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Original scientific paper

Management practice effects on biomass and soil carbon stock in European beech (*Fagus sylvatica* L.) forests on Fruška Gora Mountain, Serbia

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Abstract: European beech (*Fagus sylvatica* L.) forests are one of the largest natural renewable reservoirs of stored carbon in Europe, as well as in the Balkans and Serbia. A number of factors have been identified which influence the state of stored carbon, but a unique influence can be expected from the degree of stand preservation and the history of forest management. In the present paper, the influence of the preservation of stands and management methods on the state of ecosystem carbon (biomass carbon and soil carbon) were analyzed in beech forests situated at the Fruška Gora Mountain, Serbia. The research was conducted in three stands that were managed in the past in three different ways: a virgin forest without any management, a high stand and a coppice stand. The stored biomass carbon and soil carbon was estimated using standard methods that have been previously proven useful in Europe for the last decades. Above-ground biomass was also assessed using remote sensing. The results show a significant impact of conservation and management history on the stock of stored biomass carbon and soil carbon, but also on their mutual relationship. This research initiates that moderate management measures and the application of management systems based on the principles of continuous cover forestry (selective and group cutting) are, in addition to their well-known advantages, more efficient in carbon storage than the application of systems with surface management (clear and shelterwood cutting).

Keywords: European beech, carbon, biomass, soil, Fruška Gora Mountain, remote sensing.

1. Introduction

European beech (*Fagus silvatica* L.) is a widespread tree species in Europe and is the most represented type of natural vegetation in Central Europe (Ellenberg, 1988). As the most important tree species in Serbia, it is widely distributed throughout the state, except from the lowland areas of Vojvodina province (Stojanović et al. 2005). In the northernmost parts of Serbia, beech only occurs on the Fruška Gora Mountain and the Vršački Breg Mountain, where its growth is most often conditioned by specific orographic characteristics. Although it is located on the edge of its distribution range towards the Pannonian Plain, after Linden, Sessile oak and Turkey oak, European beech is the fourth most abundant tree species found on the Fruška Gora Mountain, whose share by volume is estimated at around 10% (Matović et al. 2022). On the Fruška Gora Mountain, beech is most often found in mixed stands with other trees species, while under favorable conditions, on northern exposures, near coves and next to streams, this species also constitutes pure stands. Considering the origin, most of European beech stands and trees on the Fruška Gora Mountain are of coppice origin, but stands and trees of seed origin are also represented. A smaller number of the most valuable stands of European beech and accompanying tree species were separated from regular management by the establishment of the National Park, and today these stands have the form of unmanaged old-growth forests or secondary virgin forests. Most of the beech stands on Fruška Gora Mountain are distributed on deep, slightly skeletal soils with high production potential.

Considering the distribution and habitat potential of beech forests and the forest lands on which these forests are distributed, they are one of the largest natural renewable reservoirs of stored carbon, in Europe as well as in the Balkans and in Serbia. According to Mund and Schulze (2006) the total carbon in a forest ecosystem is defined as ecosystem carbon, while Cannell (1996) divides ecosystem carbon into biomass carbon and soil organic carbon.

An important factor affecting the state of stored ecosystem carbon is the degree of stand preservation and the management practice history. The effects of different management systems on the state and changes of carbon biomass have been widely investigated since the 90s of the twentieth century (Cannell et al. 1992; Karjalainen, 1996; Fleming and Freedman, 1998; and others). On the other hand, the effects of different management systems on the condition and changes in soil carbon have been poorly studied (Mund and Schulze, 2006). A detailed study of the state of ecosystem carbon in dominantly managed beech forests in Serbia and Republic of Srpska was conducted by Đorem et al. (2024), but the effects of the management system on carbon was not investigated in this study either.

In the past in Serbia, almost all management systems described in the literature, from a clear felling system to a selective management system, were declaratively applied in beech forests. However, in practical forestry, single tree and group selection systems were dominantly used in regular management, often preempting quality and in extraordinary conditions (such as wars, occupation, economic crisis) of clear felling (Koprivica et al. 2013b; Matović et al. 2018). As the consequence of the above-mentioned, high uneven-aged and coppice beech forests dominate (Matović, 2019) in Serbia today. There are almost no even-aged high beech forests, but individual even-aged stands can be found on small areas. In the Fruška Gora Mountain, the management of beech forests was similar in the past.

Taking into consideration the above mentioned, the aim of this study is to investigate how the degree of preservation of stands and management practice history affect the state of ecosystem carbon in beech forests of the Fruška Gora Mountain.

2. Material and methods

2.1. The object of the study

The research was conducted as a part of the project entitled: "Climate Smart *Fagus sylvatica* Forests (CSFagus4EST)", which is funded by the European Union through FORWARDS (Horizon Europe Project No. 101084481) grants to third parties managed by European Forest Institute. It included three European beech stands that were managed in three different ways in the past: a) virgin forest without management, b) high stand, and c) coppice stand. In the following part of the study, three abbreviated terms will be used: Unmanaged, High and Coppice stand. The location of the investigated stands and their habitat characteristics are shown in the Figure 1 and the Table 1, respectively.

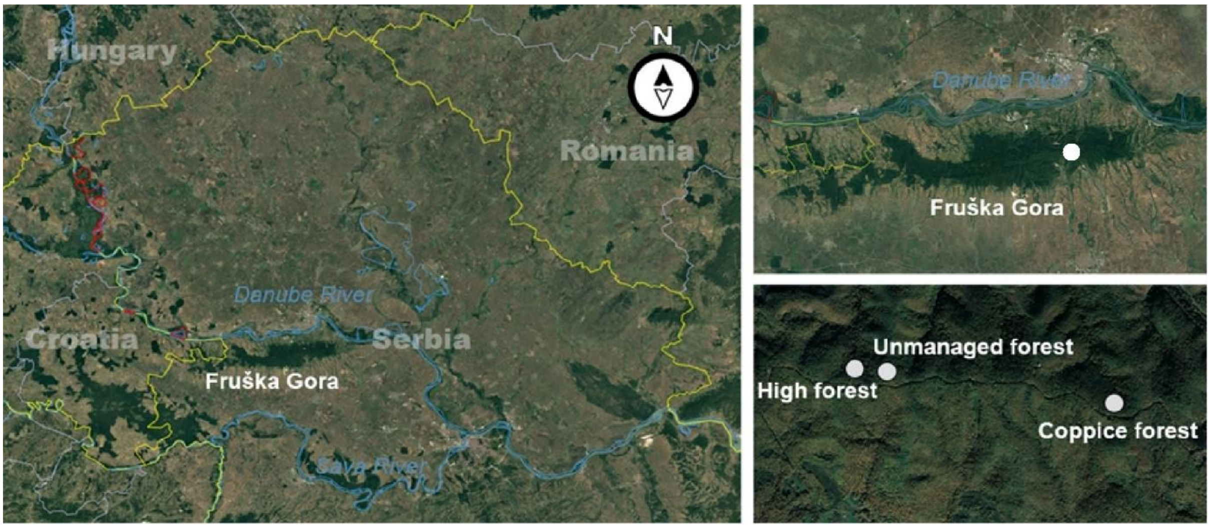

Figure 1. Location of the investigated European beech stands (source: GoogleEarth).

Table 1. Basic characteristics of the habitat of the investigated stands.

	Unmanaged stand	**High stand**	**Coppice stand**
Latitude (N)	45.1575°	45.1580°	45.1533°
Longitude (E)	19.7946°	19.7917°	19.8175°
Altitude (m a.s.l.)	459	447	463
Mean annual temperature (°C)	11.8	11.8	11.8
Sum of precipitation (mm)	624	624	624
Ellenberg's climate quotient (EQ) (1961-1990)	26.2	26.2	26.2
Ellenberg's climate quotient (EQ) (1981-2010)	28.1	28.1	28.1
Exposition	North	North	North
Soil depth	Deep	Deep	Deep
Origin	High forest	High forest	Coppice forest
Main management objectives	Unmanaged forest	Wood production	Wood production
Current management	Virgin forest	Wood production	Wood production

Meteorological data were obtained from the ClimateCharts portal (Zepner et al. 2020). The data regarding the habitat and stand characteristics of the locality was acquired from the forest management bases of the Fruška Gora National Park. Ellenberg's climate quotient (EQ) was expressed as the quotient of mean monthly air temperature in July and mean annual amount of precipitation, multiplied by 1000 (Stojanović et al. 2013).

The Table 1 shows that the investigated stands are characterized by very similar orographic, edaphic and climatic conditions. Observing the Ellenberg's climate quotient, on the basis of two climate normals, it is evident that the climate conditions on the Fruška Gora Mountain are becoming progressively unfavourable for the optimal development of beech forests. Many authors have estimated that in Central Europe, when the average values of this climate quotient of 30-year norms are higher than 30, such habitats are no longer suitable for the optimal development of beech and other mesophilic species, but are more suitable for oaks and other xerothermic species (Ellenberg, 1988; Czúcz et al. 2011; Stojanović et al. 2013).

2.2. Data collection

Due to the difficulties in identification of areas with a known management method history and the volume of measurements, individual sample plots of larger dimensions are used. Statistically, it would be more relevant if it would have been possible to conduct a larger number of trial areas (repetitions) for each management system. For the data collection in the researched stands, one circular shaped sample plot of 0.25 hectares with a radius of 28.21 m was set up. On all sample plots, living trees were counted and the diameter at breast hight (dbh) and height (h) of all trees were measured. Two cross diameters were assessed, and tree heights were measured with a Vertex Laser altimeter. Trees with dbh higher than 7 cm were measured in all stands. The measurement of dead trees was divided into three groups. Snags were measured according to the principle of living trees: chest diameter, height and, in the case of broken snags, the height of the fracture was assessed. The lying trees consisting of fallen trees, which were located entirely on the sample plots, was measured according to the principle of living trees: chest diameter was measured and instead of the height, the length of the tree was assessed. All other lying trees and their parts were measured according to the principle of the diameter in the middle of the assortment and the length of the same, and which were located on the sample plots. The diameter and height of the stumps located on the sample plots were measured. All parts of the dead wood were also assessed for the degree of decay.

Samples of fallen leaves and fruits/litter (the organic layer that constitutes all dry matter of leaves, fruits and small wood above the soil) were collected from all three sample plots. Five samples of fallen leaves/litter were collected on areas measuring 25 x 25 cm on each sample plot. In this text, we used the term litter.

Soil samples were collected from the sample plots at four depths: 0-10, 10-20, 20-40 and 40-80 cm. Soil samples were taken in their natural state using Kopecki cylinders with a volume of 100 cm^3 (Bošnjak et al. 1997). Soil samples in disturbed condition were taken according to Belić et al. (2014).

The intensity of defoliation and the presence of damage from abiotic and biotic factors were evaluated across the plots on dominant, codominant and subdominant trees, as basic indicators of the vitality and state of tree crowns. Tree defoliation and intensity of damage from biotic and abiotic stress factors on trees was evaluated in 5% classes (0%, 5%, 10%......95%, 99% and 100% (Eichhorn et al. 2016).

In order to estimate biomass, apart from terrestrial recordings, high-resolution multispectral recordings for the sample plots were made using the DJI Mavic 3 Multispectral drone (SZ DJI Technology Co., Ltd.). The latest generation drone is equipped with an integrated four-channel multispectral camera, a classic high-performance RGB camera and an RTK GNSS receiver for precise positioning. The filming was done during sunset. No challenges with wind, difficult filming or lack of light were noted.

Field measurements and samplings were carried out in June, July and August of 2024.

2.3. Statistical analyses

Processing of the collected data for the assessment of structural elements in the studied stands (the number of trees, basal area, average diameter) was carried out using standard dendrometric methods. The assembly was evaluated by using multispectral recordings.

The volume of living trees (wood above 3.0 cm) was determined using a regression equation obtained by analytically levelling data from volume tables of beech trees for Serbia (Mirković, 1969).

$$v = 0.000030499d^{2.06806}h^{0.997276}$$

The Gini index was calculated according to the formula:

$$Gdbh = \frac{\sum_{j=1}^{n}(2j-n-1)ba_j}{\sum_{j=1}^{n} ba_j(n-1)},\ 0 \leq Gdbh < 1$$

The detailed procedure for calculating this index was presented by Matović et al. (2018).

Above-ground biomass (B) of living trees was determined using a general regression equation designed to estimate the total biomass of European beech trees (Wutzler et al. 2008).

$$B = 0.0523d^{2.12}h^{0.655}$$

The root biomass of living trees was obtained according to the regression equation for beech forests in Serbia (Koprivica et al. 2012, Koprivica et al. 2013a).

$$Br = -0.429475 + 0.182227B - 0.000047499B^2$$

The Carbon (C) of living trees (above-ground) was determined using a general regression equation designed to estimate the carbon of European beech trees (Joonsten et al. 2004).

$$C = 0.023806419d^{2.1569}h^{0.66338}$$

The root carbon of living trees was determined by multiplying its biomass by a factor of 0.408 (Claus, 2003).

The volume, biomass, and carbon in the sample plots were obtained by summing the volume, biomass, and carbon of individual trees and then multiplying by 4 to obtain estimates per hectare.

The volume, biomass and carbon of snags was determined according to the same methodological approach as for the living trees.

The volume of dead wood was determined using the simple Huber formula. Based on the degree of decay of the dead wood, the obtained volume values were multiplied by different wood density factors in order to estimate the biomass of the dead wood. Based on the degree of decay, Marjanović et al. (2010) propose for European beech, five density factors: 1st degree: 0.6367 $t{\cdot}m^{-3}$; 2nd degree: 0.5252 $t{\cdot}m^{-3}$; 3rd degree: 0.4137 $t{\cdot}m^{-3}$; 4th degree: 0.3022 $t{\cdot}m^{-3}$; 5th degree: 0.1907 $t{\cdot}m^{-3}$. The decomposition level 1 refers to above-ground living wood, and level 5 to completely decomposed wood. In our case, the degrees of decomposition of dead wood are as following: 2 (healthy wood - less than 10% of decaying volume), 3 (slightly decaying wood, 10–40% of decaying volume) and 4 (decayed wood, more than 40% of decaying volume) (Koprivica et al. 2013b). In several studies in Germany, the average density of dead wood is estimated at about 0.31 $t{\cdot}m^{-3}$ (Mund, 2004).

The volume of stumps was obtained by applying the simple Huber's formula, while the biomass of the stump was obtained by multiplying the volume with the previously mentioned density factors. The root biomass of the stump was determined by a regression equation for European beech (Wutzler et al. 2008).

$$m = 0.0282\ d_{1,3}{}^{2,39}$$

The breast diameter ($d_{1,3}$) of felled trees was calculated previously from the diameter of the stump (d_P) applying the regression equation for beech trees (Nikolić and Banković, 1992).

$$d_{1,3} = 0.651965\ d_p + 0.000766\ d_p^2 + 0.000013\ d_p^3$$

The carbon content of dead wood biomass was calculated by multiplying the biomass of dead wood/tree by a coefficient of 0.5 (IPCC, 2003). Also, specifically in beech forests in Central Europe, Joosten et al. (2004) empirically determined that the carbon concentration in biomass ranges between 48.9 to 50.7% (49.7% on average). The carbon content of deadwood roots was calculated by multiplying dead wood root biomass by a factor of 0.408 (Claus, 2003).

Samples of fallen leaves and fruits/litter were dried in laboratory conditions, their mass and volume were measured. Based on these data, the biomass of dry leaves was obtained, which is expressed in kg/m^2, i.e. in t/ha. Mund, Schulze (2006) determined that the carbon content of healthy leaves is 0.479 g g^{-1}, while in partially decomposed leaves it is estimated to be 0.302 g g^{-1}. Considering that we did not fragment the fallen leaves and fruits, in this study we multiplied the leaf biomass with the average value of these two fractions (0.390).

The volumetric mass of the soil was determined in laboratory conditions according to Bošnjak et al. (1997), and the humus content according to Tyurin, modified by Simakov. The soil carbon content was determined from the humus content according to Belić et al. (2014). The total carbon content was estimated for all four depths expressed in kg/m^2, i.e. in t/ha. according to Stolbovoy et al. (2007) based on the volumetric mass of the soil, the thickness of the soil layer, the soil carbon content and the share of the fraction larger than 2 mm for each layer.

The obtained multispectral images were processed by calculating vegetation indices, the absolute and relative ratio between them, and the values of biomass, Gini index, homogeneity and density index were calculated (Li et al. 2022; Wai et al. 2022). Above-ground biomass was evaluated based on the Triangular Vegetation Index (TVI) and the Enhanced Vegetation Index (EVI). The Gini index was calculated as the leaf area index (LAI) minus the soil adjusted vegetation index and the ratio of the spectra of individual wavelengths. Homogeneity represents the average difference from the arithmetic mean of the classified vegetation indices. The density index is calculated as the sum of the Chlorophyll a and b indices, which is classified (divided) by quantiles of all calculated values. Classified vegetation indices represent a group of pixels whose value is similar or the same, that is, they differ from each other in the range of quantile or percentile values. In the Table 2 vegetation indices formulas are listed and explained.

Table 2. Vegetation indices formulas and descriptions used in the study.

Vegetation index	Formula	Index description
Triangular Vegetation Index (TVI) (Xing et al. 2020)	$TVI = \left(120 \times (NIR - Green) - 200 \times (Red - Green)\right)$	This index is calculated as the area of a hypothetical triangle in spectral space that connects (1) green peak reflectance, (2) minimum chlorophyll absorption, and (3) the NIR shoulder. When chlorophyll absorption causes a decrease of red reflectance, and leaf tissue abundance causes an increase in NIR reflectance, the total area of the triangle increases. It is good for estimating green LAI, but its sensitivity to chlorophyll increases with an increase in canopy density.

Table 2. Continue.

Vegetation index	Formula	Index description
Enhanced Vegetation Index (EVI) Wardlow and Egbert (2010)	$EVI = (NIR - Red) \div \big((NIR + 6 \times Red - 7{,}5 \times Blue) + 1\big)$	Enhanced Vegetation Index (EVI) is an advanced vegetation index created with higher sensitivity to biomass, atmospheric background, and soil condition. It is regarded as the modified version of Normalized Difference Vegetation Index (NDVI) with a high potentiality of vegetation monitoring by correcting all the external noises. Vegetation Indices are calculated from the bilateral surface reflectance that has been concealed for cloud, smoke, aerosols, water, cloud shadows, etc.
Leaf area index (LAI) (Fang et al. 2019)	$LAI = \frac{L_A}{P}$ L_A – leaf area; P – ground area surface;	Leaf area index (LAI) is a dimensionless quantity that characterizes plant canopies. It is defined as the one-sided green leaf area per unit ground surface area (LAI = leaf area / ground area, m2 / m2) in broadleaf canopies.
Soil adjusted vegetation index (SAVI) (Zhen et al. 2021)	$SAVI = \frac{NIR - Red}{NIR - Red + L} \times (1 + L)$ L = 0.5 (between -0.9 and 1.6) depending on soil;	SAVI is used to correct Normalized Difference Vegetation Index (NDVI) for the influence of soil brightness in areas where vegetative cover is low. Landsat Surface Reflectance-derived SAVI is calculated as a ratio between the R and NIR values with a soil brightness correction factor (L) defined as 0.5 to accommodate most land cover types.

Table 2. Continue.

Vegetation index	Formula	Index description
Chlorophyll a and b (CAB) (Zhang et al. 2022)	$CAB = \frac{Red}{Green^2}$	Chlorophyll is the green pigment present in the leaves and plays an important role in photosynthesis, i.e. conversion of light energy to chemical energy. Hence, it is a direct indicator of the plant's primary production and photosynthetic potential. It can be also used to understand the plant's nutrient status, senescence and stress due to water, disease outbreak, etc.

Multispectral data has been taken from the multispectral camera (Figure 2, step 1). Pre-processing of the images has been done in Pix4Dmatic (v.1.6) using default settings or images processing and corrections (Figure 2, step 2). After pre-processing, raster images have been opened in Quantum GIS (v. 3.32) for further processing. Raster images contain different band layers and used for calculation of different vegetation indices by applying formula (Table 1) in QGIS raster calculator (Figure 2, step 3). After calculation of different indices, statistical analysis has been performed to calculate quantiles and percentiles (Figure 2, step 4). These values have been compared to the ground truth values and multiplying factor has been calculated. Multiplying factor represent average sum of recent vegetation indices during year corrected by using several factors depending of the multispectral images and observed data (Figure 2, step 5). On final step (Figure 2, step 6), total numbers have been calculated as a distribution of pixels, resolution of images. Descriptive statistics have been utilized to present the final results in table format.

Figure 2. Workflow diagram for calculating forestry characteristics and factors.

3. Results and discussion

The Unmanaged stand has developed naturally without management for the last 60 years and is currently, according to our assessment, in the terminal phase (transition from the subphase of aging to the subphase of decomposition). In the researched stand, the structure is slightly disturbed, the mortality of trees is pronounced, decay of trees from the first floor are observed, and in some parts of the stand the formation of floors consisting of young trees is detected. Based on the number of registered stumps, in the high stand, we may conclude that in the last 20-25 years, management was conducted with mild to moderate logging. In addition, Matović et al. (2008) estimated that stumps in beech forests in Serbia need 20-25 years after felling to decompose so that they can't be longer measured. This stand is completely assembled with a significant presence of thick trees. For the coppice stand, based on the same criteria (the number and dimensions of stumps), we may conclude that the management was conducted with moderate logging intensity. This stand is moderately compacted, moderately preserved, without the participation of trees thicker than 60 cm. In this stand, a certain number of trees are also of seed origin. The assembly of studied stands is clearly visible on high-resolution multispectral images (Figure 3).

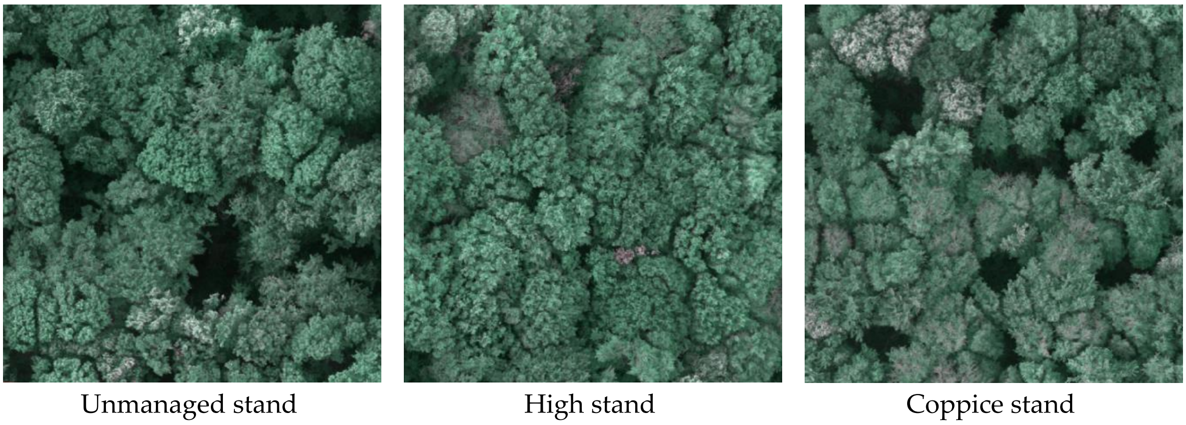
Unmanaged stand High stand Coppice stand

Figure 3. Multispectral images of the investigated European beech stands at the Fruška Gora Mt.

The highest average intensity of defoliation of the evaluated beech trees was found in the unmanaged stand and was estimated to be 12.28%. The average defoliation in the high stand was 5.54%, and 4.82% in the coppice stand. Damages from biotic factors were not detected in the researched stands. On the other hand, damage from abiotic factors were observed on three beech trees in the coppice stand resulting from the storm. In two trees, part of the crown broke off, and in one tree, the bark on the trunk was damaged. Considering that defoliation is a parameter that indicates the degree of vitality of trees and stands, it may be concluded that the highest vitality was found in the coppice stand, while unmanaged stand was found to be the least vital.

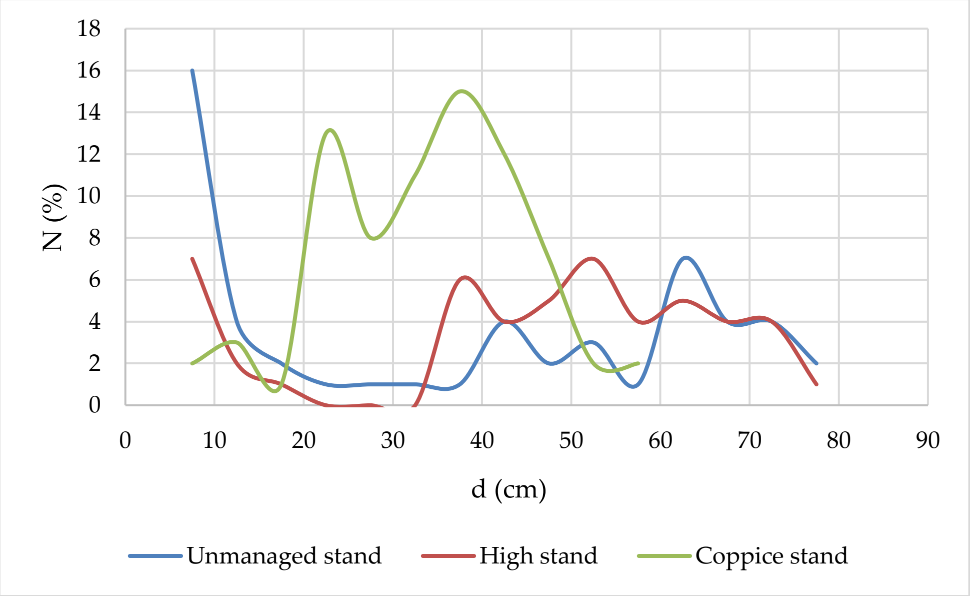

Figure 4. Diameter distribution of the researched stands.

Figure 4 shows the diameter distribution of the investigated stands. The unmanaged and the high stand have a relatively similar thickness structure, which is characteristic of stands in which there were no management measures or low-intensity management measures were applied. Both structures are characterized by a large variation in width, a decrease in the number of trees up to 30-40 cm, and then a significant share of thick trees from 50 to 80 cm. A similar diameter distribution in the compositions of beech of virgin forest character was observed by Matović et al. (2018). Researched stands, like the majority of high beech stands in Serbia, regardless of the diameter distribution, are diverse in age and uneven-aged (Matović, 2019). The coppice stand has a bell-shaped diameter distribution, with a small variation in width, which is most often a characteristic of even-aged stands.

Table 3 shows the basic structural elements of the researched stands. Interestingly, high stand has higher values of the basal area, volume and mean diameter compared to the unmanaged stand. The main reason for that was discussed previously in this paper, due to the terminal phase of development of unmanaged stand, and due to the absence of significant management measures in the high stand. Therefore, the high stand is completely closed (0.95), while the unmanaged stand is slightly thinned (0.90). However, the Gini index clearly shows that the structural heterogeneity is most pronounced in the unmanaged stand (0.55), while high and coppice stands are significantly more homogeneous regarding structure (0.39 and 0.34). The structural heterogeneity of this unmanaged stand is greater than in the three representative beech virgin forests in Serbia (Danilova Kosa, Vinatovača, Kukavica) in which the Gini index ranged from 0.45 to 0.52 (Matović et al. 2018).

Table 3. Basic structural elements of the researched stands.

Management history	N (trees/ha)	G (m^2/ha)	V (m^3/ha)	dg (cm)	Gini index	Assembly
Unmanaged stand	212	33.98	558.06	45.17	0.55	0.90
High stand	200	39.31	653.78	50.03	0.39	0.95
Coppice stand	308	31.36	436.14	36.01	0.34	0.80

Table 4 shows the estimated value of the total biomass obtained from living trees and different fractions of dead wood/tree through terrestrial surveys. The obtained values of total biomass and biomass from living trees are high, especially in the unmanaged and high stands. In three representative beech virgin forests in Serbia (Danilova Kosa, Vinatovača, Kukavica), Matović et al. (2018) estimated approximate values of biomass from living trees to be 455 to 517 t/ha, while in high managed stands the same authors determined an average value of about 320 t/ha, which is close to the coppice stand from this research.

Table 5 shows the estimated values of above-ground biomass (AGB), the Gini Index, Homogeneity and Density Index by applying multispectral images and estimated above-ground biomass obtained by terrestrial imaging. The above-ground biomass estimated using multispectral images were systematically higher than terrestrial images. When comparing with the above-ground biomass of trees obtained by terrestrial recordings, the values are higher: 1.02 (unmanaged stand), 1.16 (high stand) and 1.26 (coppice stand). However, the obtained values show the same proportion as the terrestrial surveys (the highest values for biomass were estimated in the high stand, medium in the unmanaged stand, and the smallest in the coppice stand). The Gini Index shows the distribution of biomass in space, which was found to be the most homogeneous in the high stand (37%), and the most heterogeneous in the coppice stand (47%). The Density Index shows that the biomass in space is the most concentrated in the high, and the least concentrated in the coppice stand. These values were expected considering the estimated stock of biomass.

The described Vegetation Indices and methods of calculation can be applied by forestry managers to acquire data for large areas in a faster and easier manner. Periodic observations acquire the concept of monitoring of a certain area by following not so much absolute values, but instead the relative relations between the calculated values of Vegetation Indices.

Table 4. Total biomass estimated in the investigated stands (t/ha).

Management history	Living tree			Dead wood								Total biomass
				Snags			Lying	Stumps			Total	
	Above-ground	Root	Total	Above-ground	Root	Total		Above-ground	Root	Total		
	t/ha											
Unmanaged stand	359.63	60.46	420.09	36.92	5.95	42.86	11.06	0.00	0.00	0.00	53.93	474.02
High stand	418.15	68,74	486.89	17.15	2.77	19.92	3.52	0.45	2.84	3.29	26.73	513.62
Coppice stand	288.86	47,56	336.41	7.80	1.42	9.22	1.37	1.33	7.08	8.42	19.01	355.42

Table 5. Estimated values of above-ground biomass, Gini Index, Homogeneity and Density Index using terrestrial measurements and multispectral recordings.

Parameter	Unit	Unmanaged stand	High stand	Coppice stand
Above-ground biomass (terrestrial) A	t/ha	407.61	439.27	299.36
Above-ground biomass (multispectral) B	t/ha	417.59	508.08	377.54
B/A		1.02	1.16	1.26
Gini Index	%	40	37	47
Homogeneity	%	41	55	32
Density index		180	312	105

Table 6 shows the total carbon found in wood biomass, including both living and dead wood in the investigated stands. High carbon reserves of living wood were determined in the unmanaged stand and in the high stand with values of 214 and 236 t/ha. In the coppice stand, the stock of carbon in living wood was lower, accounted about 161 t/ha. In unmanaged beech forests in Germany, Mund and Schulze (2006) estimated the carbon stock in living wood to be about 239 t/ha. The same authors determined an average of about 155 t/ha in high even-aged beech forests, and an average of 176 t/ha in high uneven-aged stands. In the area of central Serbia, Matović et al. (2018) evaluated the carbon stock from living trees in stands of virgin forests character to be approximately 236 t/ha on average, and in high uneven-aged stands on average of 158 t/ha. In the area of the western and eastern parts of Republic of Srpska (Bosnia and Herzegovina) and Central Serbia in dominantly managed stands, Đorem et al. (2024) estimated carbon reserves from living trees at an average of 155, 143 and 173 t/ha. In case of our study, a significant amount of dead wood was estimated in the unmanaged stand (over 24 t/ha), while high and coppice forest had significantly smaller but still significant values (around 13 and 9 t/ha). Mund and Schulze (2006) determined an average of only 1.7 t/ha carbon stock in living wood in managed forests, and only 6.4 t/ha in unmanaged beech forests.

Table 7 shows the estimated soil carbon in the investigated stands. The largest amount of carbon was detected in the unmanaged stand at about 166 t/ha, in the high stand that number was about 124 t/ha, and the smallest was in the coppice stand at about 76 t/ha. In managed even-aged beech stands Mund and Schulze (2006) estimated the soil carbon to be 75-98 t/ha, in managed uneven-aged beech stands about 85 t/ha, while in unmanaged beech stands about 105 t/ha. We believe that the estimated higher carbon stocks on Fruška Gora are primarily a consequence of the very deep soils on which these stands are located. In different regions in Serbia at an altitude of 200-500 m, Vidojević et al. (2021) determined the mean value of soil carbon which was 76 t/ha for depths up to 30 cm, i.e. 112 t/ha for depths up to 100 cm. Studying the carbon content for the area of alpine pastures on Durmitor Mountain, Kadović et al. (2012a) estimated the mean value of soil carbon to be 152 t/ha up to 40 cm depth. The same authors indicated a relationship between the increase in soil carbon content with higher soil moisture, the proportion of clay and dust fractions, and a moderate increase with the elevation of mean annual temperatures.

When the carbon stock in the soil is converted to 1 m^3 of soil, i.e. that each layer (0-10, 10-20, 20-40 and 40-80 cm) hypothetically has the same depth of 1 m, a clear regularity can be observed in all three researched stands that the carbon content decreases from the soil surface to the bedrock (Figure 5). Such regularity of the carbon content from the depth of the soil profile was confirmed by Kadović et al. (2012b) studying certain types of forest soils in Serbia.

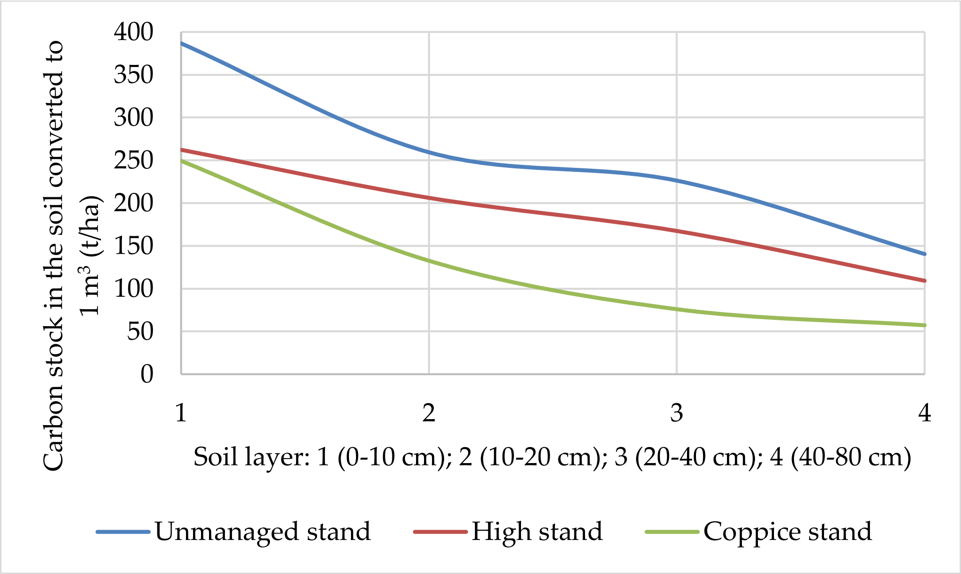

Figure 5. Carbon content in different soil layers in the investigated stands.

Table 6. Total carbon from biomass in the investigated stands (t/ha).

Management history	**Living tree**			**Dead wood**								**Total biomass**
				Snags			**Lying**	**Stumps**			**Total dead wood**	
	Above-ground	**Root**	**Total**	**Above-ground**	**Root**	**Total**		**Above-ground**	**Root**	**Total**		
t/ha												
Unmanaged stand	178.98	35.20	214.18	18.43	2.43	20.86	5.53	0.00	0.00	0.00	26.39	240.57
High stand	207.63	28.04	235.68	8.56	1.13	9.69	1.76	0.22	1.16	1.38	12.83	248.51
Coppice stand	141.86	19.40	161.27	3.85	0.58	4.43	0.69	0.67	2.89	3.56	8.97	169.94

Table 7. Estimated soil carbon in the investigated European beech stands.

Management history	**Soil carbon**	**kg/m² (average)**	**kg/m² (min)**	**kg/m² (max)**	**t/ha (average)**	**t/ha (min)**	**t/ha (max)**
Unmanaged stand	0-10 cm	3.87	3.83	3.95	38.67	38.26	39.48
	10-20 cm	2.59	2.35	2.87	25.94	23.48	28.67
	20-40 cm	4.52	4.24	4.81	45.25	42.42	48.08
	40-80 cm	5.62	5.57	5.71	56.17	55.70	57.11
	Total	**16.60**	**15.99**	**17.34**	**166.03**	**159.86**	**173.34**
High stand	0-10 cm	2.62	2.52	2.72	26.23	25.23	27.22
	10-20 cm	2.06	1.99	2.20	20.61	19.52	21.98
	20-40 cm	3.35	3.16	3.53	33.48	31.62	35.34
	40-80 cm	4.37	4.20	4.45	43.68	42.00	44.52
	Total	**12.40**	**11.87**	**12.90**	**124.00**	**118.37**	**129.06**
Coppice stand	0-10 cm	2.49	2.47	2.58	24.93	24.66	25.76
	10-20 cm	1.33	1.09	1.62	13.26	10.92	16.22
	20-40 cm	1.52	1.51	1.55	15.19	15.05	15.48
	40-80 cm	2.29	2.22	2.35	22.88	22.22	23.54
	Total	**7.63**	**7.29**	**8.10**	**76.26**	**72.85**	**81.00**

Table 8 shows the estimated biomass and carbon of litter. All three investigated stands were characterized by low estimated biomass and leaf carbon from 1.76 to 3.04 t/ha. Mund and Schulze (2006) obtained similar values, from 2.1 to 2.8 t/ha. In the area of the western and eastern parts of the Republic of Srpska and central Serbia, in dominantly managed stands, Đorem et al. (2024) estimated a smaller amount of carbon from the litter, ranging from 0.86 to 0.95 t/ha.

Table 8. Biomass and carbon sequestrated in the litter across the investigated stands.

Management history	Biomass of litter		Carbon of litter	
	kg/m²	t/ha	kg/m²	t/ha
Unmanaged stand	0.56	5.6	0.22	2.18
High stand	0.45	4.5	0.18	1.76
Coppice stand	0.78	7.8	0.30	3.04

Table 9 shows the estimation of the total (ecosystem) carbon stock in the investigated stands. The largest stock value was detected in the unmanaged stand at around 409 t/ha. Although the unmanaged stand is in a terminal phase, the ecosystem carbon stock was the highest, primarily due to the large accumulation of carbon in the soil. Investigating unmanaged beech stands, Mund and Schulze (2006) estimated an average of 352 t/ha for total carbon stock. The results of this study show that the estimated carbon stock was very high in the high managed stand, around 374 t/ha, while the lowest values were detected in coppice stand, around 250 t/ha. In managed beech forests, Mund and Schulze (2006) estimated the carbon stock values to range between 246 and 266 t/ha. In dominantly managed beech forests Đorem et al. (2024) evaluated the average ecosystem carbon stock between 250 and 379 t/ha.

Table 9. Total (ecosystem) carbon in the investigated stands (t/ha).

Management history	Living trees	Dead wood	Litter	Soil	Total carbon
			t/ha		
Unmanaged stand	214.18	26.39	2.18	166.03	408.78
High stand	235.68	12.83	1.76	124.00	374.27
Coppice stand	161.27	8.97	3.04	76.20	249.48

The share of biomass carbon in relation to the total (ecosystem) carbon was found to be the highest in the coppice stand, about 70%, in the high stand about 66%, and in the lowest in unmanaged stand about 59%. We believe that the lower share of biomass carbon in the unmanaged stand is a consequence of the terminal phase in the development of this stand, where due to the process of decomposition, the complete assembly was interrupted, which is a characteristic of unmanaged or virgin stand in the optimal developmental stage. The share of soil carbon was about 31% in the coppice stand, about 33% in the high stand, and about 41% in the unmanaged stand (Figure 6). In unmanaged beech stand, Mund and Schulze (2006) estimated the share of biomass carbon at around 70%, while in managed ones the values ranged around 65 to 68%. In managed beech stands, Đorem et al. (2024) estimated the share of above-ground carbon amounts from 64 to 67%. Naturally, this comparison is indicative because it does not refer to the share of biomass carbon, but to the share of above-ground carbon.

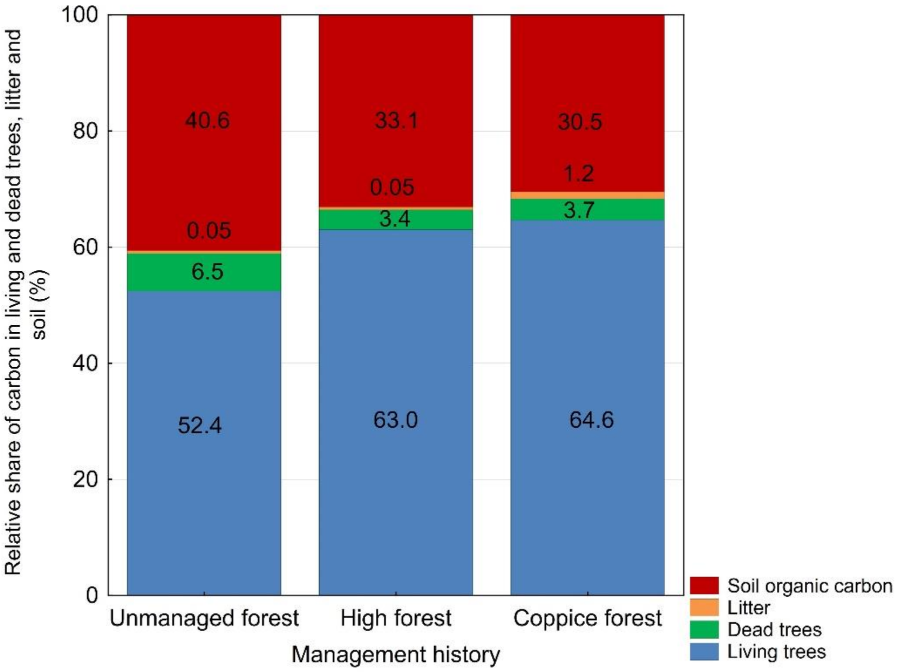

Figure 6. Relative share of different fractions in the total carbon in the investigated stands.

4. Conclusions

This research confirms that the beech forests of Fruška Gora have a great potential for storing ecosystem carbon. Large stock of stored carbon in the beech forests of Fruška Gora is significantly influenced by the high production potential of the habitat, primarily deep and fertile soils. Besides, the history of management practices has a significant impact not only on the stock of biomass carbon and soil carbon, but also on the mutual relationship. From an ecological point of view in case of beech forests, moderate management measures and the application of close to nature management systems and principles of continuous cover forestry (selective and group cutting) are, in addition to their well-known advantages, more optimal in carbon storage than the application of systems with surface management (clear and shelterwood cutting). Furthermore, this research initiates that, coppice beech forests, in addition to all other disadvantages in comparation to high forests, from the aspect of carbon storage as well, need to be converted in the long term into high primarily uneven-aged forests.

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