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Decadal decline in forest floor soil organic carbon after clear-cutting in Nordic and Canadian forests

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A R T I C L E I N F O

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A B S T R A C T

Nordic and Canadian forests store substantial amounts of carbon (C) and are largely managed in a silvicultural system with clear-cut harvest. Previous meta-analyses of harvesting effects on soil C have shown short- to long-term declines after harvest, but effects of clear-cutting on boreal and northern temperate forest soil C stocks remain unresolved. We harmonized National Forest Soil Inventory (NFSI) data from Sweden, Denmark, Finland, Norway and Canada to examine soil C stocks up to 53 years following clear-cut harvest using a space-for-time approach. We analyzed forest floor and mineral soil C stocks in coniferous and deciduous/mixed forests. Coniferous forest floor C stocks decreased for ~30 years after clear-cutting: when at its lowest stock level, *Picea* and *Pinus* forest floor C stocks had decreased by 23 % and 14 % relative to initial stock levels, respectively. *Picea* forest floor C stocks then remained close to its lowest levels until 53 years after clear-cutting, while for *Pinus*-dominated forests they increased again and recovered to the pre-harvest level 48 years after clear-cutting. No C stock changes were detected in the 0–10 cm or 10–20 cm mineral soil layers, while a small increase in 55–65 cm mineral soil was detected in Podzol soils. Data was too limited to detect statistical signals of clear-cutting for deciduous/mixed forests. Our results shows that clear-cut harvest has substantial and long-lasting effects on northern temperate and boreal forest soil C storage, and that combining data from several NFSIs can help elucidate forest management effects on soil C storage.

1. Introduction

Forests store ~46 % of total global terrestrial carbon (C) (Bonan, 2008), but it is asymmetrically distributed across biomes with 54 %, 30 % and 16 % residing in tropical, boreal, and temperate forests, respectively (Pan et al., 2024). While the largest part of total ecosystem C in tropical forests is stored in biomass, temperate and boreal forests, which are the main drivers of the global terrestrial C sink (Pan et al., 2024; Yang et al., 2023), store ~50–90 % of total ecosystem C in soils (Bradshaw and Warkentin, 2015; Pan et al., 2024; Scharlemann et al., 2014). In addition to the large proportion of ecosystem C stored in temperate and boreal forest soils, estimates suggest that these soils combined represented a sink of 11.5 Pg C between 1990 and 2007 (Scharlemann et al., 2014). In other words, forest soils are a key component of the global C cycle (Lal et al., 2021; Todd-Brown et al., 2013), and the future of the temperate and boreal forest soil C balance may have substantial impacts on global climate. Thus, accounting for soil C in these biomes is fundamental when designing management plans and policies targeting climate change mitigation.

The majority of the world's temperate and boreal forests are managed but differences are considerable in terms of both management intensity and the proportion of forest area under management (Gauthier et al., 2015; UN-ECE/FAO, 2000). While ~66 % of boreal forests are managed, management regimes in Russia and Canada tend to be of lower intensity compared to management in the Nordic region (Ceccherini et al., 2020; Gauthier et al., 2015; Högberg et al., 2021).

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Table 1
National Forest Soil Inventory characteristics (1988–2020), showing the variability in sampling schemes among the five National Forest Soil Inventory datasets and relation to the National Forest Inventories. The soil layers used in analyses were: (L)FH[a], 0–10 cm, 10–20 cm, and 55–65 cm mineral soil. Layers in parantheses were measured but not used in this study. Details on harmonization are given in supplementary materials. Forest floor (FF): L = litter, F = fibric, H = humic, MIN = mineral soil, PTF = pedotransfer function, BD = bulk density.

Country	Sweden	Norway	Denmark	Finland	Canada
Sampling years	1993–2020	1988–1992	2009, 2019	2006–2007	2000–2018
Vertical resolution (cm)[b,c]	FH, 0–10, 10–20, (E and B-horizon, 45–55 cm), 55–65 cm	Diagnostic horizons including LFH	LFH, 0–10, 10–25, (25–50), 50–75, (75–100)	FH, 0–10, 10–20, (20–40), 40–80	LFH, 0–15, 15–35, (35–55)
Sampling methodology	1–9 auger samples (FH) and pits (MIN, >0.75 liter soil per layer); pooled by depth in field	5–10 auger samples and soil pit (LFH and MIN); pooled by horizon in field	Ten 25 × 25 cm frames (LFH) and 10 continuous auger cores (MIN); pooled by depth in field	10 auger samples and 25 × 25 cm frame (LFH) and 3–5 auger cores (MIN); pooled by depth in field	20 × 20 cm frame (LFH) and 11 pits (MIN, 1–1.5 liter soil per layer); pooled by depth in data processing
Horizontal resolution and relation to NFI plot	Inside NFI circular plot of 10 m radius	Inside NFI circular plot of 8.9 m radius	Inside NFI circular plot of 15 m radius	Inside NFI circular plot of 11.3 m radius	Outside NFI circular plot of 11.3 m radius, < 25 m from NFI circle center
National representation	5 × 5 km (south) – 15 × 15 km (north), systematic subsample of NFI plots	9 × 9 km, systematic subsample of NFI plots	2 × 2 km, random subsample of NFI plots	16 × 16 km (south) – 32 × 32 km (north), systematic subsample of NFI plots	20 × 20 km, random subsample of NFI plots
Bulk density (BD)	FF: measured; MIN: PTF, model 31 of Nilsson and Lundin (2006)	FF: median of national data; MIN: PTF, Honeysett and Ratkowsky (1989) and Baritz et al. (2010)	FF: measured, MIN: PTF, national functions for bulk soil (assuming BD = 2.65 g cm^{-3} for stones >2 mm), Stupak et al. (2024) and Callesen et al. (2003)	FF: measured, MIN: PTF, model 9 and 10 Tamminen and Starr (1994); measured BD on subset	Measured (assuming BD = 2.65 g cm^{-3} for quartz)
Sources	Stendahl et al. (2017); SLU (2023)	Strand et al. (2016)	Stupak et al. (2024); Callesen et al. (2015)	Lehtonen et al. (2016); ICP Forests (2006)	Gillis et al. (2005); Canadian Forest Service (2008)

[a] Forest floor samples in Sweden and Finland do not include loose litter (L) and it was not possible to compensate for this bias during harmonization.
[b] Where *sampled* vertical resolution in the mineral soil was not identical to the *harmonized* vertical resolution, C stock estimates were approximated by weighing the C stock of each sampled layer or horizon by its spatial overlap with the target harmonized layers: i.e., 2/3 of the C stock estimate in the 10–25 cm mineral soil layer was used to represent the 10–20 cm layer C stock (Denmark, same principle for Canada); field records of horizon thickness and depth was used to find the vertical overlap with target harmonized layers (Norway); 55–65 cm mineral soil C stock: 1/4 of the 40–80 cm mineral soil C stock (Finland) and 2/5 of the 50–75 cm mineral soil C stock (Denmark).
[c] Layers in parentheses have been sampled in the National Forest Soil Inventories but are not included in the harmonized dataset. Swedish B horizon C stocks were not available for this study (however, the B horizon often overlap with 0–10 and 10–20 cm layers). Swedish samples taken 45–55 cm below the soil surface, including the forest floor layer where applicable, were discontinued in 2003 and were therefore not included in this analysis.

Forest management practices can have both positive and negative effects on the forest soil greenhouse gas and C balance and clear-cutting is one of the most impactful of practices (Mäkipää et al., 2023; Mayer et al., 2020). Studies of clear-cutting effects on soil C in boreal forests tend to be short term (<25 years after harvest) and have generated contrasting responses in C pools of both forest floor and mineral soil layers (Kreutzweiser et al., 2008; Piirainen et al., 2015). Meta-analyses based on data from temperate forests and global scale datasets have shown that harvesting leads to reduced forest floor C stocks for 25–85 years, after which the C stocks have recovered to pre-harvest levels (Achat et al., 2015; James and Harrison, 2016; James et al., 2021; Mayer et al., 2023; Nave et al., 2010). Since coniferous forests generally store more C in forest floors than deciduous forests (Vesterdal et al., 2013; Vesterdal et al., 2008), they may be more susceptible to harvest induced losses than what is suggested by these meta-analyses due to an elevated risk of disturbance-induced soil C losses for the forest floor layer (Mayer et al., 2023). In terms of mineral soil C responses, results across the meta-analyses varied depending on soil taxonomic order, mineral soil depth, climate, tree species composition, and harvest intensity, but, generally, studies suggest smaller changes in mineral soil C stocks after clear-cutting relative to changes in forest floor C stocks. Podzols, one of the most common soil types of Nordic and Canadian forests, showed no significant change in the C pool of the 5–20 cm layer, but a decrease in 20–100 cm mineral soil layer in the study of Nave et al. (2010). While the change was smaller than in forest floors, it took longer for bulk mineral soil C to recover to pre-harvest levels in the study of James and Harrison (2016).

Global scale meta-analyses of harvesting effects on soil C include boreal forests but are primarily based on data from temperate forests (Achat et al., 2015; James and Harrison, 2016) and are therefore unlikely to capture potential differences in responses across different biomes. For example, while clear-cutting is the dominating method of final harvesting in the Nordics and Canada, published meta-analyses often pool clear-cut and thinning harvests (James and Harrison, 2016; Mayer et al., 2023; Nave et al., 2010). The need for a focused yet large-scale examination of the effect of clear-cutting within a boreal and northern temperate forest context is further highlighted by the positive relationship between initial soil C stock and the magnitude and persistence of post-disturbance losses, leading to high latitude forests being considered at high risk of disturbance-induced soil C losses (Mayer et al., 2023).

The meta-analyses referenced above are based on experimental studies with harvest treatments. Another source of data is National Forest Soil Inventories (NFSI) which are often integrated with National Forest Inventories (NFI). Such data have only recently been used in regional scale studies to address the effect of harvest on soil C stocks (Nave et al., 2024; Nave et al., 2021). The data collected through NFSIs cover larger geographical extents than experiments and, hence, wider environmental gradients, potentially making them attractive for detection of patterns across larger geographical scales. Another advantage can be the availability of time series or wide age class distribution that allows the use of a space-for-time approach. On the other hand, the NFSI monitoring systems do not include paired control and harvest treatment, which introduces the risk of confounding the effect of time since harvesting and effects of site-related factors and changes over time in harvesting methods (Yanai et al., 2000).

Here we used NFI and NFSI data to create a 53 year long clear-cutting gradient representing different points in time after clear-cut harvest. Accepting the space-for-time substitution we investigated the development of soil C stocks after clear-cut harvest across large spatial scales

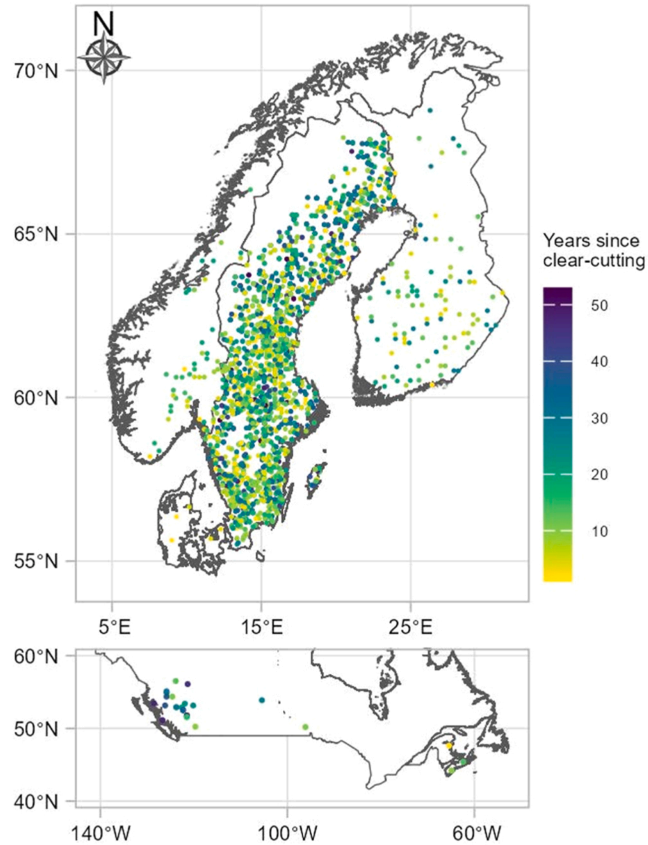

Fig. 1. Geographical distribution of available clear-cut plots in the National Forest Soil Inventories in the Nordics (top) and southern Canada (bottom). Color indicates years passed between clear-cutting and soil sampling.

and environmental gradients in the boreal and northern temperate forest biomes. We harmonized data from four Nordic countries (Sweden, Denmark, Norway, Finland) and Canada to answer the following questions:

(1) Does Nordic and Canadian forest soil C stocks change following clear-cutting? And if so,
(2) are changes similar in terms of magnitude and temporal dynamics across forest floor, top mineral soil, and deeper mineral soil C stocks, and
(3) are changes influenced by tree species composition and soil taxonomic order (pedogenesis)?

We hypothesized intermediate to long-term (~25–53 years) decreases in soil C after which the stock would increase again to approach pre-harvest levels. We further hypothesized that there would be larger decreases in coniferous than deciduous-mixed forest floor C stocks, in absolute terms, and larger relative declines in forest floor than mineral soil C stocks in both coniferous and deciduous-mixed forests.

2. Materials and methods

2.1. Data description and harmonization

We used NFSI data from Sweden, Denmark, Finland, Norway and Canada (Table 1). All datasets contained estimates of soil C stocks (corrected for stone content), and for clear-cut plots an estimate of which year the clear-cut harvest had taken place. All plots with registered previous clear-cut harvest event were included in the analyses. No information on harvest intensity (stem vs whole tree harvest or residue removal) was available. The largest number of plots were available from Sweden, less from Finland, Norway and Canada, and least from Denmark, in the latter case especially due to lack of reliable information on the time of clear-cut harvest (Fig. 1 and Table S1). The maximum registered time between clear-cutting and soil sampling was 53 years. Only the Swedish and Canadian datasets contained plots that had been sampled more than once after a clear-cutting event (Table S1). We excluded plots with soils defined as Histosols (IUSS Working Group WRB, 2022) from the Swedish and Finnish datasets and soils defined as Organic soils (Soil Classification Working Group, 1998) from the Norwegian and Canadian datasets. Such soils have organic horizons often extending beyond the deepest soil samples available for this study. No such deep organic soils (≥40 cm thick organic horizon) were present in relevant plots in the Danish dataset.

All the included plots had measurements of forest floor C stocks, and the majority included measurements of mineral soil C at 0–10 cm and 10–20 cm depths (Table 1). For plots where other sampling depths were used, C stock estimates were harmonized to the 0–10 cm and 10–20 cm intervals (Table 1). From here on, we refer to the sum of forest floor and 0–20 cm mineral soil C stocks as *topsoil* C stock. All datasets except the Canadian also included mineral soil C stock estimates from samples with a midpoint ~60 cm below the mineral soil surface and we harmonized these data to represent a 55–65 cm mineral soil C stock. Because the Swedish field sampling did not include samples from the 20–55 cm depth interval we did not include this depth interval in the analysis. The number of C stock estimates from post clear-cutting plots varied considerably among countries and harmonized sample depth intervals (Table S1). A more detailed description of the harmonization is given in supplementary materials.

2.2. Covariates for statistical analyses

In the statistical models (details in Section 2.3.*Statistical analyses*) we used additional variables as co-variates to reduce residual variance and hence improve the chance of detecting a potential clear-cutting effect. The covariates were soil texture (% sand), soil C:N ratio and pH ($CaCl_2$), mean annual temperature (MAT), mean annual precipitation (MAP), altitude, and slope (Table 2). All C and N concentrations were determined by dry combustion. Various harmonization strategies were pursued for each variable as explained in Table 2.

In order to conduct stratified analyses on sub-datasets, we also classified the plots to forest species group and soil taxonomic order. Forests were classified as *coniferous*, or *deciduous-mixed*, based on whether the proportion of total basal area of coniferous species was above or below 70 %, respectively. In pole stage forests in Norway, the classification was made from the proportion of total biomass, or crown cover, as available. Pure deciduous and mixed deciduous-coniferous forests were pooled due to the low number of C stock estimates available for these forest types (Table S1). Plots with coniferous forests were further divided into *Picea* and *Pinus* dominated stands using the same 70 % proportion of total basal area as threshold. We translated the soil taxonomy used in the Canadian and Norwegian NFSIs, based on the Canadian system of soil classification (CSSC; Soil Classification Working Group (1998)), to World Reference Base (WRB) taxonomy (IUSS Working Group WRB, 2022) using taxonomic correlation tables provided in the CSSC documentation (Soil Classification Working Group, 1998). No soil taxonomic classification was available in the Danish dataset. Further details on harmonization of co-variates can be found in supplementary materials.

2.3. Statistical analyses

To test if soil C stocks changed after clear-cutting, we used Bayesian generalized additive models (GAM; (Hastie and Tibshirani, 1986) with a random effect on the plot level to account for repeated (non--independent) sampling (Table S1). The plot level random effect also

Table 2
Co-variates used in the statistical models. Further details are found in supplementary materials and references listed in Table 1. L = litter, F = fibric, H = humic. C = carbon, N = nitrogen, MAT = mean annual temperature, MAP = mean annual precipitation, FF = forest floor, MIN = mineral soil.

Co-variate	Harmonized	Sweden	Norway	Denmark	Finland	Canada
C:N ratio[a]	**C:N ratio**	FF: < 2 cm milled, live roots > 2 mm removed. MIN: < 2 mm. Assuming all C organic	FF: < 2 cm crushed. MIN: < 2 mm. Assuming all C organic[b]	FF: < 2 cm milled, live roots removed when possible. MIN: < 2 mm. Inorganic carbon as $CaCO_3$ was removed before measurement of organic C (ISO 10694) for plots with risk of presence of $CaCO_3$, based on geological maps	FF: < 2 cm milled, live roots > 2 mm removed. MIN: < 2 mm. Assuming all C organic	FF: < 8 mm ground. MIN: < 2 mm. Inorganic C determined if pH > 6.7, otherwise assumed absent
% sand[c]	**% sand for each soil profile/plot using national particle size category definitions**[d]	Ten texture categories from field classification 10 cm below E-horizon or 20 cm below mineral soil surface (SLU, 2023; Tupek et al., 2016)[e]	%sand/silt/clay from B horizon, sieving (sand) and sedimentation analysis (silt and clay) (Elonen, 1971; Esser and Nyborg, 1992)	%sand/silt/clay available for 50–75 cm depth, measured by laser diffraction, with reservations as explained by Callesen et al. (2018) and Callesen et al. (2023)	%sand/silt/clay for each sample, dry sieving (sand and silt) and wet sieving (clay)	%sand/silt/clay for each sample, sedimentation analysis
Soil pH	**pH in $CaCl_2$**	Each sample (pH in H_2O and $CaCl_2$, the latter only up to 2012)[f]	Each/most samples (pH in H_2O and $CaCl_2$)	Each sample (pH in $CaCl_2$)	Each sample (pH in H_2O and $CaCl_2$)	Each sample (pH in $CaCl_2$) FF: ≤ 8 mm fraction, MIN: ≤ 2 mm fraction
MAT and MAP	**MAT (°C), MAP (mm)**	WorldClim MAT and MAP rasters, 1970–2000 (Fick and Hijmans, 2017)	Spatial Norwegian climate data, 1961–1990 (Engen-Skaugen et al., 2008)	WorldClim MAT and MAP rasters, 1970–2000 (Fick and Hijmans, 2017)	WorldClim MAT and MAP rasters, 1970–2000 (Fick and Hijmans, 2017)	Spatial North American climate data, 1971–2000 (McKenney et al., 2011)
Topography	**Altitude (m.a.s.l.), slope (°)**	EU-DEM (European Environment Agency, 2016)	Altitude: Altitude maps Slope: Clinometer	EU-DEM (European Environment Agency, 2016)	Altitude: GPS Slope: Clinometer	Altitude: GPS Slope: Clinometer

[a] C and N concentrations were measured by dry combustion in all countries.
[b] For Norway, C:N ratio of each individual harmonized mineral soil layer was represented by the average C:N ratio of all mineral soil horizons. C and N in 1988 was only analyzed for forest floor and Ah-horizons.
[c] For the Norwegian, Finnish, and Canadian datasets we used particle size distribution at 15–40 cm mineral soil depth to reflect texture for a given soil profile but allowed the use of data from shallower mineral soil layers/horizons when data from 15–40 cm were unavailable. For the Danish dataset we used particle size distribution from the 50–75 cm mineral soil layer.
[d] Denmark and Finland: Sand: 63–2000 μm, silt: 2–63 μm, clay: < 2 μm. Norway and Sweden: Sand: 60–2000 μm, silt: 2–60 μm, clay: < 2 μm. Canada: Sand: 50–2000 μm, silt: 2–50 μm, clay: < 2 μm.
[e] Field records are rescaled to represent only the < 2 mm fractions. Details in supplementary materials.
[f] Based on Swedish data 1993–2012 and Finnish pH data, pH in $CaCl_2$ for Sweden after 2012 was estimated by adding a constant factor of 0.5 to pH measured in H_2O. Details in supplementary materials.

accounts for potential country-level soil C biases. All analyses were conducted using the brms package (Bürkner, 2017) in R (R Core Team, 2024). Time since clear-cutting was modelled using thin plate splines (*bs = "tp"* in brms syntax (Bürkner, 2017)) while all other covariates were included as linear main effects (i.e. no interaction effects were included). We developed separate models for each forest category (*coniferous*, *deciduous-mixed*, *Picea* and *Pinus*) and sample depth interval (forest floor, 0–10 cm, 10–20 cm and 55–65 cm) to allow for unique responses to the covariates, including unique post clear-cutting soil C stock dynamics for each category and layer. Additionally, we developed models for the sum of forest floor, 0–10 cm, and 10–20 cm mineral soil C stocks, using only plots where C stock estimates from all layers were available, representing *topsoil* C stock.

We also developed models where *Pinus*-dominated stands were subdivided into stands developed on Podzol and Regosol soils, the two soil types dominating the dataset. Only *Pinus*-dominated stands were used in this context to avoid confounding the effect of soil taxonomic order with that of dominating tree species and because there were more samples from *Pinus*- than *Picea*-dominated stands available (Fig. 3). For all models, we kept all other predictors at their mean when we extracted the effect of clear-cutting (the smooth term of the GAM model) and its associated 90 % credible interval (90 % CrI). The 90 % CrI represents 90 % probability of the soil C stock trend as described by the smooth term of the GAM model. We interpreted the intercept of the model as the pre-harvest C stock level and validated the intercept in two ways: (1) by comparing its position relative to the harmonized C stock values 1–5 years after clear-cutting, and (2) by comparing this harmonized initial post clear-cutting C stock data to harmonized C stock values available from stands that had been sampled prior to clear-cutting (Figure S1 and S2). While Bayesian statistics does not involve p-values or statistical significance, throughout the manuscript we interpret non-overlapping CrIs as an analog to statistically significant differences, i.e. that there is a high probability that estimates are different. Further details on the statistical modelling are available in supplementary materials.

3. Results and discussion

Picea-dominated forest stands had higher initial forest floor C stocks (3.29 kg C m^{-2}; 90 % CrI: 2.83–3.74 kg C m^{-2}) compared to *Pinus*-dominated stands (2.13 kg C m^{-2}; 90 % CrI: 1.87–2.41 kg C m^{-2}), as estimated by the intercept of the models (Fig. 2). From these estimated initial levels, forest floor C stocks in the *Picea*-dominated stands decreased by 0.77 kg C m^{-2} on average (90 % CrI: 0.01–1.51 kg C m^{-2}), to a minimum of 2.51 kg C m^{-2} (90 % CrI: 2.22–2.82 kg C m^{-2}) 35 years after clear-cutting. Mean forest floor C stocks in *Pinus*-dominated stands decreased by 0.29 kg C m^{-2} on average (90 % CrI: −0.11–0.71 kg C m^{-2}), to a minimum of 1.81 kg C m^{-2} (90 % CrI: 1.70–1.98 kg C m^{-2}) 28 years after clear-cutting. These mean estimates of the minimum stock level of the clear-cutting gradient correspond to decreases of 23 % and 14 % relative to initial stock levels for *Picea*- and *Pinus*-dominated stands, respectively. For *coniferous* forest stands, the corresponding decrease was 0.53 kg C m^{-2} (90 % CrI: 0.16–0.91 kg C m^{-2}), from the initial level of 2.62 kg C m^{-2} (90 % CrI: 2.38–2.88 kg C m^{-2}), to the lowest level of 2.09 kg C m^{-2} (90 % CrI: 1.97–2.22 kg C m^{-2}) 29 years

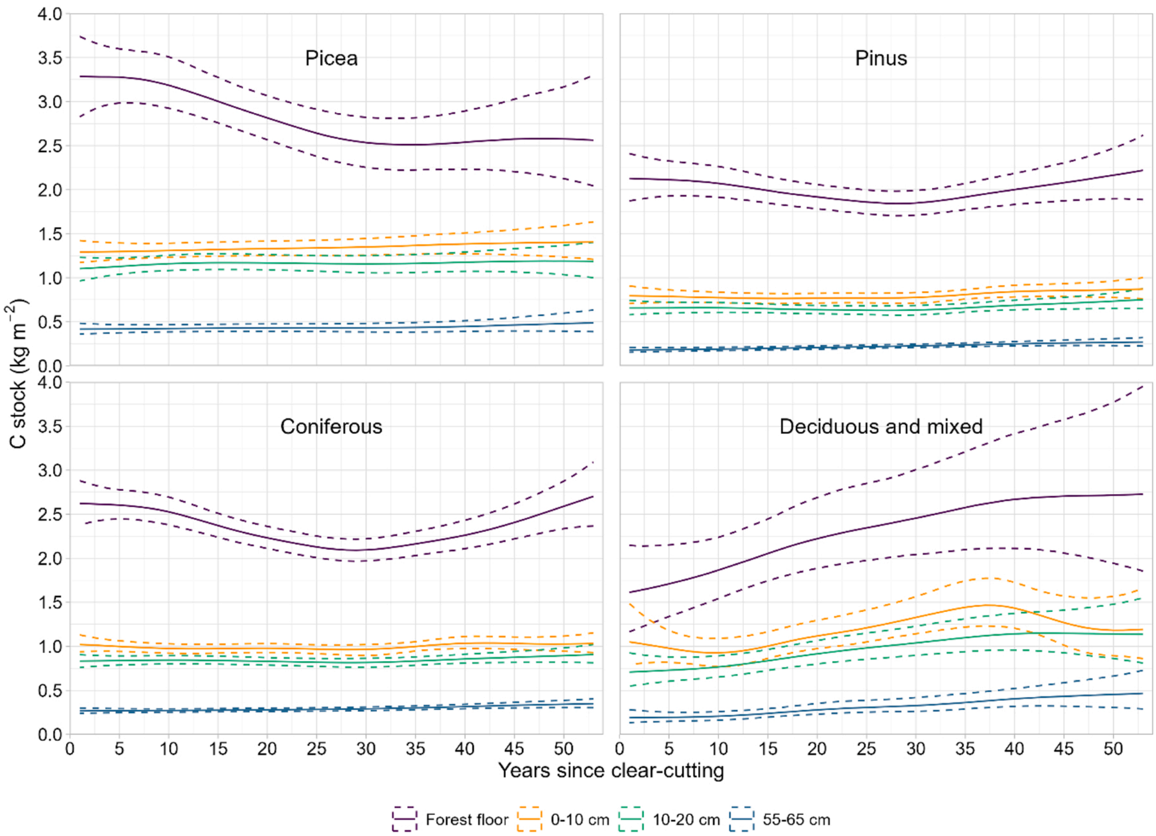

Fig. 2. Post clear-cutting carbon (C) stock development in forest floors and three different mineral soil depth intervals in forest stands dominated by *Picea* and *Pinus* tree species (top left and top right, respectively), all *coniferous*-dominated stands (bottom left), and in *deciduous*-dominated stands or mixed tree species stands (pooled; bottom right). Solid lines are mean estimates, and dashed lines are 90 % credible intervals.

after clear-cutting. For *Pinus*-dominated and *coniferous* forests, initial forest floor C stocks were similar to the mean C stock 53 years after clear-cutting. For *Picea*-dominated forests, the mean estimate remained close to its minimum level until the end of the 53-year long gradient.

The 0–10 cm and 10–20 cm mineral soil C stocks were stable throughout the clear-cutting gradient in *coniferous* forest stands as well as for *Picea*- and *Pinus*-dominated stands, separately (Fig. 2). However, the 55–65 cm mineral soil C stock increased throughout the clear-cutting gradient in *Pinus*-dominated stands. At the end of the gradient, 53 years after clear-cutting, the 55–65 cm mineral soil C stock in *Pinus*-dominated stands had increased by 0.09 kg C m^{-2} (90 % CrI: 0.01–0.17 kg C m^{-2}), from an initial level of 0.18 kg C m^{-2} (90 % CrI: 0.16–0.21 kg C m^{-2}). Similarly, for *coniferous* forests, the increase was 0.08 kg C m^{-2} (90 % CrI: 0.001–0.16 kg C m^{-2}). No change could be detected with > 90 % probability for *Picea*-dominated stands.

The mean forest floor, 10–20 cm, and 55–65 cm mineral soil C stocks of *deciduous-mixed* forests increased along the clear-cutting gradient, while the 0–10 cm mineral soil C stock seemed to oscillate. However, all C stock trajectories were associated with large CrIs, likely due to a combination of small sample sizes (Table 1 and Fig. 3) and a heterogeneous category of forest species mixtures and soil types. The observed development in soil C stocks for the *deciduous-mixed* stands was therefore rather an indication that the amount of available data was too small to detect statistical signals of clear-cutting, considering the heterogeneity of soil C stocks across large spatial scales. Consequently, the remainder of the analyses focused on forest stands dominated by coniferous tree species.

Our results show forest floor C stock declines for 28–35 years after clear-cutting, i.e. slightly longer than the 15–32 years found by Achat et al. (2015), but shorter than the ~50 years suggested by James and Harrison (2016). Our results further indicate that the period of 50–70 years suggested by Nave et al. (2010) for stands on Podzol soils is insufficient for forest floor C stock recovery in the *Picea*-dominated stands of our study, for which the mean estimate was a 0.72 kg C m^{-2} decrease at the end of the clear-cutting gradient (90 % CrI: −0.47–1.70 kg C m^{-2}). The 50–70 years is, however, in line with our estimates for forest floor C stock recovery in *Pinus*-dominated stands, for which the mean estimate was an 0.09 kg C m^{-2} increase at the end of the gradient (90 % CrI: −0.52–0.75 kg C m^{-2}), relative to initial stock levels. Forest floor C stock estimates towards the end of the gradient were associated with high uncertainty due to a decreasing number of observations when moving beyond 40 years after clear-cutting (Fig. 3). Hence, our confidence in the estimates > 40 years after clear-cutting is lower relative to estimates < 40 years after clear-cutting, as also reflected in the wider CrIs for estimates > 40 years (Fig. 2).

Direct comparison of our C stock trajectories after clear-cutting with those from the meta-analyses referenced above must be done with caution due to differences in reference levels, i.e. the type of forest used as control to estimate the initial soil C stock level prior to clear-cutting. Two principally different approaches can be used, either measuring stocks prior to harvest or those of an unharvested control plot (Kenefic et al., 2005). Furthermore, there may be differences in the successional stage of the reference forest, e.g., if it is an economically mature forest, late-successional or old-growth forest. For example, stands that had not been harvested within 30 years prior to soil sampling qualified as control plots in both Nave et al. (2010) and James and Harrison (2016), while the criteria for qualifying as control plots are not explicitly stated in other studies (Achat et al., 2015; James et al., 2021; Johnson and Curtis, 2001; Mayer et al., 2023). If plots that have been harvested ~30–40 years prior to soil sampling are used as controls, there is a risk that this reference soil C stock is close to its minimum level during the current rotation, resulting in the calculated C stock changes not reflecting a

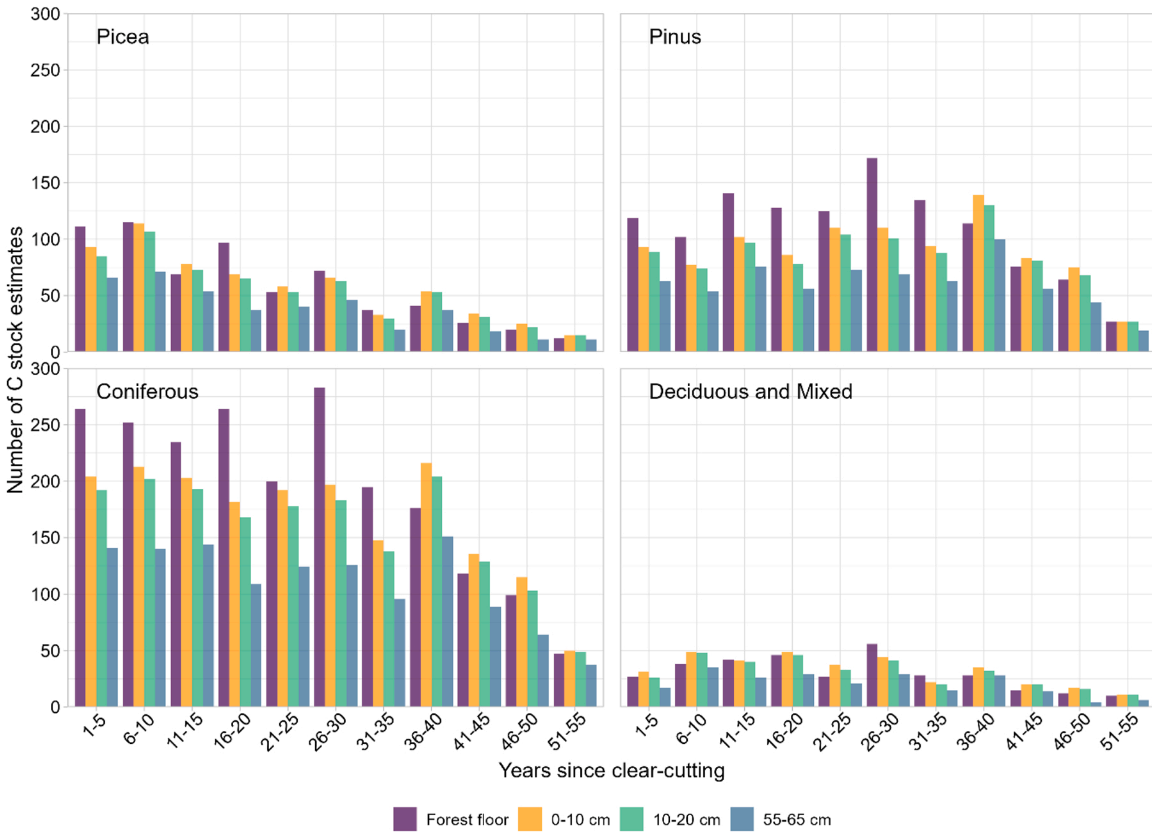

Fig. 3. Number of post clear-cutting C stock estimates available for the different forest categories, per sample depth interval and post clear-cutting year, binned in 5-year intervals.

situation of clear-cut harvest in economically mature forests, as in our case. On the contrary, forests that may not have been managed for production purposes have sometimes been included as controls (James and Harrison, 2016; Nave et al., 2010). One benefit of using NFSI data is that it ensures that the forest stands included in this study are managed in a clear-cut silvicultural system, and the results therefore reflects the changes in soil C stocks in the context of rotation forestry.

Direct comparison is further challenged by the different statistical models used for inference. James and Harrison (2016) and James et al. (2021) used a quadratic function to describe the dynamics of soil C stocks after harvesting. Such a function is rigid in shape (symmetric around the inflection point) and the rate of change in the years just after harvest is heavily influenced by the rate of change several decades after harvesting, and vice versa. In this study, we used GAMs to relax the shape constraints and better account for variation in C stock losses and gains along the clear-cutting gradient. This may have a substantial impact on estimates of how long it takes to reach the minimum C stock level, how much the C stock has decreased or increased at specific points in time as well as how long it takes to recover to the reference level.

Because we used NFSI data we did not have access to unharvested control plots/stands often used in experimental set-ups. Therefore, we relied on the intercepts of our models adequately representing pre-harvest C stock levels. When comparing C stock estimates from before clear-cutting with estimates from 1–5 years after clear-cutting we found no substantial differences (Figure S1). Furthermore, the confidence in using the intercept estimates as appropriate representations of pre-harvest C stock levels is enhanced by the fact that they were placed in high data density regions (Figure S2). It should be noted, however, that while pre-harvest C stock levels are often used as a reference in studies of the impact of harvest, and that while our understanding of soil C accumulation in relation to forest aging is limited, forest that are subject only to natural disturbances can accumulate soil C on decadal to millennial scales (Andrieux et al., 2018; Clemmensen et al., 2013; Zhou et al., 2006). Oppositely, harvest-induced soil C losses may accumulate across multiple harvesting cycles (Dean et al., 2017), with the C loss after the initial harvest of old-growth forests perhaps not being recoverable within centuries or millennia (Harmon et al., 1990). Especially in Fennoscandia, forests have been intensively harvested for centuries, even if the introduction of clear-cutting and modern production forestry is relatively recent. The implication may be that the soil C stocks in current older mature forests are lower than those of the past, and may get even lower in the future, if they do not recover within a rotation. However, neither this study nor meta-analyses of the effects of a single harvest cycle can capture the potential cumulative soil C losses after multiple harvesting cycles, or the potential gains in the absence of harvest.

The larger decreases of forest floor C stocks in *Picea*-dominated stands, relative to *Pinus*-dominated stands, are in line with the expected higher losses from soils with larger initial C stocks (Mayer et al., 2023). Larger losses of C in soils have often been observed for larger initial C stocks, yet it is not clear to what extent this is a true ecological effect, or the statistical phenomenon known as regression to the mean (Slessarev et al., 2023). However, in this study, regression to the mean is less an issue due to the space-for-time approach. Our results therefore support that more substantial losses of C can be expected where initial stocks are large. In this respect it is worth repeating that Histosols/Organic soils (WRB/CSSC taxonomy), which store large amounts of C, are not included in this study.

The 55–65 cm mineral soil C stock increase was not large enough to offset losses from forest floors, but the available dataset allowed only for a representation of a 10 cm thick mineral soil sample and therefore does not capture any potential C stock increases or decreases below or directly above this 10 cm layer. We were consequently unable to quantify to what extent losses of forest floor C result from mineralization and increased CO_2 emissions to the atmosphere or from translocation of

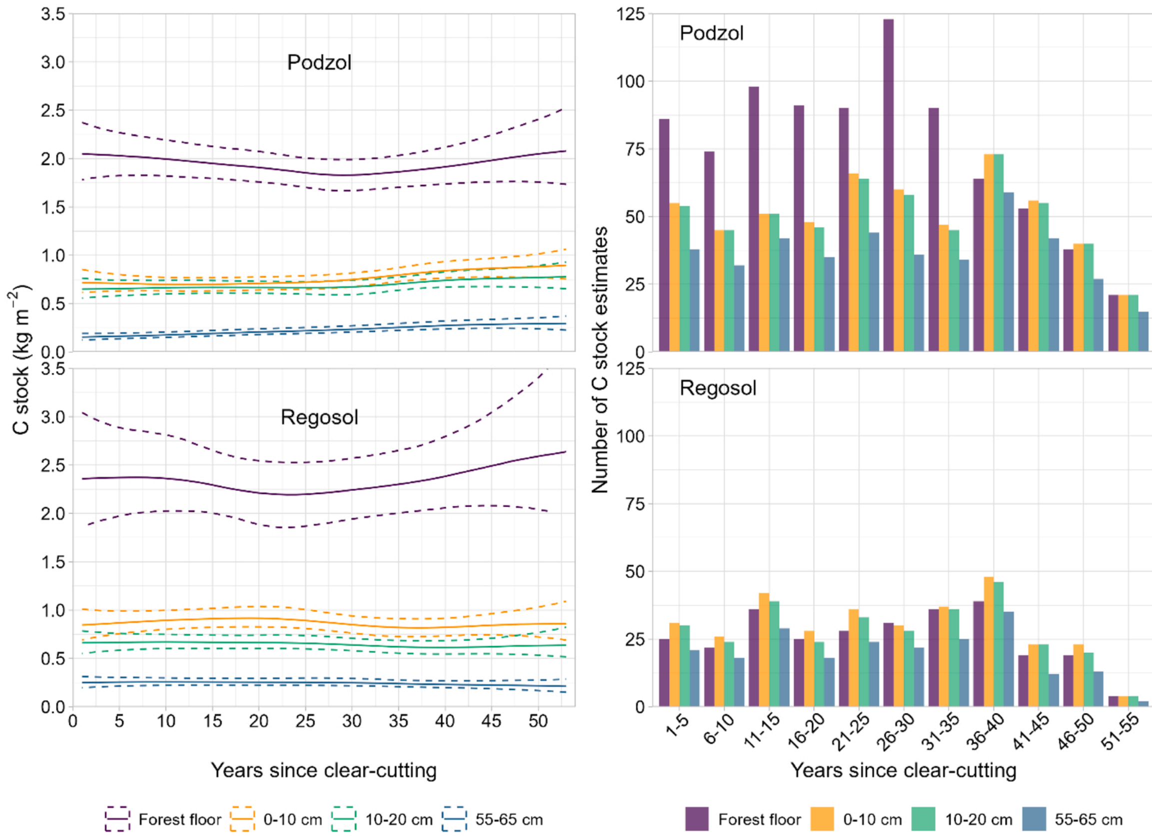

Fig. 4. Soil C stock development after clear-cutting in *Pinus* dominated stands on Podzol (top-left) and Regosol (bottom-left) soil types. On the right side, number of post clear-cutting soil C stock estimates available for the two taxonomical soil orders, per sample depth interval and post clear-cutting year, binned in 5-year intervals. Solid lines are mean estimates, and dashed lines are 90 % credible intervals.

C to deeper soil layers. In the study of Piirainen et al. (2002), conducted in *Picea abies*-dominated old-growth forests on Podzol soils in Finland, a 2–5-fold increase in dissolved organic carbon (DOC) leaching from the forest floor was observed in the three years following clear-cutting, but the resultant increase in the total mineral soil C stock was only ~0.4–0.5 % (0.0096–0.0129 kg C m^{-2}). Thus, while podzolic soils have a high C sequestration potential due to the presence of reactive metals (Garrett et al., 2024), increases in deeper mineral soil C stocks are likely small relative to C lost through mineralization because these soil layers undergo simultaneous sorption and desorption processes (Kothawala et al., 2009). It should also be noted that while the 55–65 cm mineral soil C stock was smaller than the forest floor, 0–10 cm and 10–20 cm mineral soil C stocks, bulk deep mineral SOC stores can be substantial (Jobbágy and Jackson, 2000).

Further separation of the *Pinus*-dominated stands into stands on Podzol and Regosol soil types indicated that the accumulation trend is limited to Podzol soils (Lundström et al., 2000) (Fig. 4). Other than in the 55–65 cm mineral soil, no C stock increases or decreases could be detected with a > 90 % probability in these subdivided *Pinus*-dominated stands. Despite homogenization of the forest stand category in terms of tree species and soil type, the CrIs of the estimated post clear-cutting trajectories in forest floor and top mineral soil C were wide relative to any clear-cutting signal. Again, this is most likely due to a limited number of post clear-cutting samples (Fig. 4, right panels). Soil texture has also been shown to influence the effect of forest harvesting on soil C (Nave et al., 2021). While we did not test for such an effect explicitly, the soils in our dataset were predominantly sandy (Figure S3) and the Podzol soils in our dataset were generally sandier than the Regosol soils (Figure S4).

When pooling forest floor, 0–10 cm and 10–20 cm mineral soil into *topsoil* C stock, the statistical signal of C stock change in specific layers were diluted, and no changes could be detected with a > 90 % probability. Nonetheless, for *Pinus*-dominated stands the mean estimate suggested an increase in *topsoil* C stock by 0.74 kg C m^{-2} (90 % CrI: −0.06 –1.67 kg C m^{-2}) 53 years after clear-cutting, relative to the lowest stock levels, 28 years after clear-cutting. The mean response in *Picea*-dominated forests was a decreasing stock throughout the clear-cutting gradient. For *coniferous* forests the mean response was a decrease during the first 29 years after clear-cutting, and an increased soil C stock towards the end of the gradient (40–53 years after clear-cutting), relative to initial levels.

The soil C stock trends observed in this analysis include changes induced by climate change. While we account for MAT and MAP in our models, we are unable to disentangle the effects of a changing climate from the effect of clear-cutting. Most of the plots included in our study have been sampled only once, meaning we cannot track potential effects of climatic changes over time at the plot level. Additionally, because the used MAT and MAP data is static, the plots that have been sampled more than once are associated with the same MAT and MAP value for all inventory years. Lastly, climate change involves several effects that we are unable to account for, including increased drought frequency and severity and CO_2 fertilization (IPCC, 2022; IPCC, 2023). Clear-cutting and climate change have affected the examined forest soils simultaneously, and our results should therefore be interpreted as the effects of clear-cutting in the context of a changing climate.

We acknowledge that our analysis does not account for variation in clear-cut harvest intensities and that post-harvesting soil C dynamics are likely influenced by several factors not tested for here, including site fertility, hydrological conditions and whether site preparation and/or residue removal took place. For example, the extent to which site preparation following clear-cutting is practiced differ between countries, being common practice in Sweden, Finland and partly Canada

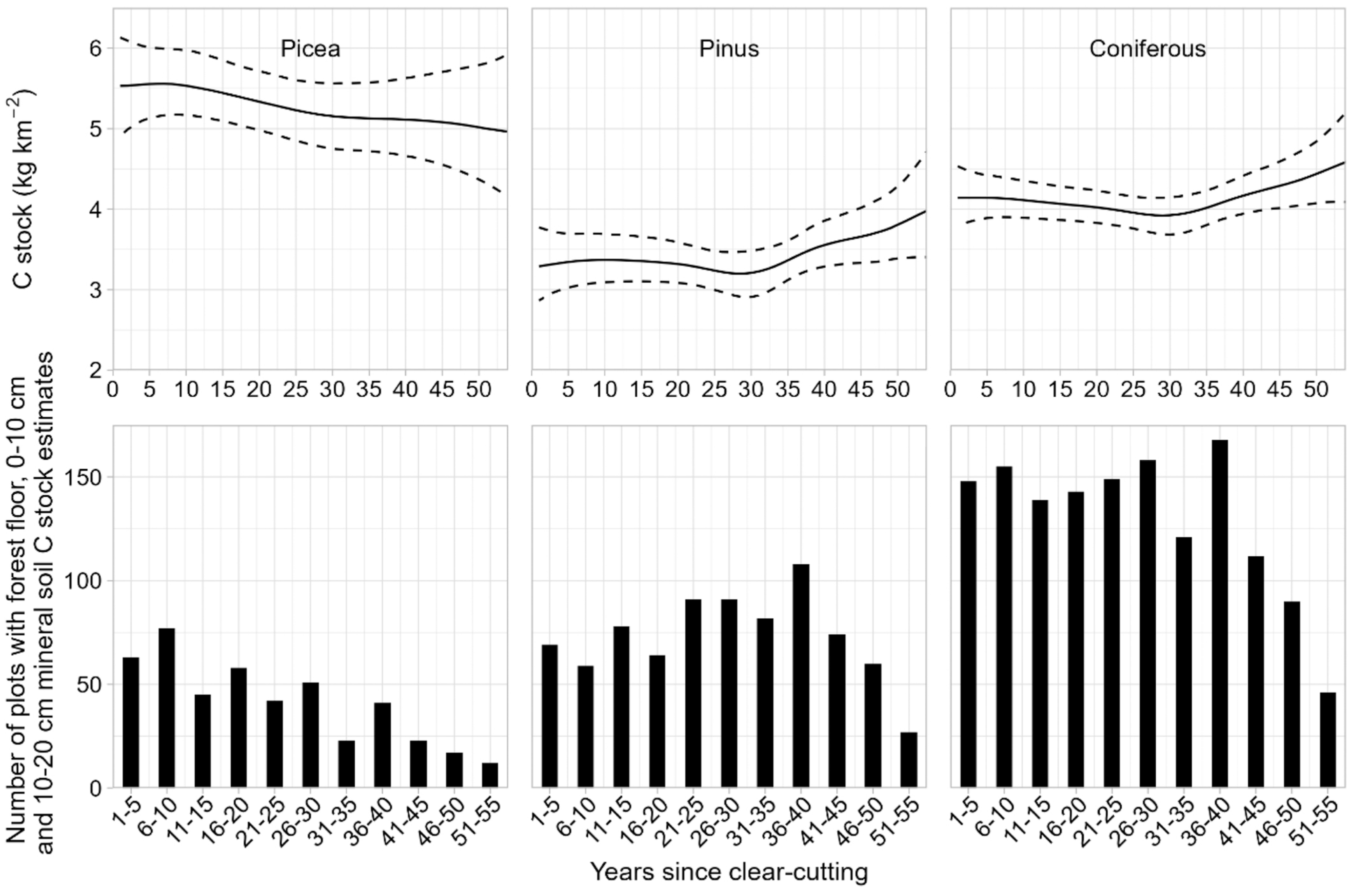

Fig. 5. C stock development in topsoil (forest floor + 0–20 cm mineral soil; top panels) in *Picea* and *Pinus* dominated stands and pooled for all coniferous dominated stands. Solid lines are mean estimates, and dashed lines are 90 % credible intervals. Bottom panels show number of plots where C stock estimates were available from all three soil layers (forest floor, 0–10 cm and 10–20 cm mineral soil) along the clear-cutting gradient for each of the forest categories.

(Korhonen et al., 2021; Ramantswana et al., 2020; Swedish Forest Agency, 2021) but is only rarely done in Norway (de Wit and Kvindesland, 1999). In addition, the forest industry in the Nordic countries and Canada underwent substantial transformations during the 20th century (Östlund et al., 1997; Ramantswana et al., 2020), making studies based on long-term data subject also to effects related to changes in harvesting intensities over time (Yanai et al., 2000). For example, an increasing degree of whole tree harvesting and residue removal over stem only harvesting will affect the soil C input. The degree of such changes in harvesting intensity also varies between countries and regions. Thus, a potential change over time in biomass removal during clear-cutting adds uncertainty to the long-term soil C trends after clear-cutting. As our dataset is dominated by Swedish NFSI data, the current findings will largely be representing the major harvesting systems as well the changes over time of Swedish clear-cut forestry. Thus, the representativity of these results for other boreal and northern temperate forestry systems is somewhat uncertain. Nonetheless, by limiting our study to clear-cut harvest we keep the most prominent change in the ecosystem constant: the close to complete removal of standing biomass.

4. Conclusion

Clear-cutting in Nordic and Canadian coniferous forests led to decreasing forest floor C stocks for 28–35 years, after which C stocks in *Pinus*-dominated forests started to increase again, which resulted in a similar pattern for *coniferous* forests. Relative to *Pinus*-dominated stands, stands dominated by *Picea* species had higher initial forest floor C stocks and exhibited larger C stock decreases during the first ~30 years after clear-cutting. At the end of the clear-cutting gradient, 53 years after clear-cutting, forest floor C stocks in *Pinus*-dominated stands had recovered to pre-harvest levels, while in *Picea*-dominated stands soil C stocks were still close to their lowest level. However, by the end of the gradient, uncertainties were large due to a low number of observations. 55–65 cm mineral soil C stocks in Podzol soils increased continuously throughout the clear-cutting gradient but no C stock changes could be detected in the top mineral soil layers for any forest category. The process of podzolization includes leaching of C from shallow to deeper soil layers where immobilization by reactive metals occurs, and the rate of C leaching can increase after clear-cutting. While the largest C stock changes in response to forest harvesting can be expected in forest floor layers, we have demonstrated that it is important to also examine potential changes in deeper soil layers in order to account for losses versus downward transport to deeper layers, especially when investigating harvesting effects in forests established on Podzol soils. We did not include organic soils in this study (>40 cm organic horizon thickness), yet our results support that forests with high soil C stocks are more sensitive to harvest-induced soil C losses relative to forests with lower soil C stocks. Lastly, while we demonstrated that data from National Forest Soil Inventories can be used to examine effects of forest management practices on soil C stocks, it is evident that it requires large sample sizes as statistical signals tend to be weak due to the heterogeneity of soil C stocks on both local and transnational scales.

CRediT authorship contribution statement

Carl-Fredrik Johannesson: Conceptualization, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **H. Ilvesniemi:** Writing – review & editing. **O.J. Kjønaas:**

Writing – review & editing. **K.S. Larsen:** Writing – review & editing, Supervision. **A. Lehtonen:** Writing – review & editing. **J. Nordén:** Writing – review & editing, Supervision. **D. Paré:** Writing – review & editing. **H. Silvennoinen:** Writing – review & editing, Supervision. **J. Stendahl:** Writing – review & editing. **I. Stupak:** Writing – review & editing. **L. Vesterdal:** Writing – review & editing. **L. Dalsgaard:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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.2025.122668.

Data Availability

The authors do not have permission to share data.

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