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Conversion of unmanaged boreal forest to even-aged management has a stronger effect on carbon stocks in the organic layer than the mineral soil

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ABSTRACT

Forest management can impact forest carbon stocks, above- and belowground. The even-aged management practice removes the aboveground carbon stock at harvest, which is thereafter restored as the new forest stand establishes. The effects of even-aged management on forest soils in earlier unmanaged stands are however less well understood, and it has been suggested that large carbon losses may occur. In this study we use a unique paired sampling approach of stands in north inland Sweden. Half of the sampled stands had been clear cut within the previous 54 years, and half were left unmanaged. Our results show that clear-cut harvesting and subsequent transformation of unmanaged stands into even-aged management resulted in lower aboveground carbon stock in the living trees. For the soil there was weak evidence for a loss of c. 15 % of the carbon stock in the organic layer. No evidence of an effect in the more stabilized soil organic carbon within the mineral soil layers was found.

1. Introduction

Boreal forests store about one third of the global forest C pool, and the majority of the C stock can be found in the soil (Gundale et al., 2024; Pan et al., 2011; Skogsdata, 2017). Impacts of forest management on soil C stocks thus has a huge potential to impact the net forest C balance, and boreal areas remain relatively understudied compared to other regions (James and Harrison, 2016; Luyssaert et al., 2007; Xu et al., 2014). This lack of data along with associated uncertainties has led to a controversial debate on how to best utilize (Bellassen and Luyssaert, 2014), and/or incorporate different types of boreal forests as components in policy frameworks to mitigate climate change (Lundmark et al., 2014; UNFCCC, 2016). Young, fast-growing managed stands are known to achieve higher rates of C uptake compared to older unmanaged stands, while unmanaged stands instead have been shown to store greater amounts of C (Gleixner et al., 2009; Gundale et al., 2024; Nord-Larsen et al., 2019), both in standing biomass and soil (Luyssaert et al., 2008; Paw U et al., 2004; Zhou et al., 2006). The suggestion that old unmanaged stands could be preserved to maintain large C stocks is therefore well represented among scientists (Knohl et al., 2003; Luyssaert et al., 2008; Naudts et al., 2016; Zhou et al., 2006). Long-term modelling studies support this conclusion, and for soils show a persistent decline in SOC levels after several rotation periods in managed forests (Dean et al., 2017; Harmon et al., 1990). Other studies suggest that long-term forest management improves the C balance in boreal forest due to avoided emissions and that C sinks can recover within a couple of decades (Peichl et al., 2023; Pukkala, 2017). The lack of consensus is in part because multiple factors cause substantial spatial variation in SOC (e.g., hydrology, soil clay content, etc.), making accurate estimates challenging (Gundale et al., 2024; Hoffmann et al., 2014). Further, a variety of sampling techniques are used to estimate SOC, which makes direct comparisons between studies difficult (Vanguelova et al., 2016). Relatively few studies have also simultaneously quantified soil C stock in unmanaged vs. managed stands.

When measuring SOC levels in response to harvesting, the biggest effects are often found in the organic layer, and seems to scale with intensifying harvest practices (Achat et al., 2015). The mineral soil is usually affected to a lesser degree, and while most studies on average show decreasing SOC trends in response to harvesting (Gundale et al., 2024; Nave et al., 2010), only a few studies have shown a significant loss of SOC in mineral soil layers (James and Harrison, 2016). Mechanical site preparation is also often used in conjunction with harvesting,

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especially even-aged management, to promote the establishment of the new stand. The degree to which this practice affects soil C stocks is unclear, with some studies showing that the effects are not permanent (Mjöfors et al., 2017). The C present in the mineral soil is also often regarded as most stable, potentially over millennial timescales, due to organic matter binding to mineral surfaces, fungal necromass or stabilization within soil aggregates (Adamczyk, 2021; Wiesmeier et al., 2019; Yang et al., 2020), and it is unclear to what degree even-aged management in older unmanaged forests destabilizes this pool.

In this study we utilized a unique experimental setup in the north-west of Sweden to compare the soil C stock in older unmanaged forest stands (hereafter referred to as "unmanaged stands"), paired with younger, even-aged managed forest stands (hereafter referred to as "managed stands"), allowing effective control for between-site heterogeneity. The study region is located downslope from the Swedish mountain range, and incorporates relatively large areas of unmanaged forest that have never been subjected to even-aged management (Shorohova et al., 2011). We compared C stock in soil and forest biomass from 23 stands, each with a paired unmanaged and managed stand (spanning stand ages of 106–223 years, and 14–54 years, respectively). We hypothesized that converting unmanaged forest into even-aged forests would cause a reduction of above-ground biomass and soil C stocks, in both the organic layer and the mineral soil (down to 50 cm depth). The data from this analysis could be of great utility for increasing our understanding of the boreal ecosystem C budgets, and for quantifying the eventual changes in the forest C balance when even-aged management practices are applied to previously unmanaged stands. The results could also be used to improve high resolution models relevant to silvicultural management in Sweden and other remaining areas across the boreal biome, where decisions about eventual management and/or conservation in mature forests may have important impacts on climate change mitigation.

2. Materials and methods

2.1. Study area and experimental design

The study includes 23 sites (Fig. 1) in north-west of Sweden (Västerbotten and Norrbotten County), lat. 65–66º, long. 16–20º, 200–630 m above sea level. The region is located just downslope from the Swedish mountain range and has large areas of intact unmanaged forests that have never been utilized for even-aged management. However, most of the forested area has historically been selectively cut with varying proportions of large diameter trees removed and/or been subject to stand replacing fires. Even-aged forestry in these areas became widespread after 1948, when regulations on land use (Lappmarkslagen) in the area were lifted, and there are still large continuous areas of old forests left. At each site we identified a paired managed (even-aged management initiated by clear-cutting) and unmanaged stand. Each managed stand was assumed to have been equivalent to the adjacent unmanaged stand prior to clear-cutting. The managed stands had a mean site index of 14.4 (H_{100}, m) and tree ages ranged between 14 and 54 years old (average age 27 years). The unmanaged stands showed a mean site index of 13.9 (H_{100}, m) and tree ages ranged between 106 and 223 years (average age 163 years). While it is somewhat contradictory to assign an age to an unmanaged forest containing a multilayered stand structure and an uneven age distribution, we did so using a well-accepted weighted arithmetic mean where the older trees with larger diameters contribute more to the assigned mean age of the plot (Nilsson et al., 2022). This was done to provide the reader with a more complete picture of the differences in tree ages between unmanaged and managed stands, (for information on all stands see Supplementary table 1). Nine of the managed stands were dominated by Norway spruce (*Picea abies* (L.) Karst and 14 by Scots pine (*Pinus sylvestris* L.), while 14 of the unmanaged stands were dominated by Norway spruce, and 9 by Scots pine, (data obtained by the forest company Sveaskog, personal correspondence). All selected sites were dry or mesic site types lying on moraine or river sediments, with soil textures ranging from silty to sandy. All measurements were carried out in squared-shaped plots of approximately 0.1 ha where the plot centers are situated at least 20 m from the boundary of the adjacent unmanaged or managed stand, and at least 50 m from any other adjacent stand. Within these plots, forest inventory (living and dead biomass) was performed in four circular sub-plots with a 7-meter radius and sub-plot centers situated 20 m from each other (Fig. 2) and soil sampling, including measurement of the ground vegetation and litter-layer were performed on points laid out in a grid pattern within each square-shaped plot.

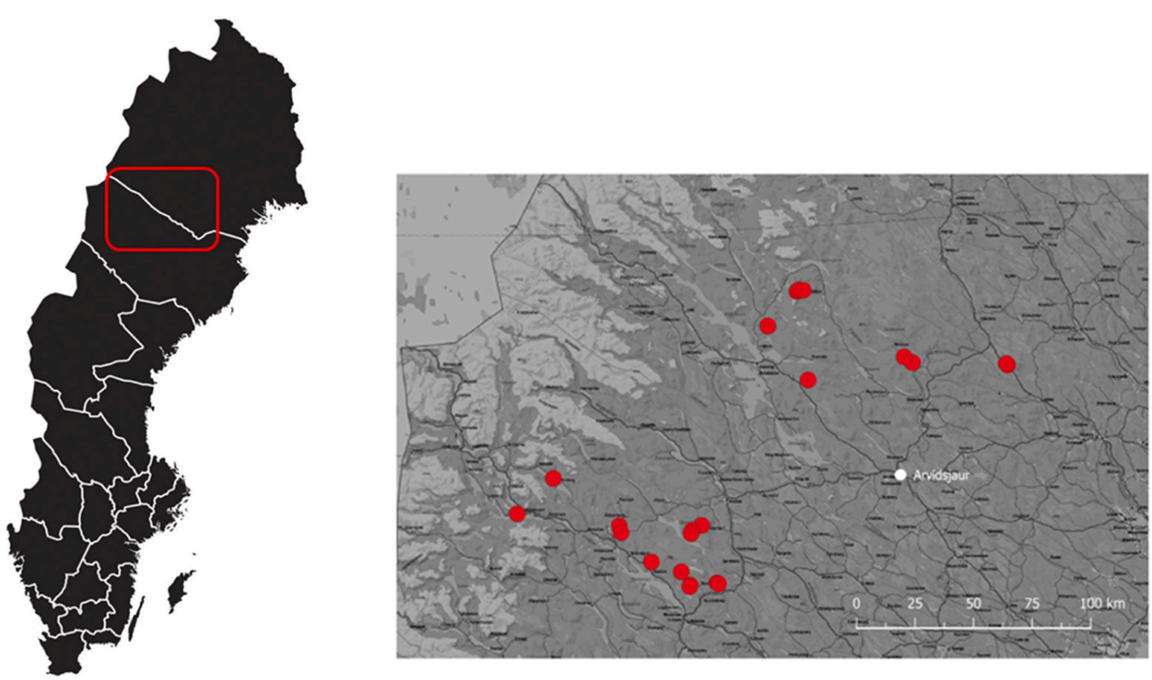

Fig. 1. The distribution of sites used in the study. Each site consisted of paired unmanaged and managed forest stand. The white dot marks the town of Arvidsjaur.

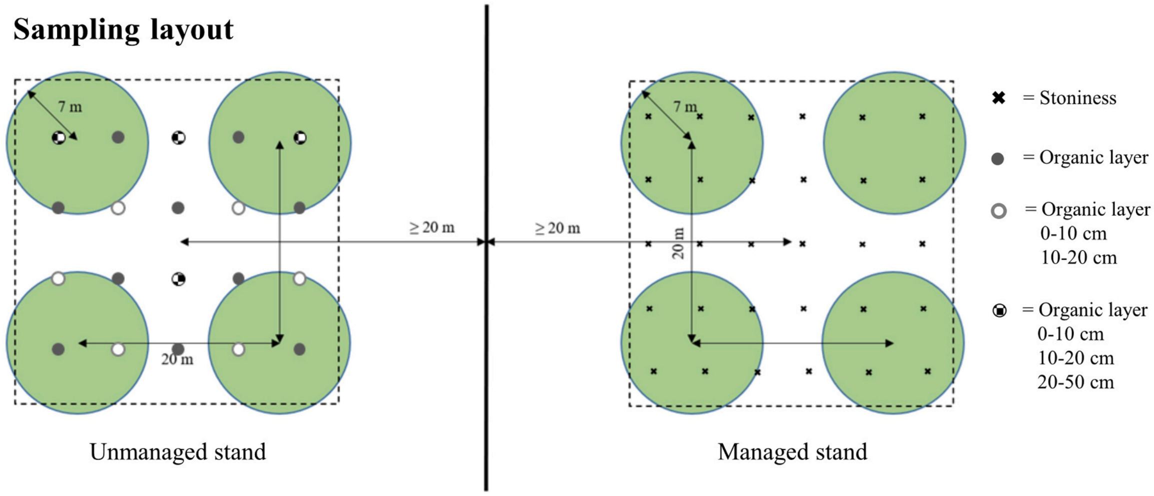

Fig. 2. A depiction of sampling at each site utilizing a paring consisting of an unmanaged stand with an adjacent managed stand. All sampling was performed within 0.1 ha plots. Living trees and dead wood were sampled within the green circular sub-plots. Stoniness, soil samples, ground vegetation and litter layer, were collected on points located on a grid within the plots marked with dashed lines. Note: Both stoniness and soil sampling were performed in all plots, the figure only depicts them separately for clarity.

2.2. Sampling and laboratory analyses

2.2.1. Living and dead tree biomass

Field measurements to assess C stocks in living and dead tree biomass were carried out between 2017 and 2019 and were estimated from four circular sample sub-plots (7-meter radius), with at least 20 m between sub-plot centers (Fig. 2). Trees with diameters > 100 mm within the 7-meter sample sub-plots and trees with a diameter of 40–99 mm within 3.5 m from the sub-plot centers were included in the study. Sample trees were used to measure both height and age (stem cores at 1.3 m). In the managed stands only the main tree layer was included when establishing stand age. Dead wood with a diameter over 100 mm and height or length of more than 1.3 m that was classified as “hard dead wood” (more than 90 % of the stem consisting of hard non-decomposed wood) according to Skogsdata (2017), was registered in each sub-plot, whereas other decay stages of dead wood were not included in our sampling. Carbon in living trees for all tree species, (*Pinus sylvestris*, *Picea abies*, *Betula spp*., *Salix caprea* and *Populus tremula*) were then calculated using Marklunds biomass functions (Marklund, 1988). For calculations of *S. caprea* and *P. tremula* biomass, the functions for birch were used, but adjusted according to the density of the wood (Heureka SLU, 2016). Biomass of coarse roots down to 2 mm were calculated for *P. sylvestris* and *P. abies* only using allometric functions by Marklund, (1988), and adjusted by 6 % based on Petersson and Ståhl, (2006). Other tree species were assumed to be minor contributors to these pools due to their low abundance in all plots. Carbon contents were assumed to be 50 % of dry mass in all living biomass, and measured values were upscaled to Mg C ha^{-1}. Biomass of dead wood was calculated based on volume estimates according to Näslund (1941) and density of the dead wood (spruce 0.29, pine 0.31 and broadleaves 0.37 g cm^{-3}). The amount of C in dead wood was assumed to be 50 % (Russell et al., 2015) and measured values were upscaled to Mg C ha^{-1}. Each of these biomass pools measured within the plots were then added together, resulting in total Mg C ha^{-1}.

2.2.2. Bulk density and stoniness

Mineral soil bulk density (BD) was sampled in a sub-set of plots, including 10 in unmanaged stands and 9 in managed stands, at three depth intervals, 0–10 cm, 10–20 cm, and 20–50 cm, with five sub-samples per depth and plot. Bulk density estimations were based on the excavation method (Gatea et al., 2018) where a ca. 15 cm diameter hemispherical pit was excavated, a soft mesh cloth was inserted in the pit and then filled with 2 mm plastic granules. The volume of the granules was then determined, and the excavated soil was sieved (2 mm). If smaller stones or larger fragments with a combined volume over 20 cm^3 (approximately 5 % of the pit volume) were found, the sampling procedure was stopped, and a new excavation pit was dug in close proximity. Collected samples were transported back to the lab, dried at 70º C for 48 hours, sieved again (2 mm) and weighed. The mass of the processed samples was then divided by the volume of plastic granules used to fill the pit, yielding bulk density estimates (g cm^{-3}). Bulk density in the organic layer (humus) was estimated with the aid of bulk density functions, (equation 18, Nilsson and Lundin, 2006)

Stone and boulder content at all sites for each pair of unmanaged/managed stands was estimated using the rod penetration method, where an iron rod with a diameter of 10 mm was driven through the soil until it reached a stone or boulder (Viro, 1952). This was done at 30 points in each sampling plot. The mean penetration depth was calculated into volumetric content of stones and boulders in percent using Viro (1952) modified by Stendahl et al., (2009), regression equation SB = 82.5 – 2.75 *Si, Si being mean penetration depth of the 30 points. Based on the assumption that it should be no ecological reason for the stoniness value to differ within a pair of unmanaged and managed plots, we used an average stoniness value per paired site ((SB on unmanaged plot + SB on managed plot)/2) for all calculations.

2.2.3. Ground vegetation and litter layer, organic and mineral soil C content

The C content of the organic layer, mineral soil, ground vegetation and litter layer were sampled during autumn 2017 and summer 2019. The organic layer (including F and H sub-layers) was sampled with methodology similar to Maaroufi et al., (2019) in a grid-pattern in each plot using a 100 mm cylinder. Material was collected from 20 points and the thickness of the organic layer was recorded. The organic layer samples were pooled and mixed thoroughly to obtain one composite sample per plot. In 2019, at nine pairs of unmanaged and managed sample plots, the ground vegetation and litter layer on top of the samples from the organic horizon was removed and transported back to the lab for determination of C content. The ground vegetation and litter were not analyzed separately, due to difficulty in separating them. Mineral soil was collected between 2017 and 2019 from soil pits with individual non-volumetric samples from multiple depth increments (0–10, 10–20, and 20–50 cm) using similar methodology as Blaško et al., (2020) and Blasko et al., (2022). The two upper mineral soil layers (0–10 and 10–20 cm) were sampled from 10 sample points in a grid across the plot, whereas the 20–50 layer was sampled from 4 points (Fig. 2), when possible (9 out of 23 pair of plots). All subsamples from each layer were pooled plot-wise, giving one composite sample for each soil layer and plot. Ground vegetation and litter, organic and mineral soil samples were transported to the lab and dried at 70º C for 48–60 hours. The organic soil was sieved (2 mm), omitting mostly roots and some coarse fragments. Organic material removed by the sieve was weighed to account for this fraction in later analyses given that the bulk density function was based on soil specifically, rather than roots. Mineral soil was sieved at (2 mm). Samples from the organic layer were then ground in a ball mill for 60 seconds while the mineral soil samples were placed on a roller mill for 24 hours. Carbon content (%) of each soil sample was then determined using an elemental analyzer (EA-IRMS; Flash EA 2000; Thermo Fisher Scientific). The C stock (Mg ha^{-1}) in each layer of organic and mineral soil was calculated using C content (%) from the EA-IRMS analysis, bulk density of the soil, and depth of each soil layer, and then adjusted for stoniness (mineral soil) or organic coarse fragments/roots (organic layer). Carbon content in ground vegetation and litter dry mass was assumed to be 50 % and measured values were upscaled to Mg C ha^{-1}.

2.2.4. Calculations and statistical analyses

We first used a mixed effects ANOVA with random effect of site to test if soil depth, forest age, or tree species had any effect on mineral soil BD. Soil depth was the only significant factor affecting BD ($p = 0.012$), Therefore, for upscaling soil C stocks (described above), we applied average BD values separately to each soil layer (0.613 g/cm^3 used for 0–10 cm, 0.639 g/cm^3 for 10–20 cm and 0.787 g/cm^3 for 20–50 cm.).

To compare SOC stocks in unmanaged and managed stands, we used mixed effects ANOVAs, with forest type (unmanaged or managed) serving as a fixed factor, and site serving as a random factor. The random factor was added to control for site-to-site variation in properties such as soil texture, moisture, topography etc., and since our response variables differed in the number of sampled stands (e.g. ground vegetation + litter and 20–50 cm soil depth were only sampled at 9 out of 23 stands), we analyzed data for each ecosystem C compartment separately. All statistical analyses were performed using R studio (v. 3.5.1; Rstudio Team,2020) and normality of residuals within soil layers was confirmed through observation of residual plots.

For all statistical tests we used a significance terminology suggested in Muff et al., (2022), where different ranges of p-values are reported on a continuum from "little or no evidence" to "very strong evidence". A p-value of 0.0001 – 0.001 subsequently equals very strong evidence, a value of 0.001 – 0.01 equals strong evidence, 0.01 – 0.05 equals moderate evidence, 0.05 – 0.1 equals week evidence and a p-value of 0.1 – 1 is considered as no evidence.

3. Results

3.1. Total ecosystem C stock

The different number of samples between the ground vegetation (and litter) and 20–50 cm mineral soil depth compared to the rest of the dataset makes statistical comparisons on total mean ecosystem C difficult. However, comparisons referring only to the means show that total mean ecosystem C was 106.8 Mg C ha^{-1} in unmanaged forest stands, and 69.5 Mg C ha^{-1} in the managed stands. The biggest difference was found in the biomass of the living trees, equivalent to 45.4 and 13.4 Mg C ha^{-1} respectively. Comparing only mean SOC (organic layer and mineral soil) the difference was 47.6 Mg C ha^{-1} in unmanaged forests and 43.4 Mg C ha^{-1} in managed forests (Table 1).

3.2. Aboveground C stock

Statistical analysis of aboveground ecosystem compartment C pools shows that there was very strong evidence for a significant difference in C pools within the living trees (*p < 0.001)* and deadwood (*p < 0.001)* compartments between unmanaged and managed stands (Fig. 3).

Table 1
Mean ± SE C pools sampled in unmanaged and managed forest types. Results are based on averaging all values for each respective layer in both forest types.

	Mg C ha^{-1}		
Compartment	Unmanaged forest	Managed forest	p-value
Living trees	45.4 ± 3.4	13.4 ± 3.3	< 0.001 * **
Ground vegetation & litter	12.4 ± 0.7	12.4 ± 2.2	0.994
Dead wood	1.4 ± 0.3	0.3 ± 0.1	< 0.001 * **
Organic horizon	21.9 ± 2.1	18.7 ± 1.5	0.054 *
Mineral soil 0–10 cm	6.5 ± 0.7	6.2 ± 0.7	0.461
Mineral soil 10–20 cm	6.4 ± 0.6	5.9 ± 0.5	0.212
Mineral soil 20–50 cm	12.8 ± 2.8	12.6 ± 3.0	0.848
Total aboveground C	59.2	26.1	Unbalanced data
Total belowground C	47.6	43.4	Unbalanced data
Total ecosystem C	106.8	69.5	Unbalanced data

Note: All compartment values are based on samples from 23 paired stands except ground vegetation & litter and mineral soil 20–50 cm, which are based on samples from 9 paired stands.

3.3. Belowground C stock

Statistical analysis of the soil organic C (SOC) ecosystem compartments shows that there was weak evidence *($p = 0.054$)* for a significant decrease of C within the organic layer when comparing unmanaged and managed stands. However, no evidence was found for differences in other measured belowground ecosystem C compartments (Fig. 4).

4. Discussion

The purpose of this study was to fill an existing knowledge gap by providing robust data on C stocks in unmanaged and managed boreal forest stands. Such data will help provide solutions to model errors and thereby get closer to a more data driven approach in discussions about boreal forest management and its effects on SOC. Any life-cycle assessment of the goods produced, and related discussions about substitution effects are however beyond the scope of this study. Our results show that the average aboveground C stock was 33.1 Mg C ha^{-1} lower in managed vs. unmanaged stands. The substantial difference in aboveground C stock is expected and in line with our hypothesis but none-the-less represents a major shift in ecosystem C stocks, as the transition from unmanaged to even-aged management transforms a large forest C stock acting as a relatively slow sink (C uptake ha^{-1} y^{-1}), into a smaller forest C stock, that acts as a relatively large sink (Coursolle et al., 2012; Gundale et al., 2024; Peichl et al., 2023). We also hypothesized that converting unmanaged forest into even-aged forests would cause a reduction in soil C stocks, in both the organic layer and the mineral soil (down to 50 cm depth). This prediction was based on expectations that clear-cutting may increase decomposition rates via altered soil surface temperature or by reduced carbon inputs from above- and belowground litter inputs (Gundale et al., 2024). In line with this assumption, we found weak evidence of a 3.2 Mg C ha^{-1} reduction in the organic horizon at an average of 27 years after clear-cutting. However, in contrast to our hypothesis, we found no evidence that management caused a decrease in mineral soil C. Adding together C in all mineral soil layers (0–10, 10–20 and 20–50 cm) resulted in a non-significant loss of 1.0 Mg C ha^{-1} C in managed versus unmanaged forest stands. Hence, only ca. 3 % of the total C stock difference between managed and unmanaged forest stands was explained by the mineral soil compartment. This result corresponds

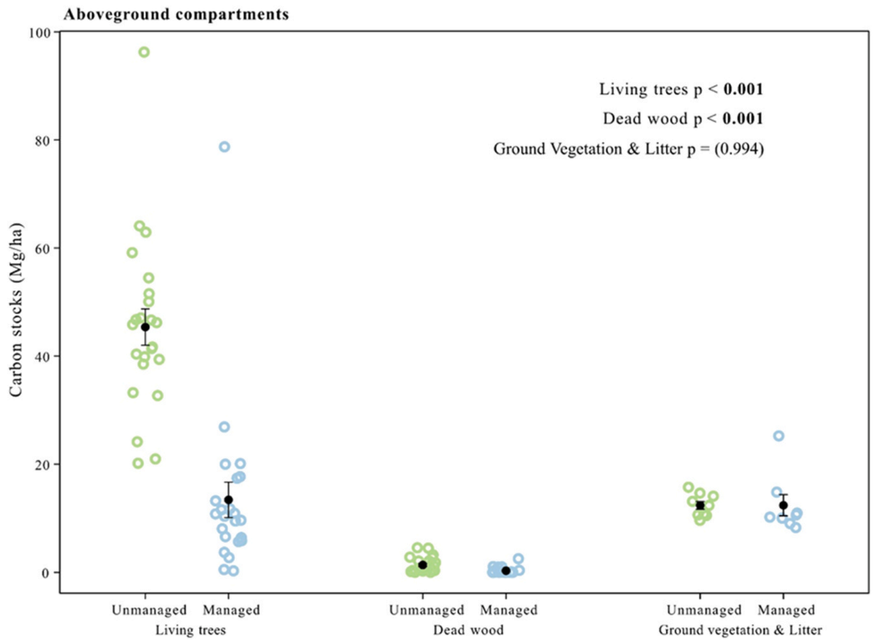

Fig. 3. Visualization of aboveground ecosystem compartments based on pooled measurements from all sites included in the study. Mean ± SE is indicated by black points and arrows while the colored circles showing the full range the measurements. P-values in bold indicating very strong evidence based on comparisons between the two forest types for each measured compartment.

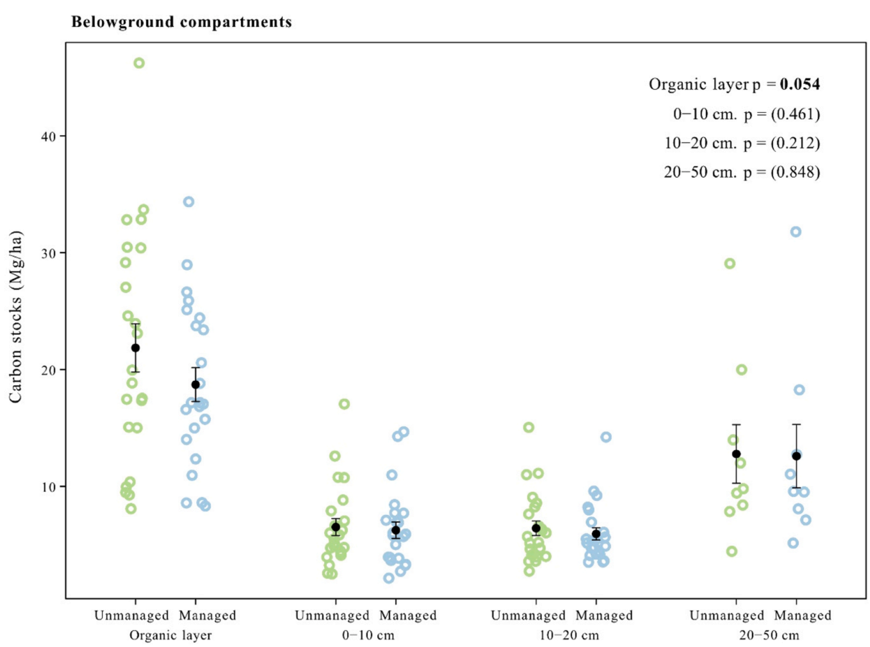

Fig. 4. Visualization of SOC ecosystem compartments based on pooled measurements from all sites included in the study. Mean ± SE is indicated by black points and arrows while the colored circles showing the full range the measurements. P-values in bold indicating weak evidence based on comparisons between the two forest types for each measured compartment.

well to other studies where mineral soil C is often less affected by harvest than the organic horizon or "humus-layer" (Achat et al., 2015; James and Harrison, 2016; Nave et al., 2010). Frequent explanations given for this greater stability of C in mineral soil are stabilizing interactions between organic matter and mineral particles within soil aggregates (Mikutta et al., 2006; Torn et al., 1997), or incorporation of C in root-derived compounds and fungal necromass (Adamczyk, 2021; Adamczyk et al., 2019). While it is not possible to estimate the recovery time of the organic layer with the data provided by our measurements, other meta-analyses suggest the time needed is > 100 years (Gundale et al., 2024; Palviainen et al., 2020). Both SOC stocks and their rate of change are however known to decrease with latitude (Olsson et al., 2009). Small changes over time might therefore be difficult to observe in high latitudes compared to the southern boreal region (Ågren et al., 2007), thus care should be taken when scaling the results of this study to other parts of the boreal region. Our study also does not allow for a complete analysis of soil C differences across a full stand rotation cycle, and it is feasible the C inputs during later stages of stand development will compensate from the losses we show occur at a relatively young stand age.

While the C stock in the living trees expectedly decreased due to clear cut-harvesting, the C stock in the ground vegetation and litter did not show any evidence of a decrease. While it is possible that the harvest of the unmanaged stands did effect this ecosystem compartment, other studies show a rapid establishment of a productive understory layer only years after harvest (Peichl et al., 2023). No effect might therefore still be visible at the time of our measurements.

The reduction in dead wood C stock between unmanaged and managed stands was 1.1 Mg C ha^{-1}. From a pure CO_2 standpoint, even though statistically significant and amounting to a loss of 80 %, this pool is of minor importance compared to other pools measured in our study. The substrate however serves as the host to a substantial number of saproxylic beetle and fungal species, including many red-listed species (Birkemoe et al., 2018; Gao et al., 2015). Therefore, while the decrease in dead wood does not contribute much to the total C balance of the studied forests, it could still have substantial negative impacts on biodiversity as it represents a major habitat loss. Assessing the climate benefits of forest management in potentially dead wood rich stands, such as the unmanaged stands in our study, thus needs to take this into account. Furthermore, the dead wood inventoried in our study only includes the most recent decay class, "hard dead wood" (more than 90 % of the stem consisting of undecomposed wood) with a diameter over 100 mm and height or length of more than 1.3 m. While legislation, policy and to some extent its low commercial value normally exclude dead wood in Swedish forests from harvest (Nilsson et al., 2020), some loss of the substrate due to forest management still occurs (e.g., exposed logs in advanced stages of decay outside retention groups are easily destroyed by machines etc., Siitonen, 2001). The inputs of new dead wood is also greatly reduced in young stands (Nilsson et al., 2020). For this reason, "hard dead wood", which represents the most recent dead wood input, would be most likely to differ between unmanaged and managed stands. However, we note that measurement of all decomposition stages may have revealed differences in other decay classes as well (Skogsdata, 2017). Although, divergence in dead wood mass for the more advanced decay stages would likely take more time to develop in the managed stands than we considered in our study (average stand age 27 years), given that it has been estimated that total dead wood decomposition has been estimated to take 200 years or longer (Hofgaard, 1993).

Our study provides a snapshot picture of the ecosystem C stocks at the time of the measurements; and further, it utilized a paired comparison and sampling approach that is not well represented in the literature, which helped to control for landscape heterogeneity that is often problematic when making forest C stock comparisons (Ortiz et al., 2013; Vanguelova et al., 2016). While this study was focused only on the forest C balance, other types of data are also relevant for understanding the climate impacts of forests. For example, boreal forests can serve as sources or sinks for other greenhouse gasses (N_2O and methane; Vestin et al., 2020). Further, boreal forests are known to impact the Earth's energy balance via their generally low surface albedo (Betts, 2000), which management may also affect. Future measurements of these other climate drivers, as well as life cycle accounting of harvested products, or consideration of the fact that these areas are often subject to other economic interests such as reindeer herding and or recreation (Margaryan and Fredman, 2017; Zhou and Gong, 2005), needs to be taken into account to provide a full picture regarding the climate and societal impacts of the forest types compared in our study.

5. Conclusion

This study presented data on how forestry can affect forest C balances from a unique experimental design where unmanaged stands could be compared to stands managed with even-aged management, established by clear-cut harvesting 14–54 years before present. From a C balance perspective the transformation of previously unmanaged stands into even-aged managed stands brought about an aboveground C stock loss of 33.1 Mg C ha^{-1}. We also found weak evidence of a decrease in C stocks in the organic layer of 15 % (3.2 Mg C ha^{-1}), but no evidence of a decrease in the more stabilized SOC present in the mineral soil was found. Our result thus supports previous research demonstrating that clear-cut harvesting can decrease soil C stocks in the organic horizon. Although the C stock difference between unmanaged stands and stands turned into even-aged management may appear proportionally minor as it decreases over time as the regenerated stands mature, forestry decisions must take into consideration that the previously unmanaged stands may contain many other values usually not present in managed stands, such as the potential for biodiversity connected to the larger volume and structural diversity of dead wood. Data on the response of the forest C balance to forestry will thus help inform discussions that seek to balance the broad array of societal values and ecosystem services forests in these remote northern regions provide.

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CRediT authorship contribution statement

Hyungwoo Lim: Writing – review & editing, Methodology, Conceptualization. **Michael J Gundale:** Writing – review & editing, Supervision, Methodology, Data curation. **Annika Nordin:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Data curation, Conceptualization. **Jenny Dahl:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marcus Larsson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tomas Lundmark:** Writing – review & editing, Resources, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

The funders had no role in the design of the study; the collection, analysis, or interpretation of data; writing of the manuscript; or in the decision to publish the results. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: A.N. reports a relationship with Stora Enso AB that includes employment. A.N. reports a previous relationship (2016–2020) with Sveaskog AB that included: Board membership. M.L reports a relationship with Stora Enso that includes Funding. J.D., M.J. G. H.L. and T.L. declares no conflicts of interest and has no affiliation with any commercial entities.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122458.

Data Availability

Data will be made available on request.

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