding 15%), with only a slight further decrease by the end of the century (Table 3), especially in the south and southeast (Figures 1 and 2).

Similarly, there is little difference in the FAI- and EQ-based mid-century projections of the distribution of European beech under RCP 8.5. Both projections predict a severe reduction of suitable habitats in the south and southeast and, to a lesser extent, in the east and west (Figures 1 and 3). Compared to their RCP 4.5 analogues, however, the overall reduction rates are up to three or four times greater (Table 3). The EQ-based late-century projection gives more promising results as compared to the almost complete reduction predicted by its FAI analogue. The EQ-based projections predicts that 30.21% of European beech (Table 3) distributed at higher elevations in west Serbia may remain intact (Figures 1 and 3).

3.2.3 Black and Scots pine

According to the RCP 4.5 mid-century FAI- and EQ-based projections, climatically-unsuitable areas for Black and Scots pine in Serbia will expand by about 20% (Table 4) in the central part of the country (in the form of several "peninsulas"). Such changes will be largely present in directions from the east to the west and from the south to the north, exclusively at lower elevations where the presence of Black and Scots pine has not been recorded (Figures 1 and 2). However, an expansion of climatically-suitable areas under the FAI-based projection is predicted in the east, where the presence of Black and Scots pine has been recorded in smaller areas (Figures 1 and 2). In the south and southeast, where pine is more common, both FAI- and EQ-based projections predict reductions of almost 100%. This contributes significantly to the overall reduction of suitable habitats in Black and Scots pine inhabited areas (which is around 15%) (Table 3, Figures 1 and 2). FAI- and EQ-based RCP 4.5 projections for the late 21st century predict almost twice the reduction rate as compared to mid-century projections (Table 4). The expansion of climatically-unsuitable areas is predicted further on the directions observed in mid-century projections, whereby they will partially enter into the areas where Black and Scots pine are present. (Figures 1 and 2). With regard to the distribution of Black and Scots pine, common in both (FAI- and EQ-based) projections is a relatively small increase of reduction rates, compared to those from mid-century projections (Table 3). This is especially pronounced in the case of EQ-based projection (Table 3). Interestingly, the increase in climatically-suitable areas in eastern Serbia predicted by the FAI-based mid-century projection under RCP 4.5 now decreases to the state in the observed climatic period (E-OBS: 1991-2019) (Figures 1 and 2).

Mid-century projections under FAI- and EQ-based RCP 8.5 predict a complete reduction of suitable habitats in the east and southeast, which makes up about half of the total area of suitable habitats in Serbia (Table 4), leaving only the western distributions of Black and Scots pine intact (Table 3, Figures 1 and 3). As usual, the FAI-based projection (under RCP 8.5) predicts a slightly higher reduction rate (Table 3), resulting in the expansion of unsuitable habitats in southwestern Serbia (Figures 1 and 3). In contrast to the FAI-based late-century projection under RCP 8.5, which predicts an almost complete reduction of suitable habitats, the EQ-based projection intensifies changes (spatially and value-wise) predicted by the mid-century projection. Howe-

ver, it still leaves some room for the survival of 24.27% of Black and Scots pine sites located in the higher elevations in the west (Tables 3 and 4, Figures 1 and 3).

3.3 Comparison and perspectives

Climate change in Serbia is already a reality; its consequences are expected to become more intense in the coming decades. Meteorological measurements provided by the Republic Hydrometeorological Service of the Republic of Serbia for the last several decades (1961-1990 and 1981-2010) point to an increasingly changed climatic situation. Several meteorological stations in western Serbia (Kopaonik, Zlatibor, Sjenica) have recorded a slight increase in temperature ($\approx 0.5^{\circ}\text{C}$), which has been accompanied by an increase in precipitation of about 5% on an annual basis. These relatively moderate climate changes can positively affect forest productivity (Gustafson *et al.* 2017). In contrast, the same pattern of temperature increase is accompanied by a decrease in precipitation of approximately 5% in the eastern (Crni vrh, Negotin, Zajecar) and southeastern (Dimitrovgrad, Leskovac, Vranje) parts of Serbia. In this case, trees struggle to maintain productivity because the increased level of transpiration caused by the increase in temperature needs to be accompanied by sufficient precipitation (Kirschbaum 2000). In both cases, the timing of precipitation shifts noticeably from the vegetation period to the winter period, with significant consequences for the forests. For example, Matović *et al.* (2018) found that extremely high temperatures during the vegetation period in combination with extremely low rainfall is the primary cause of devitalization and dieback of spruce trees. Spatial distribution of these (positive and negative) trends of climate change, observed by RHMS of Serbia, fully complies with the shift pattern of climate suitable habitats predicted by RCP 4.5 and especially RCP 8.5. The strong retreat of those habitats toward higher elevations in the west (Figures 1 and 2), predicted by the mentioned scenarios, is in line with the results of other SDM studies listed in the introduction. With regard to reduction rates, we found no reduction rate (over 35%) under any of the RCP 4.5 and RCP 8.5 EQ-based mid-century projections that would significantly jeopardize the survival of tree species habitats in Serbia as we know them today (Table 3). Surprisingly, FAI- and EQ-based projections under RCP 4.5 do not deviate significantly from one another. FAI-based projections under RCP 8.5 give much greater reduction rates than their EQ analogues, but only for species with narrow ecological niches (Silver fir and Norway spruce). These differences also exist in late-century projections, but include all species (Table 3).

3.3.1 European beech

Projections under RCP 8.5, especially those based on FAI (Table 3), are in line with the results of Kramer *et al.* (2010), which also predict that beech habitats in Greece and ex-Yugoslavia will become climatically-unsuitable by 2050. According to Saltré *et al.* (2014), this change is likely to lead to an increase in drought mortality of trees in 2081-2100 in these regions. Several other studies of European beech in Serbia (Stojanović

et al. 2013), Hungary (Móricz *et al.* 2013, Czúcz *et al.* 2011), and Slovenia (Kutnar & Kobler 2011) have come to similar conclusions; all are in agreement that almost all beech stands will be found outside climatically-suitable zones toward the end of the century. To maintain beech populations at existing sites, non-resistant populations should be gradually replaced by resistant ones with appropriate management measures. Particular attention should be given to populations of European beech at lower elevations due to their high vulnerability to drought events (Stjepanović *et al.* 2017). A study by Horváth & Mátyás (2016) in which the translocation of beech populations from different regions of Europe to the test site were used to mimic responses to climate change highlights the importance of using planting stock that is suited to the future climate conditions at the planting site.

3.3.2 Silver fir and Norway spruce

Recent research on Silver fir (Klopčič *et al.* 2017, Mina *et al.* 2015, Falk & Mellert 2011, Ruosch *et al.* 2016) and Norway spruce (Buras and Menzel 2019, Mina *et al.* 2015) predict significant reductions in their relative abundance in existing forests or even their complete disappearance. Our study and others point to significant future declines in the abundance of Silver fir (Ruosch *et al.* 2016) and Norway spruce (Buras & Menzel 2019) under RCP 8.5, particularly in the southern parts of Europe. Given that today's southern European Silver fir forests are confined to moist and cool habitats at intermediate to high elevations (Ruosch *et al.* 2016) and that forests of Norway spruce have already been raised successfully in warm localities beyond its natural distribution range (Falk & Hempelmann 2013), there is a chance that these tree species will continue to survive in their existing habitats. However, it should be noted that fir is quite sensitive to environmental (climate) variability (Carrer *et al.* 2012), which suggests that any minor changes in climate are likely to significantly affect its growth. If climate-induced degradation or extinction of existing Silver fir and/or Norway spruce habitats occurs, it may be possible to compensate for the loss by introducing these species to climatically-appropriate areas at higher elevations, especially in beech dominated western Serbia. Such stands may develop naturally as a result of climate change; the simulations of Mina *et al.* (2015) for high elevations in the Dinaric Mountains of Slovenia indicate a transition from typical upper montane beech-dominated forest stands to mixed beech–fir–spruce stands. These processes should be supported by appropriate management measures because the mixing of Norway spruce and/or Silver fir with European beech improves the overall resistance and stability of the forest, increasing its resilience to unfavourable climate conditions (Falk & Hempelmann 2013, Paul *et al.* 2019, Neuner *et al.* 2014, Schwarz & Buhus 2019). To adapt to the expected reduction in productivity, Lindner *et al.* (2014) point to the successful experience of introducing Douglas fir as a replacement for spruce in certain parts of Europe. From an economic point of view, this type of adaptation is more than satisfactory. However, the potential environmental consequences of such a management decision should be considered with care to ensure the sustainability and multifunctionality of the resulting forest.

3.3.3 Black and Scots pine

Although, compared to other species, projections under RCP 4.5 and RCP 8.5, especially those based on FAI, predict the highest reduction rates of Black and Scots pine suitable habitats (Table 3), one possible option for maintaining their populations is to establish forest plantations in areas that remain climatically suitable. Conceptual solutions are already available based on previous experiences with raising such forests. Tomić *et al.* (2011), for example, recommend that Scots pine plantations be raised in the zone of mixed forests of beech, fir, and/or spruce above 1200 m, although that may not be true for future climate conditions. This represents the upper limit at which Black pine used to grow in Serbia, whereby its introduction into the area of Sessile oak forests (with Hornbeam) to mountain beech forests is recommended (Tomić *et al.* 2011). In essence, habitats that pine trees are unable to make full use of should be avoided (Stojanović & Krstić 2009). It is important to note that the above-mentioned guidelines should be indicative, as climate change may give a significant contribution to habitat change in a vertical sense, due to the more frequent occurrence of summer dry periods at lower elevations. Such conditions can negatively affect the growth of Black pine, which are known to be sensitive to summer drought events, particularly at lower elevations (Hungary: Móricz *et al.* 2018; Turkey: Doğan & Köse 2019; Serbia: Ćirković-Mitrović *et al.* 2013, Koprivica *et al.* 2009; Spain: Herrero *et al.* 2013). This is also true of Scots pine according to studies in Spain (Bogino *et al.* 2009, Herrero *et al.* 2013), Poland and Hungary (Misi *et al.* 2019), Bulgaria (Panayotov *et al.* 2012), and Romania (Sidor *et al.* 2019).

4. Conclusion

In summary, this study and others make clear that forests will change in response to climate change, but the exact nature and extent of these changes are not yet well understood. Continued monitoring and experimentation are needed to ensure that appropriate management measures are taken to mitigate or eliminate these changes and to safeguard the health of forest ecosystems.

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