

Soil carbon and nitrogen stocks after thinning in Norway spruce plantations in the Central Balkan Mountains, Bulgaria

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Thematic field: Forest policy and key challenges

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Abstract

This study aimed to evaluate how different thinning intensities influence the accumulation of organic carbon and nitrogen in soils. We analysed key soil parameters under varying thinning regimes in Norway spruce (*Picea abies* (L.) H.Karst.) stands, compared with unthinned controls, across six state forestry management units in the Central Balkan Mountains, Bulgaria. On the territory of each management unit, soil samples were taken from three types of plots: unmanaged controls (no silvicultural intervention for over 20 years); light thinning (10–15 %, within the past 10 years); and moderate thinning (20–25 %, within the past 10 years). Soils were examined in depth layers of 0–10, 10–20 and 10–30 cm. We measured bulk density, rock content, soil acidity, and soil organic carbon and total nitrogen stocks. Results indicate that low-intensity thinning (10–15 %) significantly alters soil organic carbon. These findings highlight the need for proactive management strategies to guide thinning practices in Bulgarian forests, with particular attention to soil organic carbon and total nitrogen dynamics.

Key words: forest management, mountain ecosystems, organic matter, soil depth, sustainable management, thinning intensity.

Introduction

Forests are essential regulators in the global biogeochemical cycles of carbon (C) and nitrogen (N), acting as dynamic C sinks through biomass, litter, and soil (Lal 2005, Pan et al. 2011). Forest soils, in

particular, store approximately two-thirds of ecosystem C, and they are crucial for N cycling, soil buffering, and water retention (Batjes 1996, Galloway et al. 2008). The role of soil as a stabilising factor in ecosystem functioning is especially important in mountain regions, where climatic and

topographic variability interact strongly with land use and forest structure (Zhiyanski et al. 2016, Kirova 2024).

In Bulgaria, Norway spruce (*Picea abies* (L.) H.Karst.) is widespread in the montane and subalpine zones of the Central Balkan Mountains, occurring in both natural forests and plantations (Alexandrov and Dimitrov 2005, Panayotov et al. 2011). These coniferous plantations, established during large-scale reforestation campaigns, now play a dual role – providing timber and regulating key ecological processes, such as water retention, erosion control, and C sequestration (Zhiyanski et al. 2016, Kirova 2018). However, many Norway spruce stands are currently at or near maturity, making them vulnerable to wind damage, pests, and drought – especially when artificially structured and densely stocked (Panayotov et al. 2015, Menichetti et al. 2017, Marinov et al. 2022).

Forest thinning is widely applied in these systems to improve tree stability and resilience, reduce competition, and maintain ecosystem functions. However, thinning affects the microclimate and soil surface through increased radiation, altered water dynamics, and changes in litterfall, with direct consequences for soil C and N dynamics (Jandl et al. 2007, Zhang et al. 2024). Studies have shown that thinning can decrease C inputs to the soil due to reduced root exudation and organic debris, while simultaneously enhancing decomposition and mineralisation (Zhang et al. 2018, Stoeva and Kirova 2021). However, when conducted at low intensity and with attention to site-specific conditions, thinning does not necessarily reduce soil organic carbon stocks (SOC_{stocks}) and may even improve N availability in upper horizons (Menichetti et al. 2017, Kirova 2024). Thinning can stimulate microbial

processing and nutrient cycling, leading to greater incorporation of stable organic matter over time, which could bring the system to post-disturbance recovery of soil organic carbon (SOC), when below-ground C inputs and nutrient cycling processes are enhanced (Zhang et al. 2023). In addition, some studies have indicated that minimal interventions trigger net losses, but moderate interventions promote recovery, especially if logging residues are retained (Zhang et al. 2022, Erkan et al. 2023).

Despite the importance of these findings, regional studies in Bulgaria remain sparse. Recent work in the western Stara Planina indicates that thinning intensities of around 25 % in Norway spruce plantations do not significantly alter bulk density (BD), pH, or coarse fraction content (CF), although slight reductions in SOC and significant increases in total nitrogen (TN) were observed in managed plots compared to control plots without management (Kirova 2024). The type and intensity of disturbance – whether silvicultural or natural, such as ice storms – also affect nutrient cycling and C stocks over decadal timescales (Menichetti et al. 2017, Kirova 2024).

This study builds on these findings by evaluating the effects of various thinning intensities on key soil parameters in Norway spruce plantations in the Central Balkan Mountains. The investigation focuses on SOC_{stock} and total nitrogen stock (TN_{stock}), bulk density, soil reaction (pH), CF, and soil moisture (W), measured across three soil depth layers (0–10, 10–20, and 20–30 cm). The aim of the study was to evaluate how thinning intensity influences the accumulation of SOC and TN, thereby providing a basis for sustainable forest management in the studied type and similar coniferous plantations.

Materials and Methods

Research area

This study was conducted in 2022 on the territory of six state forestry management units (SFMU) located in the central part of the Balkan Mountains (Stara Planina), Bulgaria, specifically on the northern slopes of the range: Etropole, Teteven, Troyan, Apriltsi, Rositsa, and Gabrovo (Fig. 1).

The research area is located at altitudes ranging from 1000 to 1300 m a.s.l. The soils in the studied plots are classified as Cambisols (IUSS Working Group WRB 2015). The focus of the study was on managed Norway spruce plantations, subjected to thinning at different intensities.

Experimental design

In each SFMU, three sample plots were established in Norway spruce plantations (Table 1) with different forest thinning intensities:

- M0 – Control plots: unmanaged stands with no silvicultural intervention in the past 20+ years;
- M10 – Light-intensity thinning: plots thinned at 10–15 % within the past 10 years;
- M20 – Moderate-intensity thinning: plots thinned at 20–25 % within the past 10 years.

The information on thinning intensity was obtained from the official forest management plans and refers to the reduction in stand volume of the studied plantations.

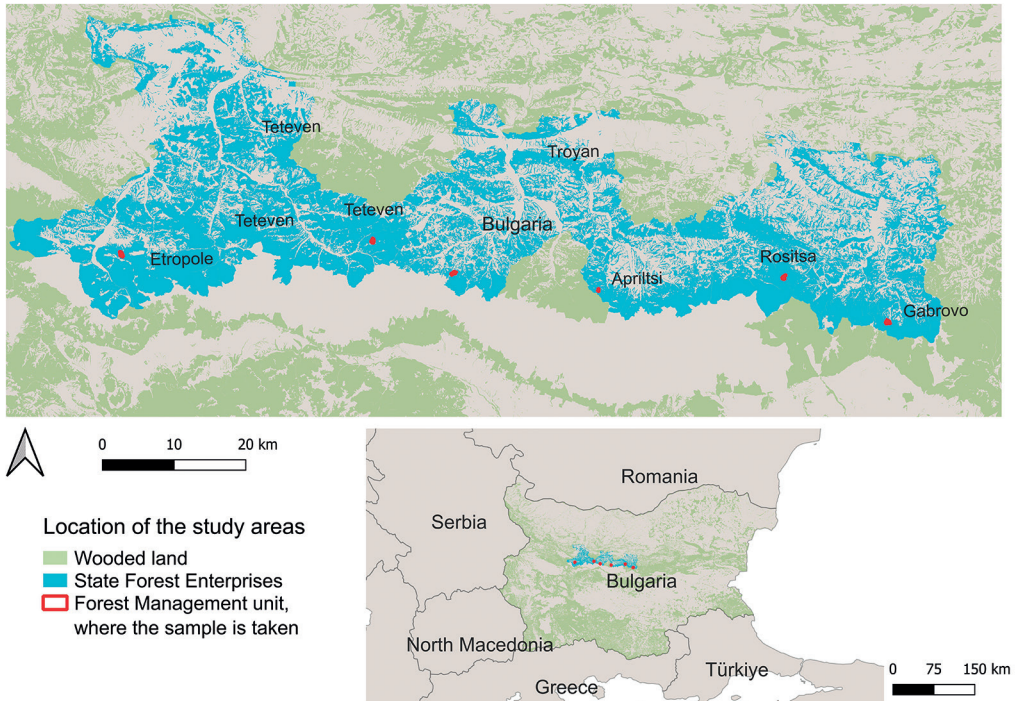


Fig. 1. Location of the study area in the Central Balkan Mountains, Bulgaria.

Table 1. Characteristics of sample plots.

State forestry enterprise sample site	Soil type, IUSS 2015	Aspect of the slope	Altitude, m a.s.l.	Mean slope, °	Stand age, years	Year of thinning
Etropole						
M0	Cambisols	NE	1200	27	50	-
M10		NE	1200	27	50	2013
M20		NE	1200	27	50	2013
Teteven						
M0	Cambisols	NW	1200	26	65	-
M10		NW	1200	26	65	2015
M20		NW	1200	26	65	2015
Troyan						
M0	Cambisols	N	1300	21	45	-
M10		N	1300	21	45	2015
M20		N	1250	14	60	2010
Apriltsi						
M0	Cambisols	N	1300	24	55	-
M10		NW	1250	29	55	2014
M20		N	1250	24	55	2013
Rositsa						
M0	Cambisols	NW	1100	26	50	-
M10		NW	1100	26	50	2013
M20		NW	1100	26	50	2013
Gabrovo						
M0	Cambisols	N	1000	26	50	-
M10		N	1000	26	50	2014
M20		N	1000	26	50	2014

Note: IUSS 2015 = IUSS Working Group WRB (2015).

Each sample plot covered 0.1 ha (1000 m²). Soil samples were collected, after removing the litter layer, using a stainless-steel auger from three depth layers: 0–10 cm, 10–20 cm, and 20–30 cm. For each depth, three replicate soil samples were randomly collected within each 0.1 ha plot. The random placement of sampling points was designed to capture microrelief heterogeneity (e.g., small slope variations, ground vegetation patches) and reduce the influence of within-plot variability on the results (FAO 2006).

Laboratory methods and approaches

Following ISO 11465:1993, soil samples were oven-dried at 105 °C for 5 h to determine soil moisture (W) and bulk density (BD).

BD and W were calculated using equations (1) and (2):

$$BD = \frac{WD}{VC}, \quad (1)$$

where:

- BD is the soil bulk density, g·cm⁻³;
- WD is the dry weight of the soil sample, g;

- VC is the volume of the sampling cylinder, cm³.

$$W = \frac{WW - WD}{WD} \cdot 100, \quad (2)$$

where:

- W is the soil moisture content, %;
- WW is the wet weight of the sample, g;
- WD is the dry weight of the sample, g.

The CF was determined gravimetrically (Donov et al. 1974) following these steps:

1. Approximately 100 g of dried soil was subsampled;
2. Organic matter was removed by washing;
3. The residue was dried and sieved through a 2 mm mesh;
4. Fragments >2 mm were weighed.
5. Calculated according to the following equation (3).

$$CF = \frac{WCF}{WMS} \cdot 100, \quad (3)$$

where:

- CF is the coarse fragment content, %;
- WCF is the weight of coarse fragments, g;
- WMS is the weight of the measured subsample, g.

Soil texture (mechanical composition) was analysed using Kaczynski pipette method, after dispersion with hydrochloric acid (Donov et al. 1974).

Chemical analyses were performed on sieved samples (<2 mm). Soil pH was measured using a HANNA HI2211 pH/ORP meter in a 1:5 soil-to-water suspension, following ISO 10390:1994.

SOC was determined using the Tjurin method via oxidation with a K₂Cr₂O₇-H₂SO₄ mixture at 160 °C, catalysed by pumice and Ag₂SO₄ (Donov et al. 1974). Titration was carried out with 0.2N Mohr's salt ((NH₄)₂SO₄·FeSO₄·6H₂O) with phenylanthranilic acid as an indicator.

TN was determined by the Kjeldahl method, in accordance with ISO 11261:1995 (1995). The C:N ratio was calculated from the measured SOC and TN values.

SOC_{stock} was estimated by equation (4), according to the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003). TN_{stock} was calculated using the same approach, following Ellert and Bettany (1995):

$$\text{SOC}_{\text{stock}} \text{ or } \text{TN}_{\text{stock}} = C \text{ or } N (\%) \cdot \text{BD} (\text{g} \cdot \text{cm}^{-3}) \cdot d (\text{cm}) \cdot (1 - CF), \quad (4)$$

where:

- C or N is the content of soil organic carbon or total nitrogen, %;
- BD is soil bulk density, g·cm⁻³;
- d is depth of the soil layer, cm;
- CF is the fraction of coarse fragments (>3 mm) expressed as a decimal.

Statistical analyses

Statistical analyses were conducted using the R environment (R Core Team 2024) via the RStudio interface, version 2024.09.0+375 (Posit Software 2024). For each of the six sample plots within the three thinning intensities (M0, M10, M20), the mean values of the three field replicates per plot were calculated and used in subsequent analyses.

Normality of the data was assessed separately for each soil depth (0–10, 10–20, and 20–30 cm) and thinning intensity using the Shapiro–Wilk test.

Two-way ANOVA was performed to evaluate the effects of thinning intensity and soil depth on the main soil properties. When significant differences were detected ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) post-hoc test was applied to identify pairwise differences among groups between thinning intensities and depths.

Results

Across all measured parameters, soil depth exerted a strong influence on soil physical and chemical properties.

Depth-related gradients were evident for W, BD, CF, SOC, TN, the C:N ratio, and SOC_{stock} and TN_{stock}. The average values along with standard deviations are presented in Table 2.

Table 2. Soil properties by depth and thinning intensity.

Parameter	Depth, cm	M0	M10	M20
W, %	0–10	24.49 ±8.94	30.02 ±8.40	24.53 ±10.11
	10–20	22.12 ±6.10	23.45 ±5.55	22.57 ±8.74
	20–30	22.19 ±6.91	20.67 ±5.17	22.66 ±9.19
BD, g·cm ⁻³	0–10	0.98 ±0.11	0.96 ±0.16	0.95 ±0.15
	10–20	1.09 ±0.12	1.13 ±0.19	1.11 ±0.11
	20–30	1.18 ±0.10	1.22 ±0.09	1.09 ±0.12
CF, %	0–10	30.96 ±4.83	21.96 ±5.24	26.02 ±4.43
	10–20	24.64 ±7.32	22.89 ±6.85	23.84 ±3.51
	20–30	29.33 ±5.09	25.59 ±5.07	21.63 ±6.35
pH	0–10	3.59 ±0.37	3.71 ±0.33	3.63 ±0.31
	10–20	3.73 ±0.39	3.70 ±0.24	3.57 ±0.28
	20–30	3.62 ±0.41	3.78 ±0.28	3.64 ±0.30
SOC, %	0–10	6.14 ±1.59	4.96 ±1.58	5.61 ±1.14
	10–20	4.38 ±1.08	3.45 ±0.77	4.01 ±1.04
	20–30	3.16 ±1.00	1.95 ±0.19	2.90 ±0.85
TN, %	0–10	0.35 ±0.13	0.31 ±0.10	0.33 ±0.13
	10–20	0.28 ±0.10	0.23 ±0.05	0.26 ±0.09
	20–30	0.23 ±0.08	0.17 ±0.04	0.21 ±0.07
C:N	0–10	19.18 ± 6.92	16.30 ± 5.00	14.41 ± 3.06
	10–20	16.79 ± 6.97	15.38 ± 3.53	12.27 ± 3.97
	20–30	18.55 ± 6.36	15.73 ± 2.76	13.93 ± 1.10
SOC _{stock}	0–10	40.48 ± 8.07	35.24 ± 7.22	25.94 ± 7.04
	10–20	35.60 ± 6.85	29.03 ± 2.74	17.69 ± 2.35
	20–30	38.33 ± 3.24	33.22 ± 5.97	24.55 ± 7.36
TN _{stock}	0–10	2.30 ± 0.82	2.29 ± 0.73	1.86 ± 0.62
	10–20	2.29 ± 0.63	1.94 ± 0.32	1.53 ± 0.38
	20–30	2.25 ± 0.70	2.18 ± 0.60	1.79 ± 0.61
Clay, %	0–10	23.61 ±8.87	31.10 ±7.96	31.84 ±8.80
	10–20	34.44 ±11.09	32.66 ±8.74	33.17 ±6.95
	20–30	33.63 ±8.97	42.84 ±16.36	32.09 ±6.69
Sand, %	0–10	76.39 ±8.87	68.90 ±7.96	68.16 ±8.80
	10–20	65.56 ±11.09	67.34 ±8.74	66.83 ±6.95
	20–30	66.37 ±8.97	57.16 ±16.36	67.91 ±6.69

Note: M0 = control (unthinned), M10 = light-intensity thinning (10–15 %), M20 = moderate-intensity thinning (20–25 %). Bulk density (BD), soil moisture (W), coarse fragments (CF), organic carbon (SOC), total nitrogen (TN), clay, and sand as percentages. Depth intervals refer to the top 0–10, 10–20, and 20–30 cm of the mineral soil. Columns 3–5 represent mean ±standard error.

W was generally highest in the 0–10 cm layer, with M10 plots showing the highest mean value (30.02 ± 8.40 %), followed by M0 (24.49 ± 8.94 %) and M20 (24.53 ± 10.11 %). At 20–30 cm, W values decreased, particularly in M10 (20.67 ± 5.55 %), whereas M0 and M20 maintained slightly higher levels (Fig. 2).

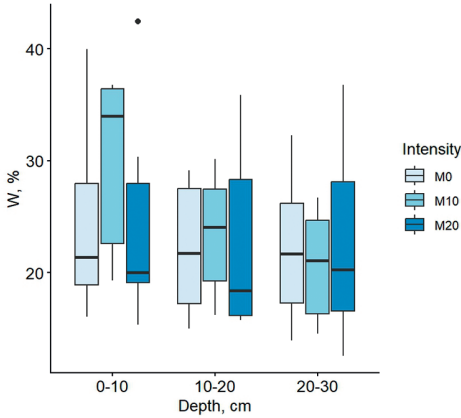


Fig. 2. Distribution of W across all studied depths and treatments.

BD increased with depth (Fig. 3), ranging from ~ 0.95 – 0.98 $\text{g}\cdot\text{cm}^{-3}$ in the surface layer to ~ 1.18 – 1.22 $\text{g}\cdot\text{cm}^{-3}$ at 20–30 cm

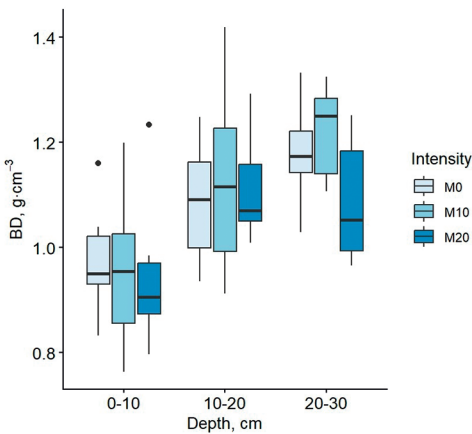


Fig. 3. Distribution of BD across all studied depths and treatments.

(Table 2). The highest BD was observed in M10 plots at 20–30 cm (1.22 ± 0.19 $\text{g}\cdot\text{cm}^{-3}$).

CF was highest in the 0–10 cm layer of M0 (30.96 ± 4.83 %) and lowest in M10 (21.96 ± 5.24 %). With increasing depth, CF tended to decrease in M0 between 0 and 20 cm, but slightly increased again at 20–30 cm. In contrast, CF showed greater fluctuations in M10 and M20 (Fig. 4).

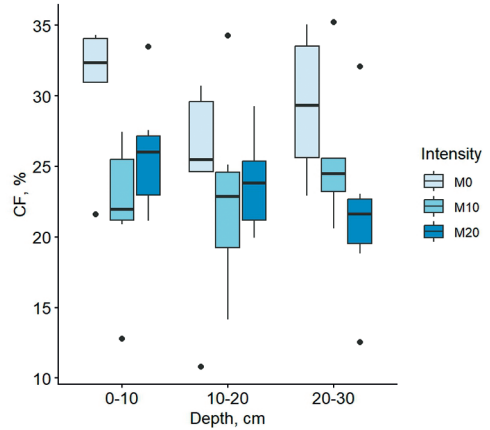


Fig. 4. Distribution of CF across all studied depths and treatments.

Soil pH ranged between 3.57 and 3.78, with slightly higher mean values in deeper layers of M10 (Fig. 5).

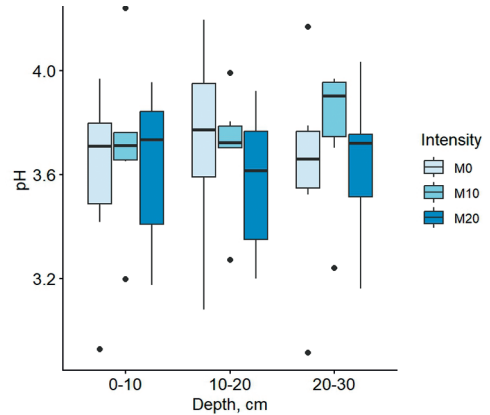


Fig. 5. Distribution of soil pH (in d.H₂O) across all studied depths and treatments.

Soil texture (clay and sand fractions) remained relatively consistent across treatments within each depth layer, but some depth-related variation was observed. Clay content tended to increase with depth in all treatments, with the highest value recorded in M10 at 20–30 cm ($42.84 \pm 16.36\%$). Conversely, sand content decreased slightly with depth in M10, reflecting a finer texture in deeper layers. SOC and TN declined sharply with depth (figs 6A and

7A). In 0–10 cm layer, SOC ranged from $4.96 \pm 1.58\%$ in M10 to $6.14 \pm 1.59\%$ in M0, while TN ranged from $0.31 \pm 0.10\%$ in M10 to $0.35 \pm 0.13\%$ in M0. At 20–30 cm, SOC and TN declined to $1.95 \pm 0.77\%$ and $0.17 \pm 0.05\%$, respectively.

SOC_{stock} was highest in M0 plots in the 0–10 cm layer ($40.48 \pm 8.07 \text{ Mg C} \cdot \text{ha}^{-1}$) and decreased with both depth and thinning intensity (Fig. 6B), reaching the lowest value in M10 plots at 20–30 cm (17.69

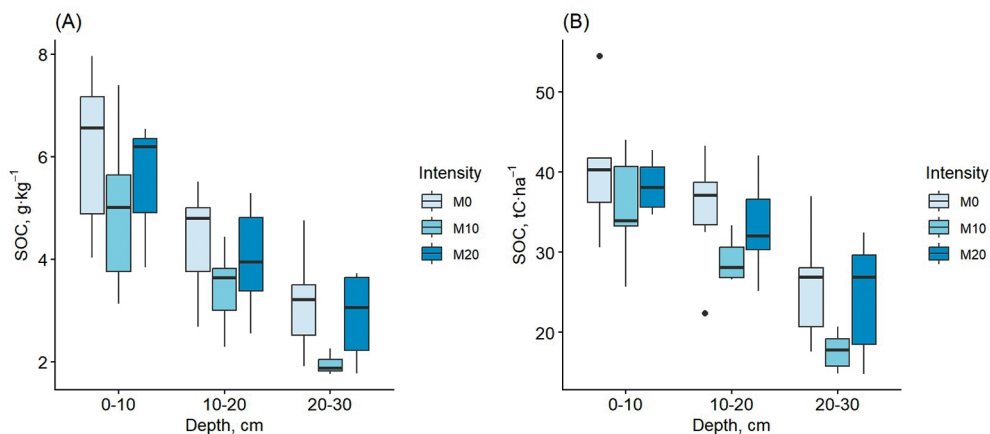


Fig. 6. Distribution of SOC across all studied depths and intensities: (A) SOC; (B) SOC_{stock}.

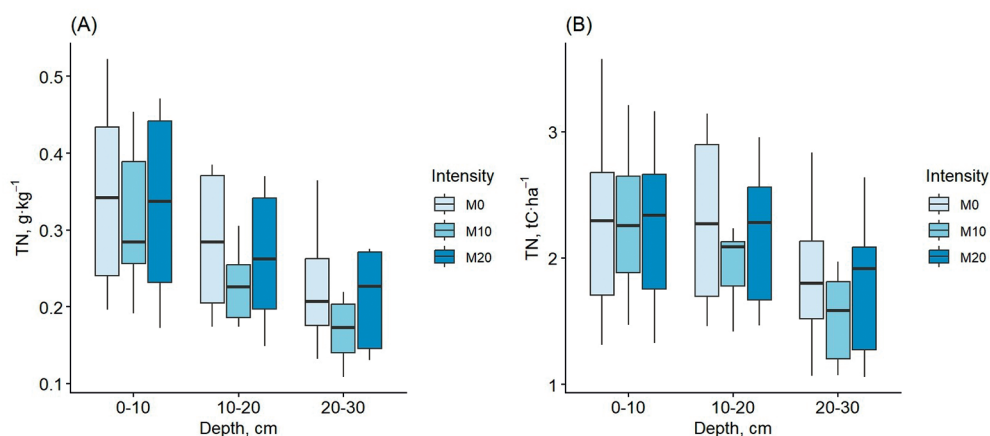


Fig. 7. Distribution of TN across all studied depths and intensities: (A) TN; (B) TN_{stock}.

$\pm 2.74 \text{ Mg C} \cdot \text{ha}^{-1}$).

TN_{stock} changes followed the trend observed in SOC_{stock} (Fig. 7B), declining with depth and showing slightly lower values in thinned plots.

The C:N ratio decreased from ~16–19 in topsoil to ~12–15 in deeper layers, with consistently higher values in M0 plots (Fig. 8).

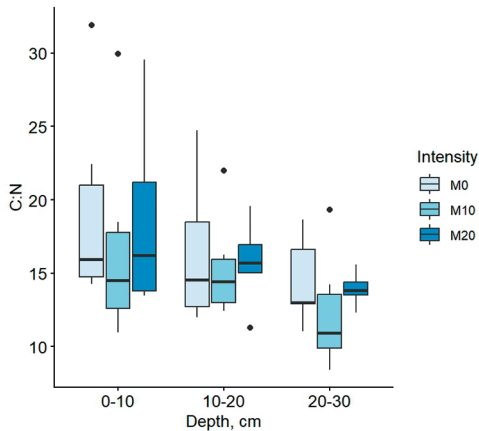


Fig. 8. Distribution of the C:N ratio across all studied depths and intensities.

Two-way ANOVA confirmed that soil depth represents a significant factor affecting most of the measured parameters, while thinning intensity had more limited but still detectable influence on selected chemical properties.

For SOC and SOC_{stock}, both soil depth

and thinning intensity had significant effects (Table 3). Both parameters vary significantly with depth with $F = 34.00$ and $p < 0.001$ for SOC, and $F = 32.17$ and $p < 0.001$ for SOC_{stock}. The thinning intensity's effect on SOC and SOC_{stock} is statistically significant – $F = 5.08$ and $p < 0.01$ for SOC, and $F = 5.82$ and $p < 0.01$ for SOC_{stock}.

Tukey's HSD test indicated that SOC decreased significantly from 0–10 cm to deeper layers, with all depth categories differing from each other (Table 3). Regarding thinning, M10 plots had significantly lower SOC and SOC_{stock} than M0 plots, while M20 showed intermediate values that did not differ significantly from either M0 or M10.

For TN and TN_{stock}, soil depth had a significant effect, with the highest N concentrations observed in the topsoil. There is no significant difference in the means of TN and TN_{stock} between the studied thinning intensities within a single soil layer. According to the two-way ANOVA, thinning intensity did not have a significant influence on either TN or TN_{stock} (Table 3).

Overall, the analysis indicated that thinning intensity had a detectable effect primarily on SOC and SOC_{stock}, while its influence on TN was negligible compared to the dominant effect of soil depth.

Table 3. Two-way ANOVA results (F and p values) and Tukey HSD pairwise comparisons across soil depths and thinning intensities.

Parameter	ANOVA-Depth		ANOVA-Intensity		Tukey's test		
	p -value	F -value	p -value	F -value	M0	M10	M20
SOC	<0.01	34.00	<0.01	5.08	a	b	ab
TN	<0.01	9.40	0.29	1.37	a	a	a
C:N	0.02	4.54	0.49	0.73	a	a	a
SOC _{stock}	<0.01	32.17	<0.01	5.82	a	b	ab
TN _{stock}	0.02	4.14	0.50	0.70	a	a	a

Discussion

Our study in Norway spruce plantations of the Central Balkan Mountains revealed that soil depth was a primary driver of variation in physical and chemical soil properties, while thinning intensity had more limited and parameter-specific effects.

Soil properties in this study followed typical depth-related patterns for mountain Norway spruce plantations, with higher *W* and lower *BD* in surface layers and more compact, less moist soils at depth, regardless of thinning treatment. Slightly higher surface *W* in M10 may reflect localised organic matter accumulation, although part of the variation may also be related to short-term weather conditions at the time of sampling, while increased *BD* at depth likely results from natural compaction rather than thinning (Lal 2005, Vesterdal et al. 2013). *CF* and *pH* varied modestly, but differences were inconsistent and likely site-specific, consistent with reports that these attributes are primarily controlled by parent material and long-term pedogenesis (Donov 1973). The absence of statistically significant treatment effects suggests that, in the short term, thinning does not markedly alter these relatively stable soil parameters. Our observations support previous findings that canopy disturbance influences dynamic soil properties, such as $\text{SOC}_{\text{stock}}$ and TN_{stock} , to a greater extent than the stable physical attributes (Bai et al. 2017). The vertical stratification of *SOC*, *TN*, and *C:N* ratio – characterised by higher values in the topsoil and declining with depth – is consistent with patterns reported for temperate and montane forest ecosystems (Jandl et al. 2007). This decline is largely attributable to the decreasing organic matter inputs from litterfall, fine root turnover, and microbial activity with increasing soil depth (Vesterdal et

al. 2013).

Thinning influenced *SOC* and $\text{SOC}_{\text{stock}}$ in the 0–10 cm layer, with the 10–15 % thinning intensity (M10) showing lower values compared to unthinned controls (M0), while the 20–25 % thinning intensity (M20) showing intermediate results. This non-linear response suggests that thinning intensity can influence the balance between *SOC* losses and inputs, with potentially important implications for sustainable management of Norway spruce plantations in the Central Balkan Mountains.

A possible explanation could be connected with the mechanical differences between these intensity levels. Light thinning typically induces small canopy openings that increase soil temperature and aeration, enhancing microbial decomposition and accelerating organic matter mineralisation (Xu et al. 2022). However, the canopy disturbance may be insufficient to stimulate significant understorey growth or root turnover, resulting in lower organic matter inputs from litter and rhizodeposition (Hoover 2011). This imbalance can lead to net *SOC* losses, particularly in surface layers where microbial activity is highest (Vesterdal et al. 1995).

In contrast, moderate thinning creates larger canopy gaps, which can stimulate understorey vegetation, increase fine-root biomass, and promote higher litterfall rates (Livne-Luzon et al. 2025). Enhanced belowground carbon inputs, coupled with improved nutrient cycling, can compensate for the initial disturbance-related *SOC* losses and facilitate recovery over time (Gao et al. 2023). Additionally, reduced stand density may alleviate competition for soil resources, allowing residual trees to increase their root allocation and contributing further to soil organic matter accumulation (He et al. 2025). Retention of slash and forest floor material

can enhance SOC stabilisation during the post-thinning recovery phase (Qu et al. 2025).

It is important to recognize that thinning effects on SOC are strongly influenced by site conditions, soil depth, and time since intervention (Xu et al. 2024). Forest floor carbon is generally more sensitive to thinning than mineral soil carbon, and deeper soil layers may respond differently from the topsoil (Gross et al. 2018). Long-term monitoring is thus essential to capture the trajectory of SOC dynamics beyond the short-to-medium term.

In contrast, TN and TN_{stock} were largely unaffected by thinning intensity, suggesting that nitrogen cycling processes in these Norway spruce plantations are more stable. As it was already mentioned, thinning alters microclimate and can stimulate mineralisation and nitrification (affecting N forms), but retention pathways (e.g., microbial immobilisation, canopy/forest-floor feedbacks, and residue retention) tend to buffer net TN_{stock} at the scale of 0–30 cm over short–medium terms, unless disturbance is severe or residues are removed (Formánek and Vránová 2003, Bai et al. 2017). This buffering could be due to stable inputs from symbiotic mycorrhiza and slow mineralisation rates characteristic of acid, organic-rich mountain soils (Ekblad et al. 2013, Kirova 2018). The finding that TN and TN_{stock} were largely unaffected by thinning intensity is consistent with broader evidence: light–moderate thinning typically shifts N cycling processes (availability, transformations) but does not necessarily translate into rapid changes in total soil N pools, which are slower to respond and strongly conditioned by site factors and time since treatment (Xu et al. 2024).

Our findings are important for sustainable forest management in Bulgaria, where Norway spruce plantations –

though not native to all elevations – play a critical role in timber production, erosion prevention, and water regulation (Alexandrov and Dimitrov 2005, Panayotov et al. 2011). The minimal effects of thinning on most soil properties suggest that carefully planned low-to-moderate thinning can be compatible with soil conservation goals, provided that surface organic matter is preserved and post-thinning regeneration is promoted.

However, the observed SOC reductions under low-intensity thinning highlight the need for long-term monitoring to detect potential cumulative impacts. Climate change scenarios project increased drought frequency and temperature rise in the Balkan region (IPCC 2021), which could exacerbate SOC losses and alter TN dynamics. Future studies should integrate microbial community analyses, litter quality assessments, and fine root productivity to link observed changes in soil parameters to belowground biological processes (Prescott 2010, Schmidt et al. 2011).

Overall, this research emphasizes that depth-stratified sampling and treatment-specific statistical analysis can detect subtle but ecologically meaningful changes. Such approaches should be standard practice when evaluating forest management impacts on soil, especially in ecologically sensitive montane regions. In the context of Norway spruce plantations in the Central Balkan Mountains, these results suggest that moderate thinning (≈ 20 – 25 %) could represent a more sustainable approach for balancing timber production with soil conservation. By optimizing canopy openings to stimulate productive understories and belowground inputs, managers can mitigate SOC losses while maintaining forest productivity and resilience.

Conclusions

Forest management practices, particularly thinning, play a critical role in regulating soil carbon and nitrogen storage in Norway spruce plantations. The results of this study indicate that light thinning (M10) can lead to greater reductions in SOC content and stock, compared to moderate-intensity thinning (M20). The TN content and stocks were largely unaffected. These findings indicate that the relationship between thinning intensity and SOC and TN dynamics is not linear, highlighting the importance of adjusting management practices to site-specific conditions.

Careful consideration of thinning intensity is essential for maintaining soil health, fertility, and long-term productivity. Sustainable forest management in Norway spruce plantations requires balancing timber production objectives with the preservation of soil functions that support ecosystem stability, water regulation, and climate change mitigation.

Long-term monitoring is needed to better understand the cumulative effects of thinning on soil C and N dynamics over time. Additionally, investigating the underlying mechanisms behind the observed differences between thinning intensities – such as changes in microbial activity, litter decomposition rates, and root system dynamics – would provide valuable insights for refining silvicultural guidelines.

Overall, this analysis offers a more detailed understanding of how thinning intensity influences soil properties, reinforcing the need to integrate soil conservation objectives into forest management planning.

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