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Total Carbon Storage in Uneven-Aged Pure Beech Stands in the Western Part of the Balkans

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Abstract

*Forest ecosystems represent one of the largest and most important ecosystems on Earth, containing close to 80% of the biomass of our planet. As such, they play a significant role in the global carbon cycle because through photosynthesis, forests absorb more carbon than they emit and thus accumulate it. The most important species in deciduous forests in Europe, European beech (*Fagus sylvatica *L.), is of exceptional importance from the aspect of carbon storage. Considering that the state of carbon in pure beech forests is poorly investigated in the western part of the Balkans, the need for total carbon research was imposed to complete the picture of its stocks and factors that impact it. Research on total carbon (TC) storage in uneven-aged pure beech stands in the western part of the Balkans was carried out in three regions located approximately at the same latitude, but different longitude, imposing different macro-habitat characteristics. This research aimed to determine the TC stock and to examine the effects of orographic factors, stand canopy, and macroclimate on its values. TC stock in forest biomass was determined using appropriate regression equations and formulas, while soil organic carbon stock was determined using ICP forests methodology. Effects of different factors on carbon stock were examined using ANOVA (Type II Sums of Squares), General Linear Hypothesis Test (GLHT), and regression analyses. It was found that the largest TC stock is located in the region of Eastern Serbia (SRB) where its macroclimate is classified as suitable for hornbeam and sessile oak or mixed beech-oak stands. It was found that anthropogenic activity plays a significant role in the size of the carbon stock stored in above-ground biomass via alteration of forest canopy. The results also indicate that Aboveground Carbon (AGC) stocks are approximately proportional to Belowground Carbon (BGC; C in belowground biomass + soil C) stocks. What makes the difference is the structure of BGC, as the share of Soil Organic Carbon (SOC) is higher in the regions of Eastern Republic of Srpska (ERS) and Western Republic of Srpska (WRS), which are climatically classified as highly suitable for beech. Further analysis has shown that the amount of SOC decreases with increasing aridity levels. Given the results, management goals should be aimed at increasing the stock of biomass for the sake of carbon sequestration and for reducing the adverse effects of climate change, as a large amount of carbon can be stored in the above-ground and belowground biomass.*

Keywords: forest biomass carbon, soil organic carbon, climate, orography, canopy

1. Introduction

Forest ecosystems represent one of the largest and most important ecosystems on Earth, covering more than 40 million km² and representing 30% of the total global land area (Keenan et al. 2015). The indisputable role of forests is that they contain close to 80% of our planet's biomass (Pan et al. 2013), representing an indispensable factor for the study of carbon storage in terrestrial ecosystems (Liu et al. 2016). As such, they play a significant role in the global carbon cycle because, through photosynthesis, forests absorb more carbon than they emit and thus accumulate it (Kägi and Schmidtke 2005). In the forest ecosystem, carbon is present in various forms (Schneider et al. 2015). According to Lal (2005), total carbon (TC) in the forest ecosystem can be divided into two basic forms – biomass carbon and soil carbon, and it is essential to note, as stated by Ontl and Schulte (2014), that it arises directly from the growth and death of plants and indirectly from the transfer of carbon-enriched compounds from roots to soil microbes. Biomass carbon, according to location, can be roughly divided into above-ground carbon (AGC), stored in living and dead standing trees, dead lying wood, stumps, and leaves, and belowground carbon (BGC) stored in the roots of living and dead trees, as well as the roots of stumps and carbon stored in the soil. The importance of forest biomass for carbon sequestration is reflected in the fact that approximately half of the weight of dry wood matter, i.e. biomass, constitutes carbon (Johnson and Coburn 2010). On the other hand, the soil represents an important source and storage of atmospheric CO_2, primarily as a result of the activity of microorganisms in the soil (Gougoulias et al. 2014) that contribute to several processes involved in carbon cycling (Lladó et al. 2017). It is important to emphasize that, according to estimates, more than 70% of global soil organic carbon (SOC) is stored in forest soils (Alemu 2014). Considering that forests, according to Sacquet (2005), Puhe and Ulrich (2001), Nabuurs et al. (2003), and IPCC (2000, 2007), have a crucial role in preserving biodiversity and absorbing carbon dioxide emissions, the research of biomass and carbon stocks in forest ecosystems has long been of great importance worldwide. Their importance is reflected in the understanding of complex problems of humanity such as the energy crisis and climate change. As human activities, such as deforestation and the burning of fossil fuels, have led to a drastic increase in the concentration of atmospheric carbon dioxide (CO_2) (Mund 2004, Ciais et al. 2013, Friedlingstein et al. 2019), the impact of various pollutants and climate change on the forest ecosystem has often been studied, as well as their contribution to mitigate the adverse effects of climate change (Körner et al. 1988, 1991, Lebaube et al. 2000, Joosten et al. 2004, Mund 2004). The importance of climate impact or the impact of climate change on carbon sequestration, especially on soil organic carbon (SOC) stock, has been pointed out in a large number of studies (Pilegaard et al. 2009, Meier et al. 2010, Brunn et al. 2014, Alemu 2014, Prietzel et al. 2016, Khan et al. 2019, Lee et al. 2020, Fekete et al. 2020, Gu et al. 2021, Azian et al. 2022). On the other hand, the way in which forests are managed should not be neglected, considering that the management systems largely define carbon stocks in forests (Johnson and Curtis 2001, Laiho et al. 2003, Nave et al. 2010, Warren and Ashton 2014, Achat et al. 2015, Simard et al. 2020, Hukić et al. 2021).

As one of the most important species in deciduous forests in Europe and the most represented type of potential natural vegetation in Central Europe (Ellenberg 1988), European beech (*Fagus sylvatica* L.) is of exceptional importance from the aspect of carbon storage. Therefore, a large number of studies investigated the state of carbon in pure beech forests in Germany (Mund 2004, Joosten et al. 2004, Cremer et al. 2016, Grüneberg et al. 2013, Wambsganss et al. 2017), Italy (Bayat et al. 2012, Innangi et al. 2015, Piovesan et al. 2010), Denmark (Nord-Larsen et al. 2019), France (Lecointe et al. 2006, Granier et al. 2000), Belgium (Vande Walle et al. 2005), the Czech Republic (Schneider et al. 2015, Andivia et al. 2016), Croatia (Marjanović et al. 2010), Spain (Santa Regina et al. 1997) and Greece (Zianis and Mencuccini 2005). Although it is one of the most abundant species in the western part of the Balkans (Balkan part of Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, and North Macedonia) (Banković et al. 2009, Božič et al. 2010, Ballian et al. 2012, Govt of RS 2012, GIZ 2017), the state of carbon in pure beech forests in this region is poorly investigated. A small number of studies dealt with the mentioned topic in Serbia (Koprivica and Matović 2011, Koprivica et al. 2013a, Koprivica et al. 2013b, Hadrović 2015), but they were limited to specific areas or mostly only to the state of AGC or BGC from biomass. On the other hand, this type of research has not been conducted on any scale in other parts of the Western Balkan. Further to the above, the need for a comprehensive research of carbon has emerged to complete the picture of its stocks and factors that impact it.

This research aims to determine the stock of total carbon and investigate the effect of different factors on carbon in three regions located at the same latitude in the western part of the Balkans. However, the three researched regions differ significantly in longitude, which determines their very different macro-habitat characteristics.

2. Materials and Methods

Research on the state of the total carbon in managed beech forests has been conducted in three regions: eastern Serbia (SRB), eastern (ERS), and western (WRS) Republic of Srpska, the entity of Bosnia and Herzegovina. In these three regions, which are ecologically very different, with an emphasis on the climate difference, 20 localities (70 sample plots), have been selected in pure uneven-aged beech forests, of which eight in SRB (30 sample plots), seven in ERS (24 sample plots), and five in WRS (16 sample plots) (Appendix 1). In the not-so -far past, these pure uneven-aged beech forests were old-growth forests. At the beginning, these forests in Serbia (SRB region) were managed as Plenter forests, but during the years group-selection management system became more common (Koprivica et al. 2013a). At present, these forests are known for bad quality and assortment structure, although they have retained their structural diversity and degree of naturalness and have relatively high production potential (Matović et al. 2018). In Bosnia and Herzegovina (ERS and WRS regions), management of pure beech forests had a similar history, as the Plenter system was widely used (Čilaš et al. 2023). As a result of such management history, pure beech forests in Serbia and Bosnia and Herzegovina, unlike pure beech forests in a large number of European countries, are mainly uneven-aged, structurally diverse, and ecologically stable.

To show the climatic differences in the best possible way, the climatic characteristics are expressed using the most commonly used climatic indices:

Ellenberg's climate quotient – *EQ* (Ellenberg 1988)

$$EQ = \frac{(T_{VII})}{P_{annual}} * 100 \tag{1}$$

Where:

T_{VII} mean monthly air temperature in July

P_{annual} mean annual amount of precipitation.

Forestry Aridity Index – *FAI* (Führer et al. 2011)

$$FAI = \frac{100 * \frac{T_{VII} + T_{VIII}}{2}}{P_V + P_{VI} + 2 * P_{VII} + P_{VIII}} \tag{2}$$

Where:

T_{VII}, T_{VIII} mean monthly air temperatures in July and August

P_V, P_{VI}, P_{VII}, P_{VII} sum of monthly precipitation for May, June, July and August.

Lower values of both indices indicate a more humid climate, while higher values, a dryer and warmer climate. For example, Miletić et al. (2021) found that beech forests in Serbia are located in areas within a range from 16.07 (*EQ*) or 3.62 (*FAI*) to 38.69 or 8.92 (*FAI*).

By the GIS software, QGIS 3.14, *EQ* and *FAI* values for sample plots in the ERS and WRS regions were obtained by processing high-resolution rasters from the Climate Atlas of Bosnia and Herzegovina (Bajić and Trbić 2016), and then by extracting *EQ* (Stojanović et al. 2013) and *FAI* values (Stojanović et al. 2014) from high-resolution rasters for sample plots in the SRB region. In each locality, sample plots were placed by laying transects with a minimum of 3 points at a distance of 1 km in the same direction, mostly from the tops of the mountains to their foothills.

Laying down of the transects was done in the GIS software QGIS 3.14, with the help of orthophoto imagery of the Republic of Srpska (Geoportal of RS 2012), European Digital Elevation Model (EU-DEM v1.1) and forestry stand maps. Data was collected in circular sample plots with a radius of 17.84 m and an area of 1000 m^2.

In the centre of each circular sample plot on an area of 1 m^2, the thickness of litter was measured, and all the leaves were collected. Within each circular sample plot, the diameters (≥5 cm) of all living and dead standing trees, dead lying trees and stumps were measured using »Haglöf« aluminium tree callipers. The decay degree was assessed for dead lying wood and stumps by applying ocular assessment and mechanical wood pressing using Koprivica et al. (2013a) scale (Table 1).

The height of all living and dead standing trees was measured using the electronic tree height measuring device »Vertex IV«, while the length of the dead lying trees was measured using a ribbon. The volumes of living and dead preserved standing trees were calculated according to the regression equations of Koprivica and Matović (2005). The volume of the measured roundwood was calculated using the simple Huber's formula (Eq. 3).

$$V = g_{1/2} * L \tag{3}$$

Elevation and aspect were determined using a GPS device »Garmin Etrex 10«, while the terrain slope was measured using »Vertex IV«. The canopy level was determined by measuring the covered and uncovered parts on two cross-diameters of the circular sample plots. At the center of each circular sample plot, from previously prepared soil pits with depths that ranged up to 40 cm, several solid-state soil samples were taken from the Ah horizon using Kopecky cylinders. The Ah horizon thickness was measured using a ribbon. To determine soil's carbon storage capacities, the soil's

Table 1 Wood degree scale

Percentage of decay	<10%	10–40%	>40%
Decay degree	Sound wood	Weakly decayed wood	Decayed wood
Categories	a	b	c

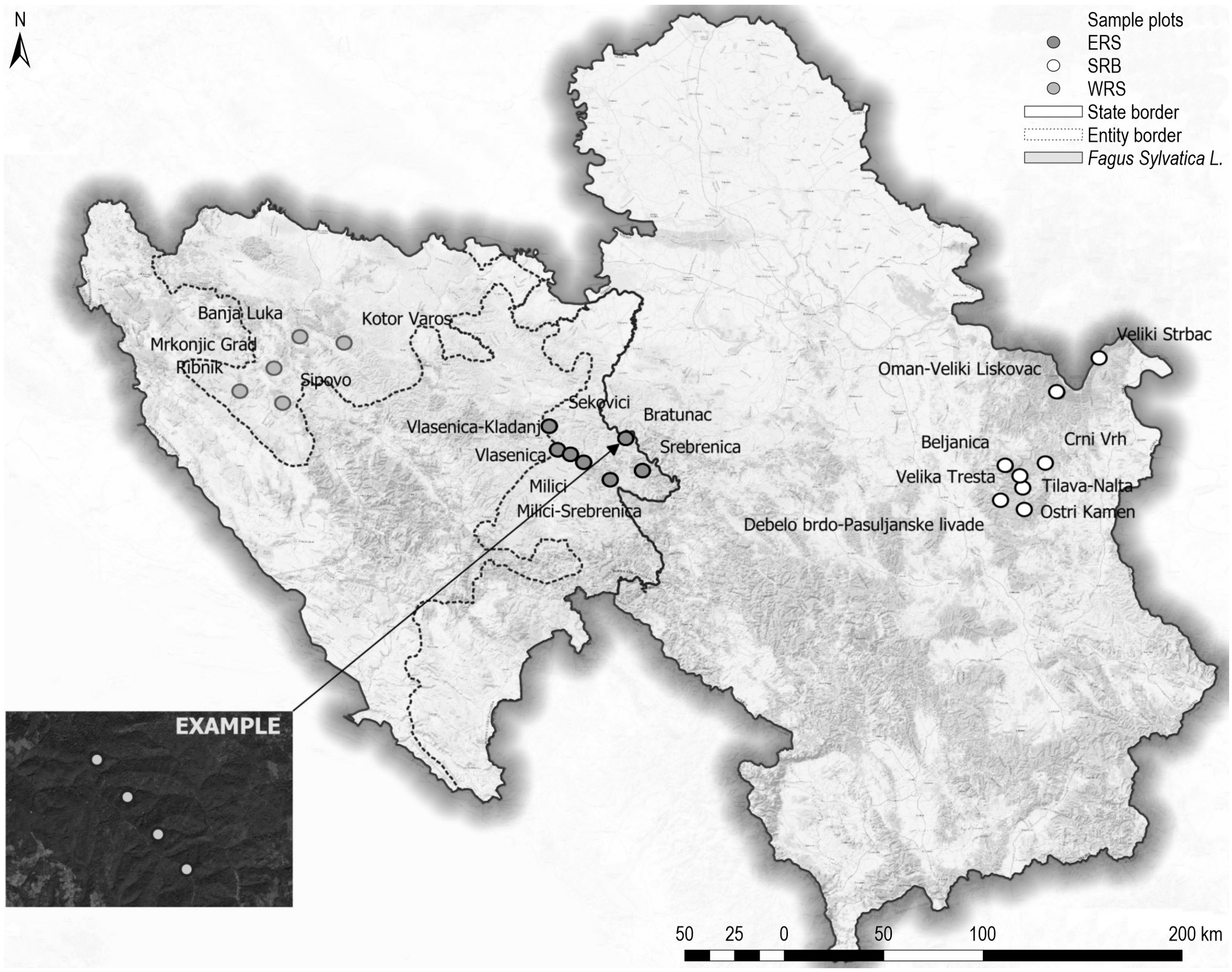

Fig. 1 Spatial distribution of sample plots

physical and chemical properties were analyzed according to the ICP forests methodology. The total dry biomass of living standing trees and the old stump roots and dead standing trees were determined according to Wutzler et al. (2008) regression equations for European beech. Deadwood biomass was determined by multiplying its volume with the beech wood density defined for different stages of its decay (Mund 2004). The carbon in total biomass of standing trees was determined according to the regression equation for European beech (Joosten et al. 2004), and the carbon of roots and deadwood by multiplying their biomass with a coefficient of 0.5 (IPCC 2003, Koprivica et al. 2012).

The systematization and processing of the collected data were carried out in the Microsoft Office Excel 2010, whereby the values of elevation, terrain slope, and aspect were reclassified into the appropriate classes. The reclassification was carried out as follows: elevation into 100 m wide classes and terrain slope into categories by the general classification of the terrain depending on the size of the terrain slope angle (Vacca 1992), which were ranked with increasing ordinal numbers. Canopy was reclassified into four classes ranked in ascending order according to Stojanović and Krstić's (2008) classification: incomplete (0.5–0.6), complete (0.7), dense (0.8–0.9) and very dense canopy (1.0). In this way, the mentioned variables were converted into the ordinal-type variables. Aspect was reclassified into three classes: sunny (S, SE, SW), semi-sunny (W and I), and shady (NW, N, NE), as well as a variable related to climatic regions, turning them into a nominal type variable. The influence of orographic factors and macroclimate on the amount of AGC and BGC was examined using ANOVA (Type II Sums of

Table 2 Stand structural elements

Region	Climate		Sample plot	Living trees		Dead trees		Stumps		Lying wood		All	
	EQ	*FAI*	*n*	m^3/ha	n/ha	m^3/ha	n/ha	m^3/ha	n/ha	m^3/ha	n/ha	m^3/ha	n/ha
SRB	25.13	5.48	30	434.12	496	11.21	37	5.49	66	20.53	179	471.35	778
ERS	15.80	3.55	24	358.87	487	2.87	34	2.99	35	11.04	54	375.47	610
WRS	13.48	3.30	16	395.13	499	1.59	14	4.42	40	5.57	72	406.71	625
All	19.27	4.32	70	399.41	494	6.15	31	4.39	49	13.86	112	423.81	686

SRB – Eastern Serbia
ERS – Eastern Republic of Srpska
WRS – Western Republic of Srpska
FAI – Forestry aridity index
EQ – Ellenberg's climate quotient

Squares) and General Linear Hypothesis Test (GLH) using R Studio (R Core Team 2021) and packages: stats (R Core Team 2021), multcomp (Hothorn et al. 2008), car (Fox et al. 2019), VCA (Schuetzenmeister et al. 2020), and readxl (Wickham et al. 2019). Given the high attention paid to soil organic carbon (SOC), the influence of microclimate on its content in soil was examined through regression analysis using R Studio (R Core Team 2021) and packages: readxl (Wickham et al. 2019), car (Fox et al. 2019), stats (R Core Team 2021), where the elimination of the outliers was performed using the Confidence Ellipse method with a 90% confidence interval, using the SIBER package (Jackson et al. 2011). Graphs were created using packages ggplot2 (Wickam 2016) and graphics (R Core Team 2021). The mentioned parametric statistical methods were used following the central limit theorem, which states if sample set is large enough (n>30) sampling distribution tends to be normal. For statistical analysis on sample sets that are composed of 30 or fewer samples (each region separately), the Shapiro-Wilk test is used for normality check using the car (Fox et al. 2019) package in R Studio (R Core Team 2021).

3. Results

The most significant average number of living and dead trees are found in the SRB region, and the smallest in the ERS region (Table 2). The average number of trees per region is pretty uniform and with very different average stand volumes, it indicates that beech forests in WRS and especially ERS region are exposed to greater anthropogenic (harvesting) activity (Table 2).

It is important to note that the share of AGC versus BGC is the highest in the ERS region, and the lowest in the WRS region (Fig. 2). Interestingly, as much as 35.21% of the AGC in the SRB region consists of carbon from dead-standing trees (21.11%) and dead-lying wood (14.10%), which is 54.73 t/ha and 67.72 t/ha higher than in the ERS and WRS regions, respectively (Table 3). However, special attention should be paid to the form of BGC, especially in the SRB region, considering that carbon from the roots of stumps, and living and dead trees have the largest share compared to ERS and WRS regions (Table 4). When it comes to the SOC, significantly larger amounts are found in the WRS and ERS regions (Table 4), which have significantly more humid climates than the SRB region (Table 2). On average, the highest amount of TC is found to be in the SRB region, and the lowest in the ERS region (Table 5).

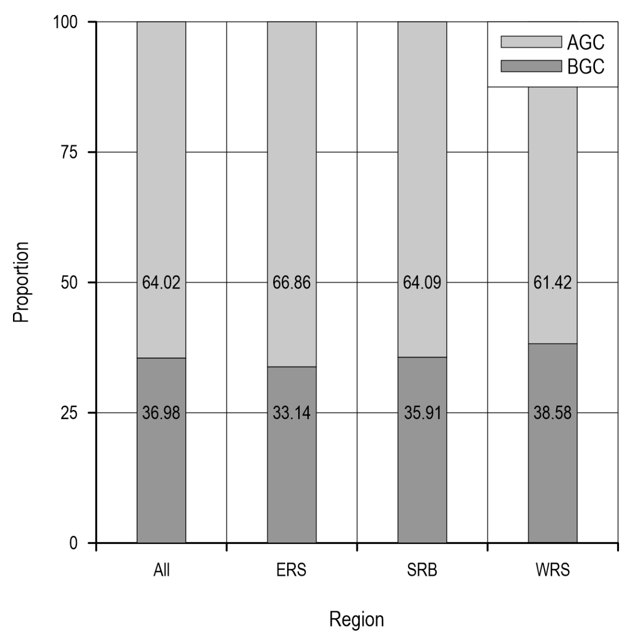

Fig. 2 Relative share of above-, and below-ground carbon in analyzed regions

Table 3 Carbon stocks in above-ground wood and litter in analyzed regions

Region	Woody carbon										Non-woody carbon	
	Living trees		Dead trees		Stumps		Lying wood		All		Litter	
	t/ha	%	t/ha	%	t/ha	%	t/ha	%	t/ha	%	t/ha	%
SRB	146.41	60.25	51.31	21.11	10.18	4.19	34.24	14.1	242.14	99.65	0.86	0.35
ERS	121.12	72.41	12.6	7.53	14.37	8.59	18.22	10.89	166.32	99.43	0.95	0.57
WES	131.48	75.82	7.17	4.14	23.18	13.37	10.66	6.14	172.49	99.47	0.93	0.53

SRB – Eastern Serbia
ERS – Eastern Republic of Srpska
WRS – Western Republic of Srpska

Table 4 Carbon stocks in below-ground wood and soil in analyzed regions

Region	Woody carbon								Non-woody carbon	
	Living trees roots		Dead trees roots		Stump roots		All		SOC	
	t/ha	%	t/ha	%	t/ha	%	t/ha	%	t/ha	%
SRB	26.73	19.63	18.06	13.26	72.9	53.53	117.68	86.42	18.49	13.58
ERS	21.99	26.53	3.73	4.5	37.54	45.28	63.27	76.31	19.64	23.69
WRS	23.42	21.5	2.26	2.08	58.9	54.07	84.57	77.64	24.36	22.36

SRB – Eastern Serbia
ERS – Eastern Republic of Srpska
WRS – Western Republic of Srpska
SOC – Soil organic carbon

Table 5 The value of above-, below-ground and total carbon in analyzed regions

Region	Sample plot *n*	*Mean*			*Min*			*Max*			*Sd*		
		t/ha											
		AGC	BGC	TC	AGC	BGC	TC	AGC	BGC	TC	AGC	BGC	TC
SRB	30	243	136.17	379.18	78.38	40.71	157.89	914.49	308.86	1116.22	157.98	68.2	187.90
ERS	24	167.27	82.91	250.18	79.15	31.18	110.34	390.47	172.24	486.07	67.16	28.96	74.76
WRS	16	173.42	108.93	282.34	85.08	35.21	120.29	331.97	206	453.89	59.88	55.4	89.22
All	70	201.13	111.69	312.82	78.38	31.18	110.34	914.49	308.86	1116.22	118.80	58.76	148.08

SRB – Eastern Serbia
ERS – Eastern Republic of Srpska
WRS – Western Republic of Srpska
AGC – Above-ground carbon
BGC – Below-ground carbon
TC – Total carbon

ANOVA has shown that one factor have a statistically significant effect on the amount of AGC, namely Canopy. The aspect should not be taken into further consideration, considering its extremely low level of statistical significance (p<0.1). Contrary to the previous one, the effect of the Canopy on AGC is characterized by a high level of statistical significance (p<0.01) (Table 6). Statistically significant differences were found between very dense and dense and very dense and complete canopy, where the amount of AGC was greater in favor of very dense canopy (Table 7).

ANOVA has shown that only the Region has a statistically significant effect (p<0.01) on the amount of BGC (Table 8). In this case, the GLHT showed no statistically significant difference in BGC between the ERS and WRS regions, although there are more than obvious differences in the macroclimatic conditions

Table 6 Results of ANOVA on orography, macroclimate, and stand canopy impact on the carbon stock in above-ground wood and litter

Factors	Total Sq	*Df*	*F* value	*Pr* (>*F*)	Signif. codes
Elevation	126,039.4	8	1.494	0.184	–
Aspect	56,726.54	2	2.69	0.078	.
Slopes	84,777.02	5	1.608	0.176	–
Canopy	105,018.4	3	3.32	0.027	*
Region	14,541.95	2	0.689	0.507	–
Residuals	516,728.3	49	–	–	–

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 7 General Linear Hypothesis Test on carbon stock differences for the Canopy factor levels in above-ground wood and litter

Difference (Canopy)	Estimates	Standard error	*t* value	*Pr* (>*t*)	Signif. codes
Complete – Incomplete	–30.425	57.521	–0.529	0.9500	–
Dense – Incomplete	–25.269	50.176	–0.504	0.9564	–
Very dense Incomplete	151.276	67.174	2.252	0.1196	–
Dense-Complete	5.156	41.189	0.125	0.9993	–
Very dense – Complete	181.701	62.748	2.896	0.0269	*
Very dense – Dense	176.545	58.275	3.029	0.0193	*

Signif. codes : 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 8 Results of ANOVA on orography, macroclimate, and stand canopy impact on the carbon stock in below-ground wood and soil

Factors	Total Sq	*Df*	*F* value	*Pr* (>*F*)	Signif. codes
Elevation	36,424.87	8	1.770	0.106	–
Aspect	4886.46	2	0.950	0.394	–
Slopes	2971.64	5	0.231	0.947	–
Canopy	11,171.15	3	1.448	0.240	–
Region	31,478.79	2	6.119	0.004	* *
Residuals	126,037.8	49	–	–	–

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 9 General Linear Hypothesis Test on carbon stock differences between Regions in below-ground wood and soil

Difference (Regions)	Estimates	Standard error	*t* value	*Pr* (>t)	Signif. codes
ERS – WRS	–23.79	18.03	–1.319	0.38677	–
SRB – WRS	61.55	25.56	2.408	0.04966	*
SRB – ERS	85.34	24.46	3.488	0.00285	**

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

expressed through climate indices (*FAI* and *EQ*). In contrast, statistically significant differences in BGC were found between the SRB and the other two regions: ERS and WRS. GLHT showed that the amount of BGC was more significant in favor of the SRB region (Table 9).

The exponential regression analysis showed that there was a relatively weak negative relationship between the climatic characteristics expressed through *FAI* (R^2=0.132) and *EQ* (R^2=0.131) with the amount of SOC (Fig. 3a and 3b). The strength of that relationship is significantly greater when the relative share of SOC in BGC is used in the analysis above (Fig. 3c and 3d). Using this data, to a certain extent, the influence of harvesting in several beech stands on the obtained results was eliminated. Since sample sets comprising data from each region alone (SRB, ERS, and WRS) don't have normally distributed data, the use of regression analysis, for this particular case, is unreasonable.

4. Discussion

The most significant amounts of TC were found in the SRB region, and the smallest in the ERS region (Table 5). In this case, the size of the TC stock is opposed to the *FAI* and *EQ* classifications of climate suitability for beech development. As a statistically significant variable, the canopy indicated that anthropogenic activity played a major role in the size of the carbon stock stored in the above-ground biomass. It is assumed that the reason for this is the application of different management systems through history and probably the long-term absence of management procedures in certain sample plots in the SRB region. The leading indicator for this is a significantly higher amount of carbon stored in dead-standing trees and lying wood in the SRB region than in the others (Table 3). The results indicate that AGC stocks are approximately proportional to BGC stocks (Table 5). Although the amount of BGC is statistically significantly higher in the SRB region compared to the other two regions, ERS and WRS, what makes the difference is the structure of BGC among the analyzed regions. It is important to note that the share of SOC is significantly higher in the ERS and WRS regions (Table 4), where the climate is classified as highly suitable for beech development, as opposed to the SRB region.

In a research that dealt with determining the TC stocks in pure beech forests in Europe, similar stocks

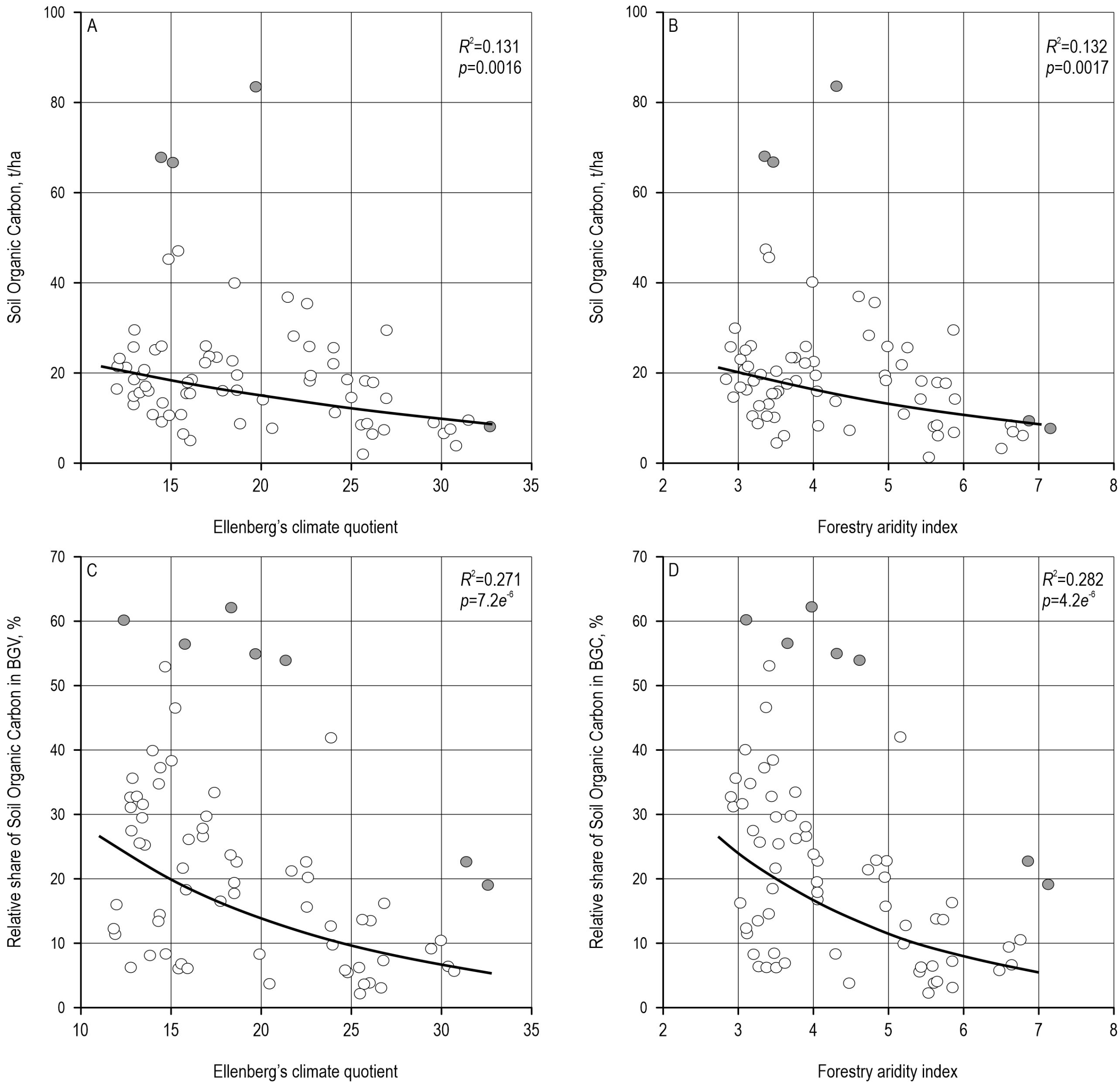

Fig. 3 Relationship between Ellenberg's climate quotient, Forestry Aridity Index and SOC in all three regions (SRB, ERS and WRS) (grey dots-outliers)

were found in areas with similar climatic characteristics. Starting from the SRB region, it can be concluded that TC stocks are highly similar to the TC stocks found in beech forests in Denmark: 395 t/ha (Nord-Larsen et al. 2019), Czech Republic: 321 t/ha (Schneider et al. 2015), Germany: 352 t/ha (Mund 2004) and France: 373 t/ha (Lecointe et al. 2006). On the other hand, similar total carbon stocks as those in the ERS and WRS regions have also been recorded in several locations in Italy: 247 t/ha (Bayat et al. 2012) and 192–268 t/ha (Piovesan et al. 2010), Germany, Slovakia and Ukraine: 212 t/ha (Pandey 2012). Interestingly, according to the classifications of Führer et al. (2011) – *FAI* and Ellenberg (1988) – *EQ,* the SRB region is classified as an area suitable for hornbeam and sessile oak or for mixed beech-oak stands. An even more interesting fact is that the largest stock of TC was found in the given area (Table 5). Although, according to the mentioned classifications, ERS and WRS regions are classified as highly suitable for pure beech forests, the TC stocks are significantly lower than in the SRB region (Table 5). According to our assessment, this is the result of different management systems and, in some sample plots in the SRB region, probably the result of the long-term absence of forest management procedures. The best example of this is the site Oštri kamen 1, which is characterized by a huge TC stock, which is dominated by carbon from dead standing trees and the absence of stumps (Appendix 1). Statistically significant effect of the canopy on the amount of AGC (Table 6) validates this, considering that stands with a higher degree of canopy are better preserved (Đorem et al. 2022) due to the weak or complete absence of anthropogenic activity, which, according to Harmon et al. (1990), Cannell et al. (1992), Karjalainen (1996), Fleming and Freedman (1998), Trofymow and Blackwell (1998), Weber (2001), Crow et al. (2002), Askar et al. (2018), Duncanson et al. (2019), Urban et al. (2014) usually leads to the fact that the average living and dead above-ground biomass of managed forests reaches only 20–60% of that present in the virgin forests. The above aspect should not be ignored in the case of BGC, as its stocks are statistically significantly larger in the SRB region compared to the ERS and WRS regions (Table 9). Given that a large part of BGC in the SRB region consists of carbon originating from the roots (Table 5), a high degree of forest preservation plays a major role in this case. The basis for this conclusion is found in the research of Bolte et al. (2004), who concluded that the size of the breast diameter was highly correlated with the amount of beech coarse root biomass. Overall, it can be concluded that the anthropogenic impact is very significant regarding to the amount of carbon stored in the above-ground or below-ground forest biomass. As climate change can threaten the survival of forests in Serbia (Miletić et al. 2021) and Bosnia and Herzegovina (Miletić et al. 2022) by the end of the 21st century, anthropogenic activity should be under strong control. This is crucial as climate-induced changes can lead to poor growth performance (Stjepanović et. al 2018) and even mortality (Horváth et. al 2016) of beech trees, which can be worsened by increased management pressure, leading to a severe loss of carbon stored in the above-ground and below-ground wood.

Although it was mentioned several times that the forests in the ERS and WRS regions are exposed to a significantly higher harvesting intensity, which, according to Achat et al. (2015), Hukić et al. (2021), and Leuschner et al. (2022), leads to significant losses of SOC, its absolute share in BGC is higher in the ERS and WRS than in the SRB region (Table 4). Further analysis showed that the amount of SOC or its relative share in BGC decreased with the increase in *EQ* (Fig. 3a and 3c) and *FAI* (Fig. 3b and 3d). In this way, it was shown that the climate was extremely important for soil carbon sequestration in addition to the significant anthropogenic impact that resulted in the reduction of wood stocks and even SOC. The research by Fekete et al. (2020) in Hungary showed that the climate had an extremely significant impact, while our study showed the opposite because it was found that the amount of SOC increased with the increase in *EQ* values. Therefore, it can be concluded that the influence of climate on the amount of SOC cannot be generalized for all beech habitats.

5. Conclusions

Having in mind that forest management and climate change play a major role in AGC and BGC stock formation, in the future stakeholders should consider relieving pressure on overmanaged pure beech forests, especially those in the ERS region. Improving their productivity and ecological stability needs to be our primary goal. This can be done by strictly implementing ecosystem management systems, such as the Plenter and group-selection system, or combination of those two, as well as introducing drought-resistant beech provenances in climate change-endangered areas, such as lowland parts of the SRB region. Based on the results, the chosen management system should support trees with a high growth performance, as these trees have high carbon sequestration capacity. Where possible, a gradual introduction of other species in beech forests, such as Norway spruce, Silver fir, and Sessile oak, should be considered as well, as these forests are well-known for improved overall resistance, stability, and productivity. As the results show that the amount of SOC decreases with increasing *EQ* and *FAI* values, increasing the stock of biomass for the sake of carbon sequestration increase and reducing the adverse effects of climate change is a must. This especially applies to beech forests with a large amount of SOC in the WRS and ERS region, because it is evident in the example of beech forests in the SRB region that a large amount of carbon can be stored in the above-ground and below-ground biomass. To complete the picture of the processes that affect the state of carbon in beech forests, in future research, it would be essential to conduct a similar analysis in virgin forests to avoid the negative impact of anthropogenic activity on carbon stocks, primarily on AGC stocks.

Appendix A

Table A1 Carbon stocks in above- and below-ground wood, litter, and soil per sample plots

Region	Sample plots	*FAI*	*EQ*	LT	LTR	DT	DTR	S	SR	LW	L	SOC	TC
	Location: *XY*			t/ha									
SRB	Beljanica 1 21.6996, 44.1163	3.97	18.44	126.99	24.47	0.00	0.00	0.00	0.00	12.37	1	40.21	205.03
	Beljanica 2 21.6995, 44.1253	4.30	19.97	56.85	10.30	0.00	0.00	20.38	143.95	0.15	1	13.83	246.45
	Beljanica 3 21.6993, 44.1342	4.61	21.40	125.06	23.97	11.90	7.92	0.00	0.00	3.43	0.7	37.19	210.17
	Beljanica 4 21.7004, 44.1438	4.84	22.47	140.84	26.89	7.26	6.59	11.531	88.47	11.96	0.8	35.66	329.99
	Beljanica 5 21.6994, 44.1546	5.16	23.96	172.68	30.48	0.00	0.00	0.00	0.00	0.00	0.8	22.01	225.98
	Crni vrh 1 21.9626, 44.1313	4.98	22.60	127.61	24.68	1.66	0.912	6.82	63.01	12.13	0.8	25.95	263.57
	Crni vrh 2 21.9538, 44.1378	5.43	24.71	112.39	21.10	22.38	23.26	24.30	245.93	97.35	0.7	18.58	565.98
	Crni vrh 3 21.945, 44.1439	5.59	25.49	77.45	14.02	0.51	0.20	14.47	107.56	28.06	0.3	8.15	250.72
	Crni vrh 4 21.936, 44.1505	5.73	26.14	95.51	16.52	12.95	3.41	14.20	94.60	2.93	0.4	17.86	258.39
	Debelo brdo-Pasuljanske livade 1 21.6727, 43.9619	5.20	24.01	120.83	21.35	20.76	9.30	13.74	68.76	30.75	0.4	10.86	296.75
	Debelo brdo-Pasuljanske livade 2 21.6617, 43.9663	5.53	25.56	137.51	22.54	0.27	0.10	13.34	47.69	20.79	0.7	1.56	244.50
	Debelo brdo-Pasuljanske livade 3 21.6508, 43.9708	5.64	26.07	103.62	17.29	12.40	6.71	27.15	130.27	57.57	0.3	6.07	361.36
	Oman-Veliki Liškovac 1 22.023, 44.4534	5.86	26.87	115.49	24.41	105.25	49.84	15.54	111.74	29.12	1.2	14.35	466.94
	Oman-Veliki Liškovac 2 22.0328, 44.4581	6.63	30.43	83.06	16.79	68.99	17.80	9.54	72.37	7.78	2.3	7.27	285.91
	Oman-Veliki Liškovac 3 22.0438, 44.464	6.86	31.46	102.03	19.62	7.66	3.46	1.46	8.41	4.93	1.1	9.21	157.89
	Oman-Veliki Liškovac 4 22.0547, 44.4687	7.13	32.70	172.96	27.60	21.61	5.43	0.00	0.00	26.33	0.3	7.76	261.98
	Oštri kamen 1 21.794, 44.0308	4.48	20.52	280.44	55.00	567.22	139.42	0.00	0.00	64.63	2.2	7.33	1116.22
	Oštri kamen 2 21.8008, 44.024	4.95	22.68	169.11	33.67	46.70	15.10	3.95	27.22	35.77	0.6	19.28	351.40
	Oštri kamen 3 21.8077, 44.0169	5.23	23.93	158.87	32.80	253.80	102.83	10.05	42.67	43.55	1.5	25.63	671.70
	Tilava Nalta 1 21.8202, 43.9247	4.96	22.56	180.50	36.25	6.90	3.09	11.70	59.78	54.30	0.7	18.29	371.52
	Tilava Nalta 2 21.8084, 43.9255	5.64	25.72	43.49	9.01	0.69	0.35	19.12	104.41	22.72	0.8	17.97	218.56
	Tilava Nalta 3 21.7954, 43.9268	5.85	26.73	133.80	23.76	9.69	6.45	28.31	189.55	41.48	0.4	6.97	440.41

Region	Sample plots	*FAI*	*EQ*	LT	LTR	DT	DTR	S	SR	LW	L	SOC	TC
	Location: *XY*			t/ha									
SRB	Velika Tresta 1 21.7707, 44.0741	5.84	26.90	123.62	20.24	5.43	1.54	15.47	131.49	33.89	0.6	29.66	361.95
	Velika Tresta 2 21.783, 44.0763	5.61	25.82	220.92	36.92	0.99	0.30	15.26	180.61	9.53	1	8.48	473.99
	Velika Tresta 3 21.7946, 44.0778	5.42	24.89	158.62	29.30	0.00	0.00	22.06	217.52	115.80	1.2	14.23	558.73
	Velika Tresta 4 21.8073, 44.0797	4.74	21.74	203.47	37.35	139.37	66.70	0.00	0.00	52.38	0.8	28.24	528.31
	Velika Tresta 5 21.8192, 44.0816	4.31	19.71	224.53	40.75	0.36	0.10	2.96	27.84	25.55	1	83.59	406.67
	Veliki Štrbac 1 22.2986, 44.6133	6.48	30.76	220.71	36.31	19.38	5.24	2.79	17.12	26.84	0.7	3.52	332.60
	Veliki Štrbac 2 22.3066, 44.6187	6.75	30.09	272.49	44.02	9.42	3.74	1.20	6.03	121.30	1	6.29	465.48
	Veliki Štrbac 3 22.2944, 44.6058	6.61	29.51	130.91	24.36	185.87	61.99	0.00	0.00	33.72	0.6	8.75	446.18
ERS	Bratunac 1 19.2707, 44.2473	4.00	18.32	133.03	23.22	154.68	38.75	7.03	10.94	94.72	1	22.70	486.07
	Bratunac 2 19.2788, 44.2405	4.06	18.71	147.05	26.05	1.56	0.55	0.90	2.49	6.78	1.2	8.52	195.09
	Bratunac 3 19.287, 44.2337	4.05	18.56	160.82	28.33	6.52	2.42	20.44	35.81	30.86	1.3	16.08	302.58
	Bratunac 4 19.2946, 44.2273	4.05	18.56	71.10	14.43	5.08	2.35	33.59	73.18	2.37	0.9	19.50	222.50
	Milići 1 19.0213, 44.1351	3.38	15.44	56.92	10.40	2.95	0.98	53.39	150.27	1.52	0.7	10.60	287.73
	Milići 2 19.0181, 44.1264	3.46	15.93	79.68	13.21	1.89	0.65	20.55	54.00	27.20	0.8	15.28	213.25
	Milići 3 19.0149, 44.1178	3.38	15.29	158.76	23.17	7.83	2.52	5.28	28.93	0.00	1	47.63	275.12
	Milići-Srebrenica 1 19.1974, 44.0455	3.62	15.57	103.43	18.44	23.82	7.28	27.27	57.91	28.93	0.8	6.06	273.93
	Milići-Srebrenica 2 19.1858, 44.0488	3.65	15.82	78.15	13.58	0.00	0.00	0.00	0.00	0.00	1	17.61	110.34
	Milići-Srebrenica 3 19.1742, 44.0522	3.47	14.78	62.91	11.77	16.40	6.77	39.00	95.54	10.90	1	10.27	254.57
	Milići-Srebrenica 4 19.1626, 44.0555	3.40	14.41	104.30	18.66	1.07	0.35	22.61	60.12	11.07	0.8	13.33	232.30
	Šekovići 1 18.8121, 44.2911	3.76	17.45	51.93	10.97	2.76	0.65	15.47	35.34	9.26	1.1	23.45	150.93
	Šekovići 2 18.8002, 44.2884	3.70	17.03	114.49	19.69	9.86	2.40	17.55	34.03	23.93	1	23.80	246.75
	Šekovići 3 18.7882, 44.2857	3.50	15.69	73.81	11.73	6.73	2.32	6.68	41.85	13.57	0.9	15.45	173.06
	Srebrenica 1 19.3985, 44.1000	3.91	16.85	135.36	25.21	12.07	5.02	6.68	41.85	7.12	0.8	26.00	260.10
	Srebrenica 2 19.3886, 44.0946	4.05	17.76	138.40	25.87	5.31	1.70	19.10	53.66	0.36	0.8	16.07	261.26
	Srebrenica 3 19.3787, 44.0891	3.89	16.77	160.42	28.93	0.00	0.00	5.28	28.93	0.00	0.8	22.28	246.64

Region	Sample plots	*FAI*	*EQ*	LT	LTR	DT	DTR	S	SR	LW	L	SOC	TC
	Location: *XY*			t/ha									
ERS	Srebrenica 4 19.3688, 44.0836	3.77	16.03	150.35	30.19	6.09	1.98	4.04	19.35	50.11	0.9	18.27	281.27
	Vlasenica 1 18.9417, 44.1546	2.91	12.80	167.78	32.53	8.12	3.86	3.70	17.02	5.17	1	25.84	265.01
	Vlasenica 2 18.9309, 44.1592	3.11	14.03	132.84	24.25	10.66	3.42	9.15	10.15	0.00	1.2	25.25	216.93
	Vlasenica 3 18.9524, 44.1501	3.16	14.33	153.10	30.10	1.18	0.35	9.43	18.34	51.32	0.9	26.00	290.71
	Vlasenica-Kladanj 1 18.8634, 44.1777	3.04	13.44	120.08	20.60	5.33	1.99	7.92	14.14	58.27	0.8	16.87	246.00
	Vlasenica-Kladanj 2 18.851, 44.177	2.95	12.83	89.81	15.78	0.00	0.00	9.90	17.10	1.90	0.8	14.82	150.11
	Vlasenica-Kladanj 3 18.8366, 44.1762	2.96	12.84	262.35	50.74	12.56	3.33	0.00	0.00	1.95	1.3	29.79	362.01
WRS	Banja Luka 1 17.1895, 44.6485	3.35	14.43	115.98	20.25	0.00	0.00	31.05	94.63	13.05	1	68.10	344.06
	Banja Luka 2 17.179, 44.6535	3.47	15.10	95.32	16.30	2.58	0.57	32.38	90.88	3.49	1.1	66.89	309.51
	Banja Luka 3 17.1686, 44.6586	3.41	14.70	126.76	22.78	18.35	4.86	7.34	12.84	5.88	1.1	45.70	245.61
	Kotor Varoš 1 17.4756, 44.6366	3.20	13.88	164.12	29.31	0.00	0.00	37.12	88.92	0.00	1.1	10.50	331.07
	Kotor Varoš 2 17.4630, 44.6370	3.27	14.35	118.22	21.24	3.89	1.19	16.63	35.91	0.00	0.9	8.96	206.94
	Kotor Varoš 3 17.4504, 44.6374	3.52	15.93	94.31	17.22	0.00	0.00	23.86	54.29	12.71	0.8	4.62	207.81
	Mrkonjić Grad 1 17.0222, 44.4963	3.30	13.32	68.36	12.50	0.00	0.00	21.69	44.35	0.62	0.8	19.49	167.83
	Mrkonjić Grad 2 17.0249, 44.505	3.20	12.84	90.07	16.44	43.60	10.09	12.27	22.29	3.41	1	18.45	217.62
	Mrkonjić Grad 3 17.0275, 44.5138	3.11	12.37	76.97	13.79	0.90	0.25	0.00	0.00	6.11	1.1	21.18	120.29
	Mrkonjić Grad 4 17.0302, 44.5226	3.04	12.03	111.01	19.31	0.00	0.00	50.62	100.98	4.50	0.9	23.04	310.35
	Ribnik 1 16.8272, 44.3947	3.53	13.58	167.63	31.53	38.97	15.92	0.00	0.00	9.58	0.9	15.99	280.52
	Ribnik 2 16.8149, 44.3929	3.45	13.15	179.90	29.98	0.51	0.20	0.74	1.95	5.56	0.8	15.66	235.31
	Ribnik 3 16.8023, 44.3911	3.50	13.42	259.79	46.12	5.99	3.09	0.00	0.00	65.39	0.8	20.60	401.79
	Šipovo 1 17.1012, 44.3433	3.28	12.81	164.97	28.52	0.00	0.00	48.79	164.60	33.34	0.8	12.88	453.89
	Šipovo 2 17.0889, 44.3451	3.11	11.87	130.04	23.71	0.00	0.00	42.37	92.79	1.76	0.8	16.32	307.79
	Šipovo 3 17.0766, 44.3469	3.12	11.92	140.18	25.68	0.00	0.00	46.04	137.93	5.08	0.9	21.32	377.12

SRB – Eastern Serbia, ERS – Eastern Republic of Srpska, WRS – Western Republic of Srpska, *FAI* – Forestry aridity index, *EQ* – Ellenberg's climate quotient, LT – Living trees, LTR – Living trees roots, DT – Dead trees, DTR – Dead trees roots, S – Stumps, SR – Stumps roots, LW – Lying wood, L – Litter, SOC – Soil organic carbon, TC – Total carbon

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