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Short-Term Impacts of Harvesting Intensity on the Upper Soil Layers in High Karst Dinaric Fir-Beech Forests

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Abstract: The present study addresses the short-term effects of different harvest intensities under close-to-nature selective management on the upper soil layers in Slovenian and Bosnian Dinaric karst fir-beech forests. The different harvest intensities coincided with the single-tree and irregular shelterwood management, common in the region. The effect of harvesting intensity on the upper soil layers (Ol, Of, Ol and 0–10 cm mineral soil) was investigated by a repeated measurements experiment in Slovenia on 27 research plots in close-to nature managed forests. The properties of the upper layers (concentration of SOC and TN, C/N ratio, weights, BD and SOC stocks) were analyzed twice, before (2011) and after (2014) treatment of 50% and 100% harvest intensity in relation to the total standing growing stock of trees. As a control, we used no-treatment <20% harvesting intensity plots. To extend this experiment, we added three comparable plots from the Bosnian site: one in an old-growth forest with 0% harvest intensity and two in the managed forest with <20% harvest intensity. The results of the assessment of mean differences indicated a significant influence of harvesting intensity on the decrease in SOC, TN concentrations, weights and SOC stocks in the organic layers and the increase in BD and SOC stocks in the 0–10 cm mineral soil. The highest relative decreases in Ol, Of and Oh SOC stocks occurred in 50% (−10 and −38%) and 100% (−16 and −49%) harvest intensities. Negligible relative differences in both organic and 0–10 cm mineral layers were found for the <20% harvest intensity in the region. The change in forest light conditions resulting from differences in canopy openness as a function of applied harvest intensity explained the significant difference in the properties of the upper soil layers. The impact of the short-term losses in SOC stocks, in terms of overall soil productivity, may depend on the regeneration dynamics and melioration methods.

Keywords: close-to-nature forest management; harvest intensity; Calcic Cambisol; forest soil; soil organic carbon

1. Introduction

The well-preserved condition of high karst Dinaric fir-beech forests is closely related to their low management intensity in the past [1]. Their uneven-aged structure resembles that of old-growth reserves [2], with elevation being the key factor controlling the microclimate in these temperate mountain forest stands [3]. Liberal selection of felling regimes in uneven-aged fir-beech forests, also known as close-to-nature silviculture [4], employs relatively low-intensity and small-scale felling regimes to mimic natural forest composition, structures and natural disturbances at the lower end of the stand-level disturbance intensity gradient [1,5], which is practiced in some European countries.

The result of such a forest management approach can be seen in high Dinaric karst fir-beech forests, which have an uneven-stand structure, multiple canopy layers, horizontal heterogeneity and a considerable amount of deadwood [6–9]. Compared to other geological substrates, karst ecosystems are considered vulnerable due to the rock–soil system [10] and forests growing on a calcareous bedrock, sensitive to changes in microclimatic conditions and extreme weather events [11,12]. However, the effects of different levels of stand changes in this region have not been adequately studied.

Soil organic matter properties are particularly important for the productivity of shallow mountain soils on limestone and dolomite in the Dinaric region. Soil properties, especially total soil organic carbon (SOC) and total nitrogen (TN), are used as elementary predictors of forest stand stability [13]. Losses in SOC stocks resulting from abiotic and biotic changes influence the decline in soil function. Although soil organic matter has some inherent resilience to environmental change through stabilization mechanisms [14,15], the upper layers, including the humus layer and upper mineral soil, respond to a change in stand conditions. Short-term or long-term reductions in the SOC stock depend on the degree of site disturbance, which varies between harvest intensities in the humus layer [16] and miner soil layers [17]. Despite the importance of knowing the current status and changes of SOC stocks depending on the applied forest management practices, little is known in this regard in the Dinaric karst region [18].

Selective harvesting and practices that promote continuous canopy cover are usually considered to maintain and increase SOC content. Modeled data show that the selection system causes an increase in SOC stocks [19]. The comparison between single-tree-selection management and conventional age-class management in Norway spruce stands in Austria showed an 11% increase in SOC stocks in the upper mineral soil [20]. Applied shelterwood harvesting systems in the Lenga forest of Chilean Patagonia reduced SOC at short-term levels [21]. Single-tree selective and irregular shelterwood harvests should increase the rate of decomposition at the short-term level without causing long-term SOC declines. There is an important influence by increasing the mineralization rate on forest stand recovery and increasing productivity. Because there is no clear evidence on how different harvesting practices under selective management affect soil organic matter properties, this is investigated in this study.

For the Dinaric region, it was reported that the SOC stock in 0.1-hectare canopy gaps decreases, compared to the old-growth reserves [22]. The creation of small canopy gaps can lead to a significant change in soil conditions [23]. Moreover, SOC declination has been reported in mountain forest soils of the Bavarian limestone Alps, where the single-tree selection system was applied [24,25]. We hypothesize that high-intensity harvesting, equivalent to 50 and 100% removal, even if applied to a small forest area, would significantly affect SOC stocks in high karst Dinaric forests. We hypothesize that a single-tree selection vs. an irregular shelterwood system, corresponding to different levels of harvest intensity, would cause different levels of site change, reflecting SOC storage. Therefore, we believe it is critical to evaluate the effect of different harvest intensities on the upper soil layers that are most susceptible to change. Understanding the mechanisms of post-harvest carbon loss is far from complete and requires deeper understanding [26], especially under the threat of extreme weather events and global climate change.

Studies of how soils on limestone and dolomite are affected by harvesting are rare, and more data and studies are needed for a better understanding of the SOC dynamic in these areas. Because soils on limestone and dolomite are regularly shallow and rocky, they have a lower water storage capacity [27–29]. Stable soil conditions are maintained under a continuous canopy cover, which may be an indicator of changes in soils. Thus, the forest canopy determines the light and thermal microsite conditions [30,31] and hence the SOC dynamics. It influences the soil organic layer through the amount of litterfall [32] and the mineral SOC content through root debris [33]. Studies show that higher concentrations of soil organic matter and mineral N coincide with tree canopy density [34]. Canopy openness, as a function of harvest, intensity can therefore be considered as an indicator of environmental change at the site, which is crucial for understanding the nature of such a relationship in assessing optimal openness for SOC conservation.

In the present study, it was hypothesized that the quantity and quality of SOM would be similar in all plots studied (1) and that the intensity of harvest would be reflected in light conditions (canopy openness, site light factors) and upper soil layer properties (pH values, SOC, TN concentrations, C/N ratio, SOC stock). The objectives of the present study are (1) to determine the quantity and quality of soil properties in the upper soil layers; (2) to evaluate the effect of harvest intensity on the upper soil layers, especially on SOC stocks and (3) to characterize the relationship between canopy openness, light conditions and upper soil layer properties, i.e., pH values, SOC, TN concentrations, C/N ratio and SOC stocks.

2. Materials and Methods

2.1. Site Description

The study sites were located in the high karst Dinaric fir-beech forests of Bosnia and Herzegovina (BA) and Slovenia (SL), starting from the southernmost site on the Bjelašnica Mountain (1420 m a.s.l.), through Kočevski Rog (871 m a.s.l.), Snežnik (870 m a.s.l.) to Trnovski Gozd (814 m a.s.l.) (Figure 1). All sites had similar ecological factors.

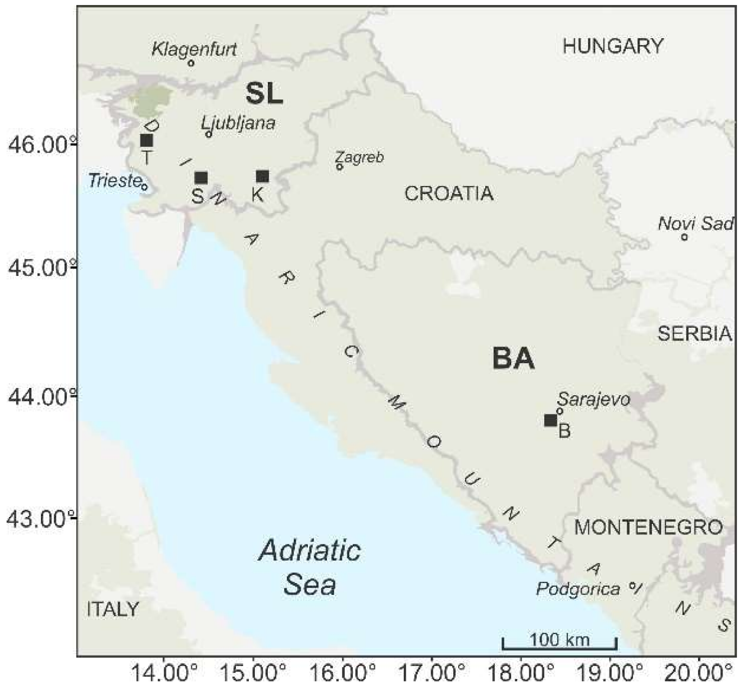

Figure 1. Location of the sites in Bosnia and Herzegovina (BA, Bjelašnica Mt.—B) and Slovenia (SL, Kočevski Rog—K, Snežnik—S and Trnovski gozd—T).

On each of these sites, the predominant tree species were European beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* (L.) H. Karst), belonging to the *Omphalodo-Fagetum* association. Each site is characterized by high plant diversity [35,36]. A comparable forest structure was attributed to each site, which is related to the applied close-to-nature forest management. A canopy cover of 95%, necessary for natural regeneration, is the typical characteristic of forest canopy conditions (Table 1). Furthermore, forest sites with growing stocks between 270 and 442 m^3 ha^{-1} and increments between 6.2 and 9.4 m^3 ha^{-1} yr^{-1} were described (BA: Forest Management Base for the Igmansko forest area for the period 2004 to 2014; SL: [37]). Climate and soil data indicate similar site conditions. Mean annual temperatures (MATs) varied between 7.6 and 11.3 °C and mean annual precipitation (MAP) between 1192 and 1619 mm for the period 1985–2015 (meteorological data were obtained from the website Royal Netherlands Meteorological

Institute "Climate Explorer" http://climexp.knmi.nl, accessed on 2015). The sites were attributed to calcareous and dolomitic bedrock and the typical soil type complex of Leptosol, Rendzic Leptosol, Cambisol and Luvisol in BA [38] and in SL [37]. The soils found at the sites were predominantly shallow to moderately deep, rocky, rich in soil organic matter and clay content.

Table 1. Dinaric karst fir-beech forest site characteristics.

Experimental Site	BA [1]	SL(K) [2]	SL(S) [2]	SL(T) [2]
Latitude (°N)	43.738	45.668	45.672	45.989
Longitude (°E)	18.254	15.033	14.46	13.759
Altitude (m a.s.l.)	1420	871	870	814
MAT (°C)	7.6	9.0	8.4	11.3
MAP (mm)	1192	1465	1573	1619
Growing stock (m^3 ha^{-1})	270	352	442	292
Increment (m^3 ha^{-1} yr^{-1})	6.2	9.4	8.3	6.2
Surface rockiness (%)	19 ± 10	38 ± 13	31 ± 18	17 ± 11
Soil $pHCaCl_2$	5.2 ± 0.8	5.3 ± 0.6	5.3 ± 0.7	4.6 ± 0.4

[1] BA: Bosnia and Herzegovina Mt Bjelašnica—B; [2] SL: Slovenia sites Kočevski Rog—K; Snežnik—S; Trnovski gozd—T; a.s.l. = above sea level; MAT = mean annual temperature; MAP = mean annual precipitation. Surface rockiness and $pHCaCl_2$ were determined on site.

Harvesting intensity, which, in practice, depends on the single-tree or irregular shelterwood harvesting method, influenced the formation of small canopy gaps typical for close-to-nature forest management. The close-to-nature silviculture differs from plantation forestry and clear-cutting [4]; it is characterized by site-appropriate species composition, avoidance of clear-cutting, focus on stability, reliance on natural processes and focus on the development of individual trees and mixed and uneven-aged, structurally diverse forests [39]. Typical openness in these forests does not exceed 5%. This practice is defined in the Forestry Laws BA and SL, which prohibit larger areas of intensive logging in both countries (Forest Law, Official Gazette of the Federation of Bosnia and Herzegovina, No. 20/02 and Forest Act, Official Gazette of the Republic of Slovenia, No. 30/93).

2.2. Study Approach

The effect of harvest intensity was studied in a repeated-measures experiment. At SL, 27 research plots were studied (2011 and 2014) before and after the harvest treatments; eighteen with 50% and 100% (SL50% and SL100%) harvest intensity, representing harvested tree volume compared to total growing tree volume; and nine control plots (SL < 20%) with no treatment in 2011, representing a regularly managed forest with the harvest intensity up to 20% of the total growing tree volume. To gain a more complete insight into the effect of harvest intensity in a paired-plot experiment using an identical sampling methodology, we compared a 0% plot (unmanaged forest since 1960) and two <20% plots (managed forest in 2012). The control plot in BA 0% represented an old-growth forest without treatment. Surveys and sampling at BA were conducted in 2015. The area of each plot at the observed sites was 0.50 and 0.45 hectares, adjusted to the proposed minimum experimental area for fir-beech forests [40].

2.3. Field Work

The soil sampling design followed a number of samples suggested by the ICP Forests Forest Soil Co-ordinating Centre and the Expert Panel on Soil and Soil Solution to detect differences in treatment effects [41]. Organic (litter layer (Ol), fragmented/fermented layer (Of), humified layer (Oh)) and top mineral soil (top 0 to 10 cm (M10)) were collected at designated sampling points in each plot. The number of exact sampling points was 8 (0%) and 16 (<20%) in BA and 45 (per each < 20%, 50%, 100%) in SL (Figure 2). The distance between sampling points was at least 10 m. Three soil samples were collected at each point to create a composite sample. The Ol, Of, Oh and M10 soil layers were sampled separately.

Each separate organic layer was excavated below a 25 × 25 cm frame; each mineral soil layer to a depth of 10 cm was sampled with a stainless-steel auger (diameter = 6.7 cm). For the organic layer, the determined thickness was delineated on four sides of the square frame. Due to the significant influence of the type on soil organic carbon (SOC) stocks [42], only Rendzic Leptosols and Cambisol were considered for sampling. Above-ground stoniness was estimated for each plot.

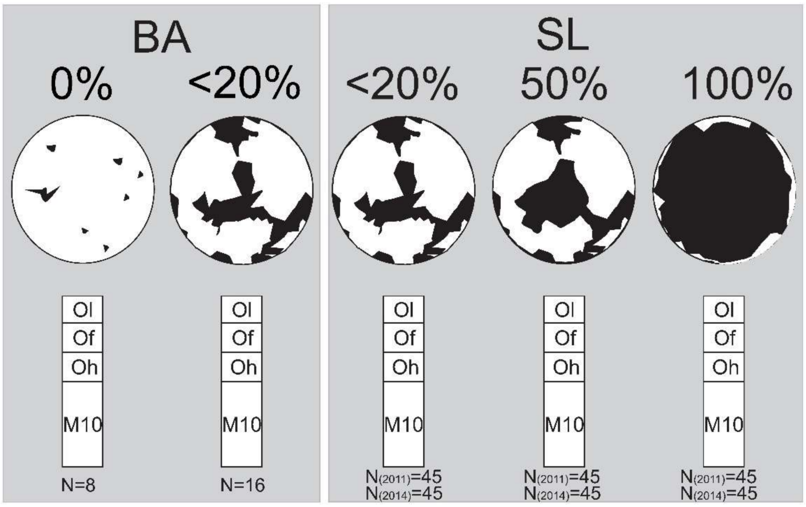

Figure 2. Scheme of the experimental plots (BA0% 1; BA < 20% 2; SL < 20% 9, SL50% 9, SL100% 9) showing the total number of sampled points. The study approach combines paired-plot comparison (Bosnia—BA) and repeated measurements approach (Slovenia—SL). White color represents the forest canopy and black the canopy openings. Ol (litter), Of (fragmented/fermented), Oh (humified) and M10 (top mineral 0 to 10 cm) are sampled upper soil layers and N represents the number of sampling points per plot.

The canopy openness was analyzed using 40 digital color hemispherical photographs (HPs) at BA (at 0% 8 points and at 20% 24 points) and SL (at 100% 8 points) sites. Canopy condition is considered an indicator of change in the fir-beech forest canopy and was used to characterize the relationship between canopy openness and soil organic matter. The HPs were taken in the high growing season using a DSLR Canon EOS Rebel T3i digital camera with a calibrated fish-eye lens and analyzed using WinScanopy software (2010 pro-d). Exposure was fitted to the above-canopy conditions on each plot prior to shooting, as described by [43], with no significant noteworthy blooming effects [44]. Canopy openness (%), direct site factor (DSF%), indirect site factor (ISF%) and total site factor (TSF%) were presented using Surfer® (Golden Software, LLC, Golden, CO, USA).

2.4. Laboratory Analysis

Organic and mineral soil samples were air-dried immediately after removal from the field. Both were weighed and then ground after the removal of stones and roots, and an aliquot of the sample was analyzed for concentrations of SOC and total nitrogen (TN), by dry combustion using a CNS analyzer (Elemental Analyser LECO CNS 2000, St. Joseph, MI, USA). The volume of stones in the soil was evaluated. The ratio of C to N was calculated from their concentrations. The pH values of the soil were determined in 0.01 *M* $CaCl_2$ solution. From the weight (kg m^{-2}), the SOC stock of Ol, Of and Oh layers (Formula (1)) and from the bulk density of the fine soil (kg dm^{-3}) the stock M10 SOC (Formula (2)) were calculated.

In addition, a possible carbonate content was determined for samples that reacted with hydrochloric acid or exceeded a pH value in $CaCl_2$ of 6.5 on a calcimeter (Scheibler instrument, Eijkelkamp Soil & Water, Giesbeek, The Netherlands). Most samples did not contain carbonates, as soils on limestone and dolostone are rarely calcareous. Concentrations of SOC were calculated from the difference between total organic carbon and inorganic carbon concentrations. Samples with a pH less than 6.5 were assumed to have total carbon consisting entirely of organic carbon.

Ol/Of/Oh-layer:

$$\text{SOC-stockOl/Of/Oh} = \text{SOC} \times \text{weight} \times 10. \quad (1)$$

SOC-stockOl/Of/Oh = stock of soil organic carbon in the Ol/Of/Oh layer (g/m^2/100 t/ha).

SOC = concentration of organic carbon in the organic layer (%).

Weight = dry weight of the organic layer (kg/m^2).

M10-layer:

$$\text{SOC-stock M10} = \text{SOC} \times \text{BD} \times \text{d} \times \text{CFst}{*}10. \quad (2)$$

SOC-stock M10 = soil organic carbon stock in mineral soil (kg/m^2 × 10 = t/ha).

d = depth class/horizon thickness (m).

SOC = concentration of organic carbon (%).

BD = bulk density (kg/dm^3).

CFst = correction factor for stoniness, 100 − (% stones)/100.

2.5. Statistical Analysis

Statistical analyses included descriptive–statistical parameters and univariate statistical methods to compare soil properties between plots. Differences between treatments at the SL site for each variable (SOC, TN, C/N ratio, weight (organic layer) and SOC stocks for the observed layers (repeated measurements in 2011 and 2014)) were analyzed using a paired *t*-test ($p < 0.05$). For the BA site only, we used the *t*-test ($p < 0.05$) to compare soil properties between control and 20% harvest plots. Before performing univariate statistical analysis, the Shapiro–Wilk test was performed to check the normality of the sampling distributions. Homogeneity of variance was determined using Levene's test. Variables that did not conform to the normal distribution were sqrt-transformed before further testing.

Relative differences in SOC, TN, C/N, weights or BD, SOC stocks were calculated between initial and after post-treatment values. A one-way test ANOVA was performed to determine significant differences ($p < 0.05$) between the effects of <20% BA, <20% SL, 50% SL, and 100% SL harvest intensities.

Redundancy analysis (RDA) aimed to present a general pattern of variation and relationships among plots with different canopy openness conditions and focused on determining the most distinguishing parameters among 0%, 20% and 100% harvest intensity. Response variables were log-transformed. We used the Vegan package developed in R Studio Version 1.3.1093 (RStudio Team, 2020). Pearson correlation was applied to examine the relationships between principal components and light parameters.

3. Results

3.1. Quantities and Quality of Soil Organic Matter

Based on the quantity and quality of the soil organic matter, observed by SOC and TN concentration, C/N ratio, weight/BD and SOC stocks, the BA and SL Dinaric forest sites showed high similarity of upper soil layers (Table S1). The organic layers Ol, Of and Oh layers showed high similarity, while the mineral layer M10 proved to be more variable. Moreover, the variability of soil organic matter properties increased with increasing soil depth in the Dinaric karst region.

However, despite the similarities, the SOC stocks in the upper soil layers varied in a wide range between 0.36 and 2.58 t ha^{-1} in Ol, 0.73 and 4.07 t ha^{-1} in Of, 2.54 and 7.43 t ha^{-1} in Oh and 25.2 and 41.9 t ha^{-1} in M10 (Figure 3, Table S1). These variations, starting from an old-growth forest BA0% to the close-to-nature managed forest plots BA < 20%, SL < 20%, SL < 50% and SL < 100%, affect the ability to detect the effect of harvesting.

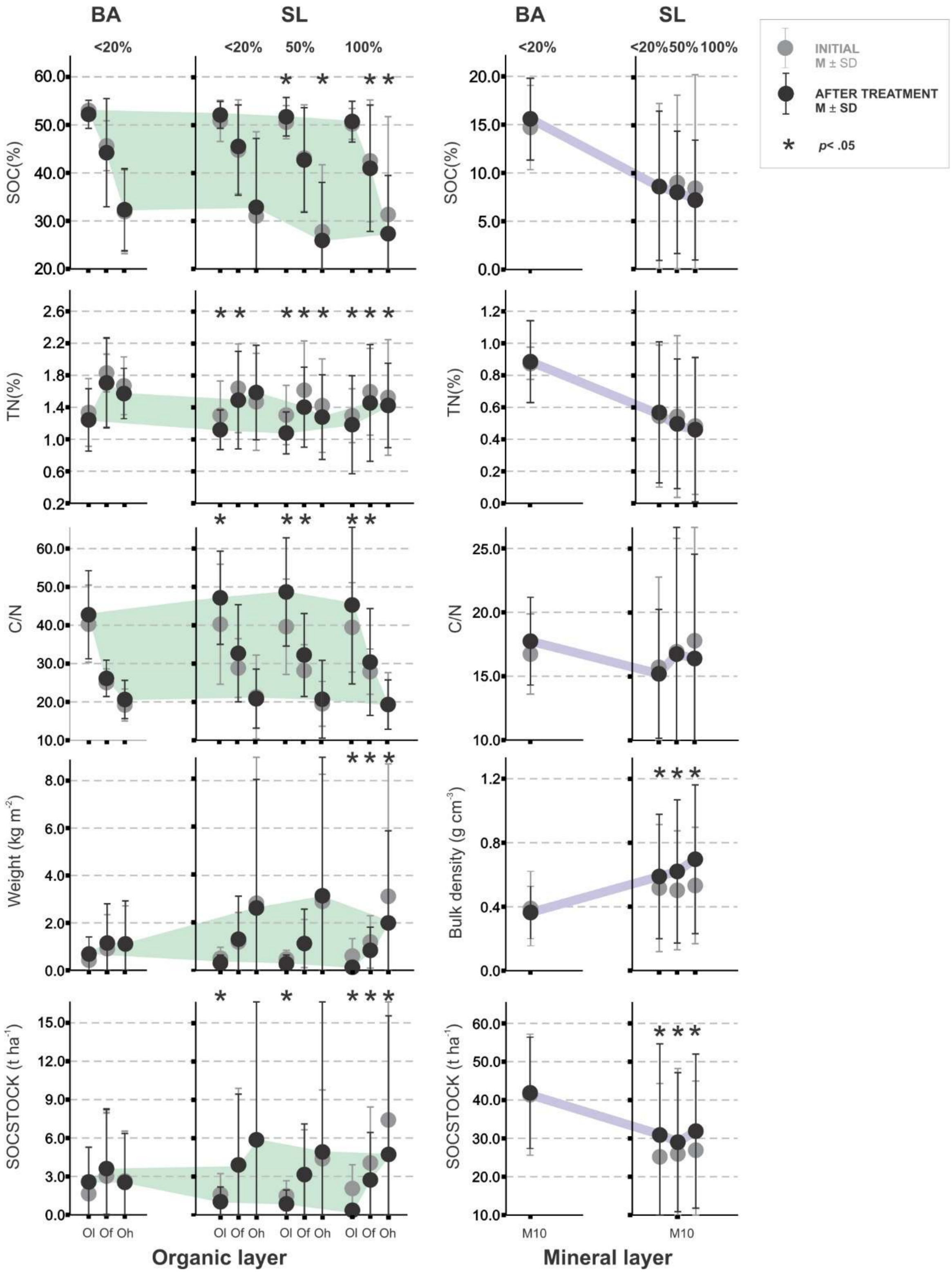

Figure 3. Means and standard deviations of soil organic carbon (SOC; %), total nitrogen (TN; %), C/N ratio, weights or bulk densities (kg m^{-2}, kg dm^{-3}) and carbon stocks (SOC stock; t ha^{-1}) distributed in the organic (Ol, Of, Oh) and mineral (M10) layers at the BA (Bosnian) and SL (Slovenian) sites. The green and violet dashed areas represent connected external mean values between sites. The labels 0, <20, 50 and 100% represent harvest intensity. * defines significant ($p < 0.05$) difference between initially measured values and after the treatment.

3.2. The Effect of Increased Harvesting Intensity on the Upper Soil Layers

The results of the analysis of mean differences show the significant influence of harvesting intensity on the values SOC, TN concentrations, C/N ratio, weights or BD and C stocks (Figure 3). The significant level of differences between the initially measured variables and after treatment (50% and 100%) indicates a clear effect of increased harvesting intensity on the decrease in SOC, TN, weights and C stocks. The effect was not observed in the deeper part of the organic layer Oh or in a mineral M10 layer. This indicates that there is no short-term response in mineral soil to an increase in harvest intensity. On the contrary, no significant differences were found in the observed variables at BA after comparing the control plots with 0% (old-growth forest) and 20% harvest intensity. This means that the effect of 20% harvest intensity has negligible influence on both organic and top mineral soil layers.

The relative differences in the upper soil layer indicate the effect of harvest intensity on soil organic matter quality observed from TN concentrations and C/N ratios (Figure 4). The decreases were not only observed in the plots with high harvest intensity but also in the plots without treatment, which points to annual variation in the observed characteristics in the upper soil layer. A significant decrease is shown with respect to the individual (Ol, Of and Oh) and the sum of organic layers (∑Ol, Of, Oh) for harvest intensities of 50 and 100%.

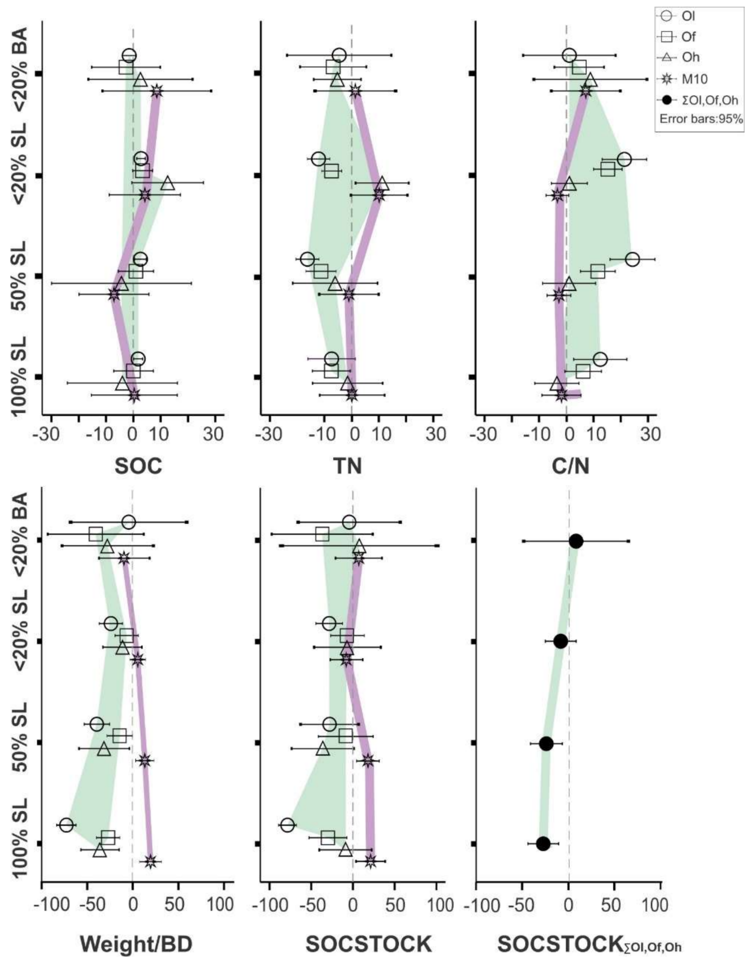

Figure 4. Mean relative differences and standard errors of soil organic carbon (SOC), total nitrogen (TN), C/N ratio, weight or bulk density (BD) and SOC stocks in Ol (litter), Of (fragmented/fermented) and Oh (humified) layers calculated between control plots versus harvested plots (harvest intensity <20% in Bosnian site: <20% BA, harvest intensity <20% in Slovenian site with no treatment: <20% SL, harvest intensity 50% and 100% in Slovenian site: 50% SL and 100% SL). The green and violet dashed areas connect external mean values.

Decreased weights and SOC stocks in the organic layer differed significantly ($p < 0.01$) between harvest intensity treatments in SL. Relative differences in SOC stocks ranged from −10 to −38% for 50% and from −16 to −49% for 100% harvest intensity. Increases in BD and SOC stocks of the upper mineral layer also differed significantly ($p < 0.01$) between harvest intensities.

As shown in Figure 4, there was a negligible difference in SOC stocks in the total organic and M10 layers at BA20%.

3.3. The Relationships between Forest Canopy and Light Conditions with the Upper Soil Layer

An increase in the canopy openness reflects light conditions and indicates thermodynamic changes in the forest stand. For this reason, we investigated the relationship between topsoil properties and canopy indices based on measurements from three BA (0% and 20%) and two SL (100%) plots.

Harvest intensity influenced different values of canopy openness (%), ranging from 6.87 to 8.40% (0%BA), 5.30 to 15.8% (20%BA) and 5.02 to 43.4% (100%SL, Kočevski Rog). These variations were also consistent with measured light parameters (ISF%, DSF% and TSF%). As shown in Table S2 in the order BA0%, BA20%, SL100%, the increases in calculated light values were followed by decreases in the upper soil layers (SOC, TN and SOCSTOCK). The quality of the organic soil matter, as indicated by a greater C/N ratio, was also influenced by the canopy openness and the light conditions.

Based on the RDA results of the upper soil layers the first two axes explained 15.2% (Ol) 15.5% (Of), 15.9% (Oh) and 16.1% (M10). The restricted proportion of variation explained by the first two axes was 99.8% (Ol), 98.0% (Of), 95.6% (Oh), and 97.7% (M10).

The properties of the upper soil layer pH values, SOC, TN, C/N ratio and SOC stocks scores are shown in Table 2. In the graphs shown in Figure 5, the closer the points in the RDA graphs, the higher the degree of similarity between them. For example, the topsoil layer in the 100% plot appeared to be different from the 0 and 20% harvest intensity plots, which appeared to be more similar to each other. The closer the distribution of the samples to the explanatory vectors in the graph, the more similar the sample is to openness (%), DSF(%), ISF(%) and TSF(%).

Table 2. Sample scores for upper soil layer and variables pH values, soil organic carbon (SOC), total nitrogen (TN), C/N ratio and SOC stocks.

Layer	Score	pH Value	SOC	TN	C/N Ratio	SOC Stock
Ol	RDA1	0.003	0.025	0.171	−0.288	0.543
	RDA2	−0.003	0.005	0.087	−0.119	−0.091
	PC1	0.005	0.008	−0.022	0.047	1.416
	PC2	−0.004	−0.010	−0.316	0.572	−0.024
Of	RDA1	−0.057	0.062	0.096	−0.104	0.649
	RDA2	0.012	0.114	0.183	−0.202	−0.069
	PC1	0.016	−0.060	−0.021	−0.028	1.505
	PC2	−0.091	0.206	0.406	−0.492	0.006
Oh	RDA1	−0.028	0.313	0.265	−0.117	0.444
	RDA2	0.005	0.166	0.211	−0.213	−0.299
	PC1	−0.028	0.313	0.265	−0.117	0.444
	PC2	0.005	0.166	0.211	−0.213	−0.299
M10	RDA1	−0.079	−0.675	−0.322	0.268	−0.153
	RDA2	−0.081	0.172	−0.073	0.319	−0.007
	PC1	0.098	1.103	0.378	0.176	−0.015
	PC2	0.028	−0.013	−0.114	0.228	−0.974

Note: Labels define organic litter (Ol), fragmented/fermented (Of), humified Oh and mineral 0–10 cm (M10) soil layers. The RDA1 and RDA2 are first and second redundancy analysis axes. The PC1 and PC2 are first and second principle components.

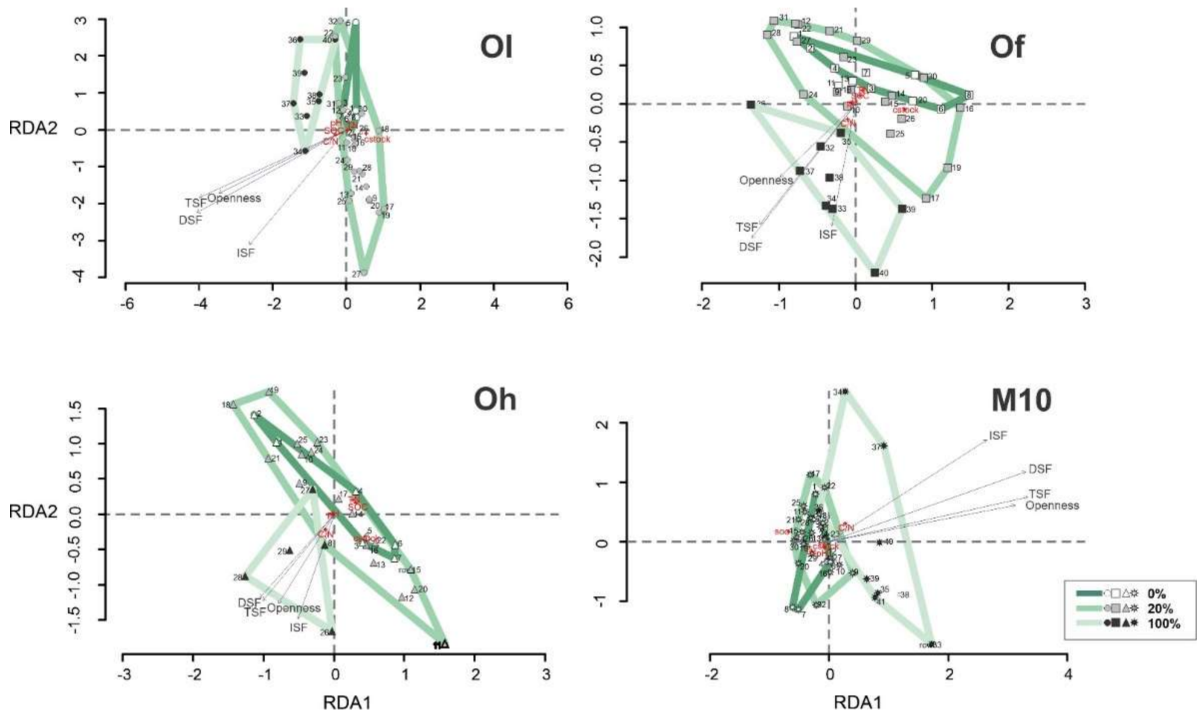

Figure 5. Redundancy analysis (RDA) for upper soil layers (organic litter (Ol), fragmented/fermented (Of), humified Oh and mineral 0–10 cm (M10) layers). Response variables are soil organic carbon (SOC), total nitrogen (TN), C/N ratio, SOC STOCK and pH values and explanatory variables are openness (%), direct site factor (DSF, %), indirect site factor (ISF, %) and total site factor (TSF, %).

The arrow length of each soil property indicated its contribution to the order axes. High correlations between RDA1 and PC1 with explanatory vectors were found for both the Of and Oh layers (Table 3).

Table 3. Correlation coefficient (R^2) values between vector values, first axe of redundancy analysis (RDA1) and first principle component (PC1) for the analyzed upper soil layers.

Layer		Openness (%)	DSF (%)	ISF (%)	TSF (%)
Ol	RDA1	−0.477	−0.477	−0.477	−0.477
	PC1	0.879	0.879	0.879	0.879
	R^2	**0.41**	**0.57**	**0.24**	**0.55**
Of	RDA1	−0.418	−0.418	−0.418	−0.418
	PC1	0.908	0.908	0.908	0.908
	R^2	0.15	**0.29**	0.02	0.25
Oh	RDA1	−0.470	−0.470	−0.470	−0.470
	PC1	−0.883	−0.883	−0.883	−0.883
	*R*2	0.20	**0.35**	0.08	**0.32**
M10	RDA1	0.625	0.625	0.625	0.625
	PC1	0.780	0.780	0.780	0.780
	R^2	**0.61**	**0.68**	**0.44**	**0.70**

Note: Labels define organic litter (Ol), fragmented/fermented (Of), humified Oh and mineral 0–10 cm (M10) soil layers. Bold and underlined values represent significant ($p < 0.05$) correlation coefficients.

4. Discussion

4.1. Upper Soil Layer Properties in the Dinaric Karst Region

The estimated SOC stocks (Table S1) were in good agreement with previously determined values (Ol + Og + Oh: 2.8 and 5.3 t ha^{-1}; M10: 25.8 to 52.5 t ha^{-1}) for similar site conditions at Snežnik in Slovenia [22]. The SOC stock for the organic layer fits perfectly with the estimates of other relevant studies [45] but also with reports from calcareous alpine forest stands [24,46]. The almost equal composition of SOC and TN in the organic layers could be explained by similar stand conditions and species compositions. The data support the statement that shallow calcareous mountain soils contain the highest concentrations of SOC [18]. Minor variations in soil organic horizons were most likely influenced by variations in a mixture of herb species, microrelief and elevation in fir-beech forests in the region.

4.2. Harvest Intensity Impact

Our results confirm that a harvest intensity of up to 20%, corresponding to the single-tree harvesting method, has no effect on SOC stocks and changes in soil organic matter composition SOC, TN or the C/N ratio in the upper soil layers. In contrast, 50 and 100% harvest intensities affect short-term losses in SOC stocks in the organic layer and alter organic matter composition. The effect was not consistent with upper mineral soil.

Differences indicating losses in SOC stocks are explained by reductions in above-ground litter input and increased mineralization due to changes in abiotic factors in harvested plots after canopy removal. Higher solar radiation, more heat energy adapted from the soil and temporarily higher moisture might have caused more favorable microbial conditions for decomposition [47,48]. The decomposition process is expected to be most pronounced in labile organic horizons [49], which is confirmed by our results. Our estimation of the effect is supported by the reported soil CO_2 efflux, which increased after harvest for both intensities on the same study plots [50]. We assume that soil conditions are not altered enough to prevent enzymatic activity in soil due to the protective function of forest surrounding the gap. The long-term impact is difficult to predict based on these findings. In the short term, the increased rate of organic matter turnover is a favorable outcome of harvesting that supports faster forest regeneration. Some reports from the region suggest that lower forest density, which can be associated with openness, means higher forest ecosystem stability [9], but this does not consider the gap formation. Such short-term losses in the amount of soil organic matter and accelerated litter decay have been reported in beech-dominated limestone stands of the Austrian Alps [51]. The effect of enhanced decomposition can last up to 4–5 years [52], so a longer period should be considered for repeated measurements.

Low-intensity harvesting up to 20%, commonly applied as selective, single-tree harvests, had an insignificant effect on soil organic matter according to our results from the Bosnian site on Mount Bjelašnica, which is consistent with the general understanding that no reduction [53–56] or even an increase [57] occurs after the application of low-intensity harvests. Moreover, no losses in the SOC stocks or even an increase were observed in the upper ten centimeters of the mineral soil. A meta-analysis evaluating the response of SOC stocks to timber harvesting at more than 20 forest sites showed an increase in SOC stocks in the mineral soil [17]. The applied forest practices in the Dinaric region are evaluated as SOC protective. This conclusion is supported by the practice of preserving branches and woody debris in forests [58] and protective measures considering soil disturbance [59].

The relationship between canopy openness and soil properties (Figure 5) supports the accelerated decomposition explanation. This openness may regulate soil organic matter redistribution and decomposition. Canopy openings of alpine fir forests of the Eastern Tibetan Plateau have been reported to increase litter decomposition, with the highest rates in the middle of gaps [60]. We hypothesize that one consequence, based on the character of the relationships, is the increased leaching of carbon and nitrogen into the mineral soil. This process may imply a shift to deeper horizons and stabilization of organic matter with a mineral component. Moreover, SOC can be sequestered in deep soil layers, among others [61]. We hypothesize that it is critical to find an optimal size of an area to harvest in order to preserve SOC and improve soil productivity. Impact detection is challenging due to the heterogeneity and high dispersion of mean values of SOC, which usually vary between 42% and 70% [62]. Given the importance of gap formation to soil productivity, further studies are needed to optimize canopy openness and better understand long-term impacts and possible shifts from SOC to more stable forms in mineral soils of the Dinaric Karst region. Gaps represent favorable sites for natural regeneration [31], where increased canopy openness could lead to strong changes in SOM quantity and quality.

There was a redistribution of SOC between the organic and mineral layers of the soil, indicating that the entire soil profile should be analyzed to better assess the effects of management [63]. In addition, losses of SOC from the organic horizon were accompanied by gains in the M10 layer, which can be attributed to the combined effect of the increased decomposition and transport of SOC deeper into the soil. This raises the question of the possible effect of forest thinning on the translocation of SOC from labile to more stable forms and mineral soils.

5. Conclusions

We combined soil data from a fir-beech forest in the Bosnian and Slovenian Dinaric region to investigate the influence of harvest intensity on soil organic matter properties, especially soil organic C stocks. A harvest intensity of <20% of the growing stock did not lead to a decrease in SOC stock, which is the most predictable result and indicates no change in soil and site productivity. Harvest intensities of 50 and 100% on 0.45 ha induced a SOC stock decrease in the organic layer (on average 24% to 32%) and increases in the 0–10 mineral layer, explained by changes in soil bulk density. The impact of short-term losses on soil productivity may depend on regeneration dynamics and restoration methods.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f12050581/s1, Table S1: Soil organic matter quantity and quality in Bosnian (BA20%) and Slovenian sites (SL0%, SL50% and SL100%). Means and standard deviations of the soil organic carbon (SOC) and total N (TN) concentrations, C/N ratio, weights, bulk densities (BD) and SOC stocks are shown for the organic and 0–10 cm mineral (M10) layer.; Table S2: Means (bold) and standard deviations for openness (%), light condition parameters—direct site factor (DSF%), indirect site factor (ISF%), total site factor (TSF%) and soil organic matter properties pH values, soil organic carbon (SOC in %), total nitrogen (TN in %), C/N ratio, SOC stocks (t ha^{-1}).

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