Abstract

Boreal forests are able to store large amounts of carbon in soil and biomass, and forest management is considered an important strategy for mitigating climate change. Sweden has a long history of forest management that have intensified during the last century, but there are still old-growth forests that have not been disturbed by management. These forests have accumulated carbon in the soil during a long time. Since this carbon stock is large, even small changes can affect carbon dioxide levels in the atmosphere. Therefore, it is important to know how soil carbon is affected by management. The aim of this study was to investigate how a change in land use from old-growth forest with long tree cover continuity to young, managed forest affects the soil carbon stock. This was done by quantifying carbon stock in soil and tree biomass in 15 sites of adjacent old and younger forest in Västerbotten and Norrbotten in northern Sweden. The results shows a reduction of total soil carbon stock in managed forests. The reduction was mainly driven by a decrease in humus layer carbon stock, causing an 11 % decrease in total soil carbon stock. It is likely that this was caused by disturbance of the humus layer during harvesting and site preparation, and lack of litter fall during the clear cut period. Mineral soil carbon stock was not significantly affected by management, indicating that above ground operations have little effect on deeper soil layers. These results are in line with earlier studies. It has previously been proved that soil carbon has slow turnover and long term modelling studies predict a decline in soil carbon after several rotations. This study focuses on a short time perspective and the results can be different with a longer time frame perspective.

Key words: Forest management, unmanaged forest, harvesting effects, mineral soil

Sammanfattning

Boreala skogar kan lagra stora mängder kol i mark och biomassa, vilket gör skog och skogsskötsel till en viktig del i arbetet för att minska klimatförändringar. Sverige har en lång historia av skogsbruk, vilket har intensifierats under det senaste seklet. Trots det finns det fortfarande äldre skogar som hittills har undantagits trakthyggesbruket. Där har det ackumulerats kol i marken under mycket lång tid. Kolförrådet är stort och även små förändringar i det kan påverka kolhalten i atmosfären. Därför är det av stor vikt att veta hur markkolsförrådet reagerar på störning från avverkning. Syftet med den här studien är därför att undersöka om en förändring i markanvändning från gammelskog med lång trädkontinuitet till en yngre, brukad skog påverkar kolförrådet. Det gjordes genom att kvantifiera kolförrådet i mark och trädbiomassa på 15 lokaler med intilliggande äldre och yngre skog Västerbotten och Norrbotten i norra Sverige. Resultaten visar en minskning i markkol i de brukade skogarna. Den är främst driven av förändring i humuslagrets kolförråd, vilken orsakar en minskning på elva procent i markens totala kolförråd. Troliga orsaker är att humuslagret påverkats av störningen från avverkning och markberedning, och minskat förnafall under hyggesperioden. Kolförrådet i mineraljorden påverkades inte signifikant av avverkningen, vilket indikerar att störningar ovan jord inte påverkar djupare jordlager. Tidigare studier av hur skogsskötsel påverkar markkol visar liknande resultat. Det har tidigare visats att det kan ta lång tid innan mineraljordens kolförråd reagerar, och modelleringar har visat att över en längre tidshorisont över flera rotationsperioder minskar kolförrådet till följd av avverkningar. Den här studien har ett relativt kort tidsperspektiv och det är viktigt att ta i beaktan att resultatet kan bli annorlunda sett över längre tid.

Nyckelord: skogsskötsel, obrukad skog, avverkningseffekt, mineraljord

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1 Introduction

Boreal forests have the ability to store large amounts of carbon in biomass and soil, and are therefore important climate regulators. Management of forests is recognized as an important strategy for mitigating climate change by UNFCCC (United Nations Framework Convention on Climate Change, 2014). The forest carbon pool consists of tree biomass above- and below ground, non-tree vegetation, litter, coarse woody debris and soil organic matter (Dixon, et al., 1994). The largest pool of carbon in Swedish forests is soil carbon (Skogsdata, 2017), of which the major part is located in the top 0-50 cm of the soil (Eriksson, et al., 2005). Carbon is assimilated from the atmosphere via photosynthesis and transported to the soil through decomposition of organic matter and leaching of dissolved organic carbon (Stockman, et al., 2013; Berggren Kleja, et al., 2008). A fraction is also added via mycorrhizal fungi (Clemmensen, et al., 2013). Soil carbon stock is controlled by the input from these sources, and output through leaching and respiration by microorganisms. (Raich & Schlesinger, 1992; Hyvönen, et al., 2007).

The turnover of carbon in vegetation and soil can vary from years to centuries. The majority of soil carbon is relatively stable with long turnover time, but there are also labile fractions that decompose quickly under suitable site conditions (Berggren Kleja, et al., 2008; Jandl, et al., 2007). Turnover rate of soil carbon depends on form of carbon, but is also affected by tree species, site conditions, forest management and other disturbances (Dixon, et al., 1994; Naudts, et al., 2016). Boreal forests have relatively low productivity and long rotational periods. Low temperatures results in a slow respiration rate and a large storage of carbon in biomass and soil can be accumulated over a long time (Raich & Schlesinger, 1992; Clarke, et al., 2015).

Disturbance from forest management release carbon to the atmosphere (Fisher & Binkley, 2000; Covington, 1981). Tree harvesting and wood extraction decreases the total carbon pool of the ecosystem (Finér, et al., 2001). Soil carbon is affected by increased soil respiration from higher temperature and water availability after harvesting (Berggren Kleja, et al., 2008), reduced litter fall (Toland & Zak, 1994;

Covington, 1981) and site preparation (Hyvönen, et al., 2007). If stem-only harvesting is used, the input of logging residues can add to soil carbon stock during some years after harvesting (Finér, et al., 2001; Olsson, et al., 1996), while extraction of harvest residues from the forest decreases the amount of soil carbon more (Ågren & Hyvönen, 2003). After establishment, young fast-growing trees quickly start to sequester carbon into biomass and soil again, restoring carbon stock. The ecosystem is a carbon source for some time after harvesting, before turning back to a sink (Peltoniemi, et al., 2004; Liski, et al., 1998).

Intensification of forest management during the last century have increased volume growth and sequestration of carbon into the ecosystem, while at the same time opening for use of more wood material as replacement of fossil fuel products (Lundmark, et al., 2014). Forest productivity declines with age, meaning that potential of climate change mitigation can be higher in younger forests (Wardle, et al., 2004; Pukkala, 2017; Sathre & O'Connor, 2010). The intensified forest management can be positive in a climate change mitigation perspective but might affect soil carbon stock.

Old-growth, previously never clear-cut forests are of interest in the climate debate, due to their large soil carbon stock (Tas, et al., 2009). Some researchers argue that these forests are important carbon sinks and that they should remain unmanaged to preserve the carbon stock (Luyssaert, et al., 2008; Wharton & Falk, 2016; Naudts, et al., 2016; Knohl, et al., 2003; Zhou, et al., 2006). Studies of harvesting effects on soil carbon stock are contradictory. Some argue that soil carbon has been increasing in managed boreal forests, and is expected to further follow this pattern (Ågren, et al., 2007; Liski, et al., 2002). Pukkala (2017) and Ågren & Hyvönen (2003) conclude that soil carbon can be restored to the same level as if natural succession had occurred relatively quickly after clear felling, while for example Olsson et al. (1996) showed that 16 years after clear-felling of spruce stands in northern Sweden soil carbon stock was still decreased by 22 %. In contrast, long-term modelling studies show a decline in soil carbon after several rotation periods (Dean, et al., 2017; Harmon, et al., 1990; Liski, et al., 1998).

So far, most soil carbon studies focus on different types of forest management. Few focus on harvesting effects on soil carbon in old-growth forests. Sweden has about 3.2 million hectares of forest older than 140 years, 12 % of the forested area, most of it located in the northern part (Skogsdata, 2017). These forests are more likely to be untouched than younger ones, meaning that large amounts of carbon in biomass and soil may have been accumulated during a long time. The large carbon stock means that even small changes in it can have large effects on atmospheric carbon and climate (Ortiz, 2012; Raich & Schlesinger, 1992; Berggren Kleja, et al., 2008). It is of great value to know the implications for the carbon stock if these old-growth forests are harvested and converted into managed forests.

The aim of this study is to investigate if a change in land use from old forest with long tree cover continuity to young, managed forest affects the carbon stock.

This is done by

- measuring biomass of living and dead trees
- sampling and analyzing carbon stock in the humus layer and in the mineral soil at 0-10 and 10-20 cm depth

15 sites in northern Sweden are used in the study, each site with adjoining stands of old-growth and younger forest. The hypothesis is that the carbon stock is affected by the disturbance from harvesting and site preparation.

2 Materials and methods

2.1 Identification of sites and site requirements

The sites should have two adjoining stands: one old-growth without extensive human influence such as clear-felling (stand A), and the other stand should originally have been the same stand as the older one, but be younger and extensively influenced by humans in the last decades (stand B). In northwestern Sweden, there are large areas of relatively homogenous older forest (Wester & Engström, 2016). This means that, in many cases, the delimitation of forest management actions in the area has not been based on stand characteristics. The border between two stands is often relatively straight and clear, which made it easy to delimit the old and young stands. The suitability of the older stands was assessed subjectively based on stand age and structures such as dead wood and old trees, and indication of human influence such as stumps. The forests should not be a part of a protected area. Assessment of whether the younger stand had been the same as the old one before being harvested was made subjectively and based on stumps, stoniness and general site characteristics.

The search for suitable sites was limited to Västerbotten and the south part of Norrbotten in northern Sweden. The sites were identified after contact with Swedish Forest Agency, The National Property Board of Sweden and the National Forest Inventory, by using satellite images and by searching for key biotopes using the software pcSKOG (pcSKOG, 2018). All proposed sites were visited before sampling to assess their suitability.

2.2 Site description

15 sites in Västerbotten and southern Norrbotten that met the requirements were chosen for the study (figure 1). Average age and dominating tree species for the sites and stands are specified in table 1.

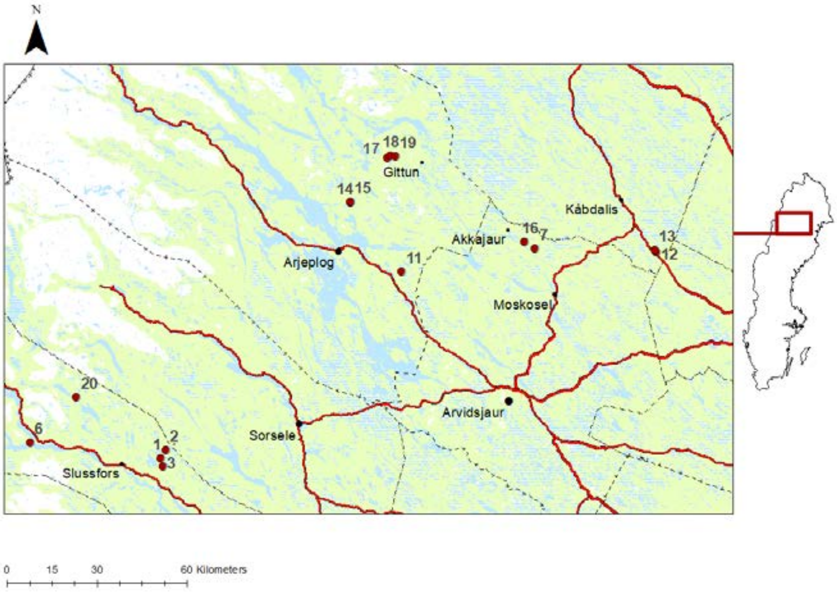

Figure 1. Location of the study sites. Adapted version of Översiktskartan vektor © Lantmäteriet.

Table 1. Average stand age and dominating tree species in the 15 sites.

Site	Stand age		Dominating tree species	
	Old (A)	Young (B)	Old (A)	Young (B)
1	139	19	*Picea abies*	*Picea abies*
2	106	31	*Picea abies*	*Picea abies*
3	223	20	*Picea abies*	*Picea abies*
6	161	25	*Picea abies*	*Picea abies*
7	172	23	*Pinus sylvestris*	*Pinus sylvestris*
11	142	28	*Picea abies*	*Pinus sylvestris*
12	165	22	*Pinus sylvestris*	*Pinus sylvestris*
13	158	28	*Pinus sylvestris*	*Pinus sylvestris*
14	203	15	*Pinus sylvestris*	*Pinus sylvestris*
15	210	14	*Pinus sylvestris*	*Pinus sylvestris*
16	136	22	*Pinus sylvestris*	*Pinus sylvestris*
17	133	17	*Pinus sylvestris*	*Pinus sylvestris*
18	165	14	*Pinus sylvestris*	*Pinus sylvestris*
19	122	54	*Pinus sylvestris*	*Pinus sylvestris*
20	138	44	*Picea abies*	*Picea abies*

2.3 Sample design

Four sample plots with 7-meter radius were placed in each stand, with a distance of 20 meter between plot centers (figure 2). The first plot was placed with 20 meters distance from the border to the sample plot center, perpendicular to the stand border. The starting point along the border between the two stands was chosen randomly. Coordinates of each sample plot were registered by GPS.

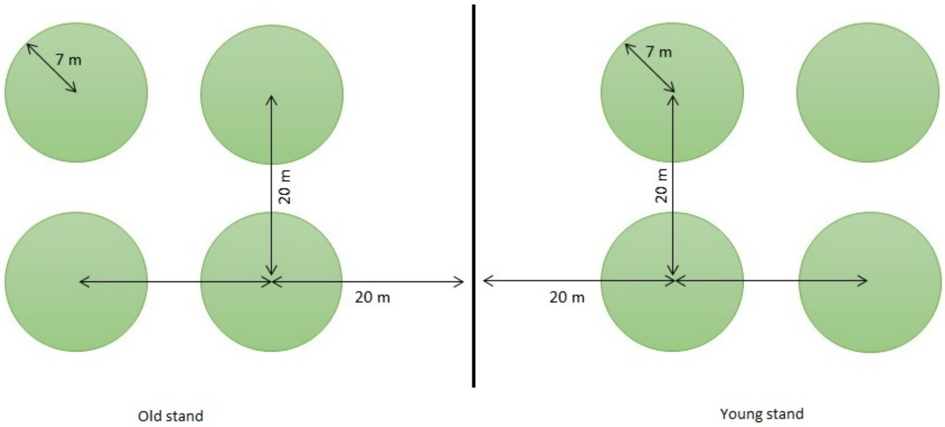

Figure 2. Overview of the sample plot design in the old-growth stand (A) and the younger stand (B).

2.4 Sampling and measurements

Methods for measuring living trees, dead wood and sampling of humus and soil was based on the Swedish National Forest Inventory (Riksskogstaxeringen, 2017):

2.4.1 Tree biomass and stand age

Trees with a diameter larger than 100 mm within the 7-meter sample plot, and trees with a diameter of 40-99 mm within 3.5 meters from the center were included. The diameter and height were measured and tree species was registered.

Hard dead wood (more than 90 % of the stem consists of hard wood), with a diameter over 100 mm and height or length of more than 1.3 m was registered. Diameter and height was measured.

Average age of the trees in the stands was assessed by taking stem cores at 1.3 m height from the three trees with largest diameter at each plot. In the younger stands only trees in the main tree layer were included when assessing stand age, and not remnant older trees from the previous stand.

2.4.2 Soil and humus

Sampling of mineral soil and humus was made from eight sample plots per stand. Two subsamples of soil was collected in each of the four sample plots, in north and south direction from the sample plot center (figure 3). If sampling was not suitable at these sites, the soil sample plot in question was moved 90º clockwise. Reasons for moving the sample plot could for example be that soil layers had been mixed during soil preparation. The two subsamples from each sample plot and soil layer were mixed together.

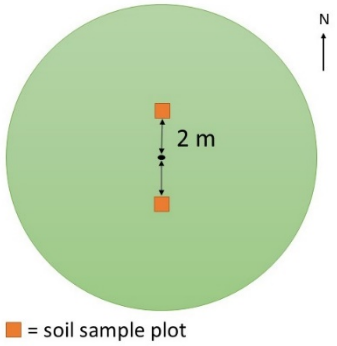

Figure 3. Overview of the soil sample plots in each 7-meter sample plot.

Mineral soil was sampled from 0-10 cm (M10) and for 10-20 cm (M20) depth, 375 ml per layer and soil sample site. Humus was sampled by using a soil corer (100 mm). Humus cores was taken from 1, 3, 6 or 9 sites at each soil sample plot, until 1.5 l material was collected, to follow the routines of the Swedish forest soil inventory (Riksskogstaxeringen, 2017). The humus samples were taken to a maximum of 30 cm depth.

2.5 Sample preparation and analysis

Soil and humus samples were dried at 40º C for 3-6 weeks, with regular control weighing until stable. Total dry weight was registered before the samples were sifted through a 2 mm sieve. The fraction of the mineral soil samples with particle size below 2 mm was placed on a rolling mill in glass jars overnight. Humus samples were also separated into two fractions, less than 2 mm and greater than 2 mm. The fraction less than 2 mm in size were grinded for 60 seconds in a mixer. Since humus is degraded organic material (Eriksson, et al., 2005), the organic material with a size greater than 2 mm from the humus samples were considered litter and not analyzed.

The milled samples were dried at 70º C overnight, before being placed in an airtight cooler to prevent the samples from absorbing moisture.

A certain weight of each sample of M10, M20 and humus were put into tin capsules before analysis; 25 mg, 50 mg and 5 mg, respectively, depending on expected carbon content. Analysis of carbon content was performed by an elemental analyzer-isotope ratio mass spectrometer (EA-IRMS).

2.6 Calculations

2.6.1 Carbon in living biomass and dead wood

Average age of the trees in the stand (weighted with basal area) was based on the age at 1.3 m height of the three trees with largest diameter per plot,

$$\mathrm{SA} = \sum \frac{BA}{A}$$

where SA is stand age, B is basal area and A is the age of the tree at 1.3 m height.

Marklunds biomass functions were used for calculating carbon content in living biomass, for all tree species in the study (*Pinus sylvestris, Picea abies, Betula spp., Salix Caprea* and *Populus tremula*) (Marklund, 1988 and appendix 1, table 6). For *P. sylvestris* and *P. abies* functions were available for stem wood, living and dead branches, stump and roots divided in fine and coarse roots. Coarse roots were calculated for trees with a diameter of more than 100 mm. All parts were summed up into total tree biomass. For calculations of *S. caprea* and *P. tremula* carbon content, the functions for birch were used but adjusted according to the density of the wood (Heureka SLU, 2016), *P. tremula* 400 kg/m^3 and *S. caprea* 490 kg/m^3 (Wikipedia, 2017; Träcentrum, n.d.). For *Betula spp.*, only biomass functions for stem wood, living and dead were branches available. Therefore, no belowground biomass calculations were made for broadleaves.

Dry weight of biomass per plot was calculated into carbon stock by using carbon content in percent (appendix 1, table 1) and scaled to tonnes per hectare.

Biomass of dead wood was calculated according to Näslunds smaller volume functions (Appendix 1 table 7, Näslund, 1941), before calculated into tonnes carbon per hectare via density of the dead wood (spruce 0.29, pine 0.31 and broadleaves 0.37 g/cm^3) (Skogsdata, 2008). The amount of carbon in dead wood was assumed to be 50 % (Russell, et al., 2015).

2.6.2 Carbon stock in humus and mineral soil

Bulk density (g/cm^3) was calculated based on equations from Nilsson & Lundin (2006):

$$\text{Humus BD} = \text{OC}/(-2.1278 + 0.1528 * \text{OC} + 0.2105 * \text{OC}^2$$

$$\text{Mineral soil BD} = 1.5463 * \text{EXP}(-0.3130 * \text{OC}^{0.5}) + 0.00207 * depth,$$

where OC is the organic carbon amount in percent of dry weight and depth is the sample depth in cm from the mineral soils upper limit (Nilsson & Lundin, 2006).

Carbon content from the analysis was calculated into tonnes carbon per hectare and soil layer, by multiplying it with bulk density and thickness of each soil layer. Carbon stocks in the mineral soil is not corrected for stoniness.

2.7 Statistics and analysis

Paired t-tests was used to compare mean of carbon stock the old and young stands in humus, mineral soil 0-10 cm (M10) and 10-20 cm (M20). Each layer were tested separately, and all three soil layers together. Paired t-test was also done on humus layer thickness and carbon content in percent. For the paired t-tests, H_0: $\mu = 0$ and $H_1 = \mu \neq 0$. n = 15. $\alpha = 0.05$ but was corrected using a sequentially rejective Bonferroni with a stepwise correction of significance level (Holm, 1979).

Relative reduction of carbon stock in percent between old and young stands was tested using one sample t-test. This was done for humus, M10 and M20, and all three soil layers together.

H_0: $\mu = 0$, $H_1 = \mu \neq 0$. $\alpha = 0.05$, also corrected according to Holm (1979). n = 15.

The statistical software used for the tests was Minitab 17 (Minitab, 2018).

3 Results

Soil carbon represent a large part of total ecosystem carbon stock, especially in the younger stands (figure 4). The variation in carbon stock between sites is high for all soil layers (figure 4 and 5).

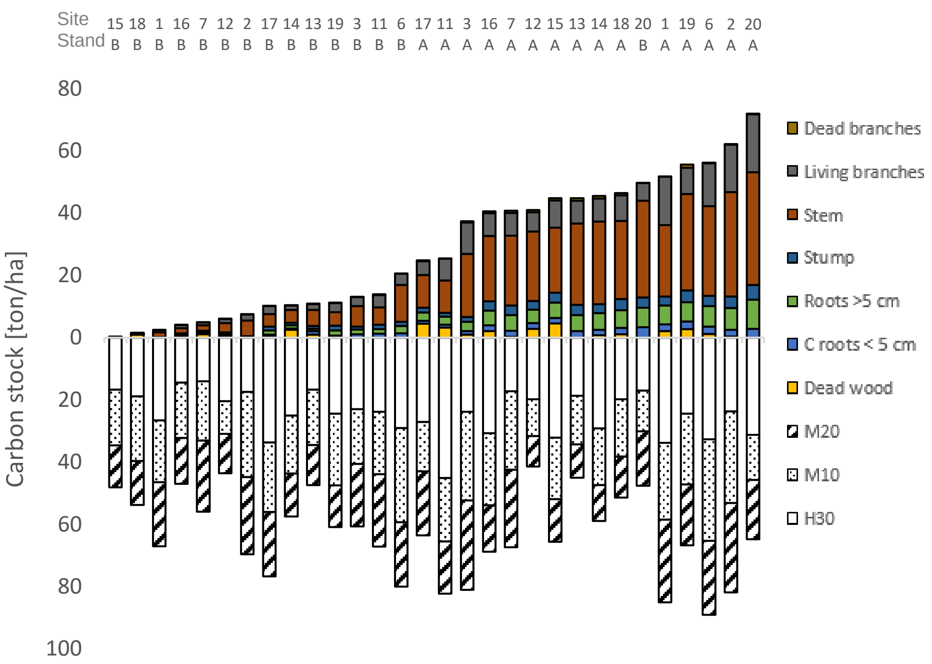

Figure 4. Carbon stock in tree biomass, humus (H30), mineral soil 0-10 cm (M10) and 10-20 cm (M20), at each stand and site, sorted by tree biomass. Old stands = A, young stands = B. Soil carbon stock is not corrected for stoniness.

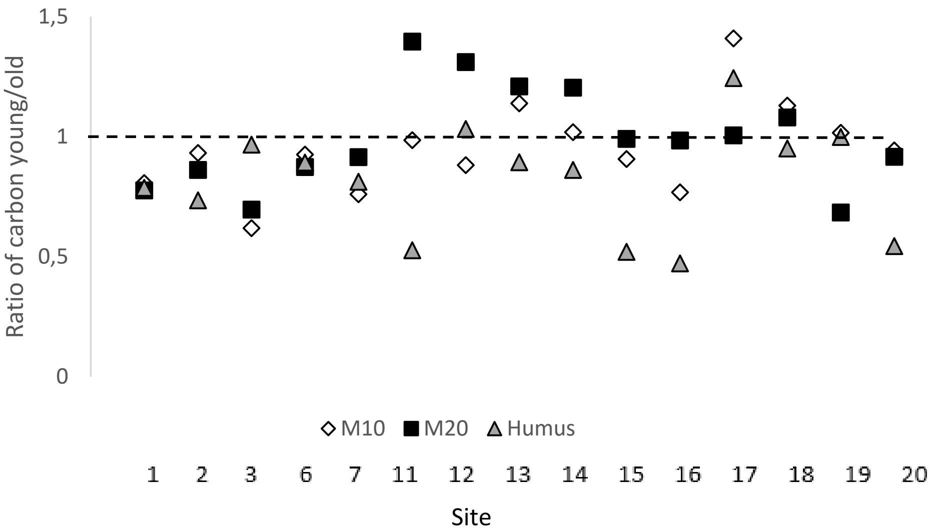

Figure 5. Ratio of tonne carbon per hectare in $\frac{young}{old}$ stands, in humus, mineral soil 0-10 cm (M10) and 0-20 cm (M20). 1: old = young, <1: old>young, >1: old<young.

Total soil carbon stock in the three soil layers humus, M10 and M20 together was significantly lower in young stands. The three soil layers tested separately shows different results. In the mineral soil, there was no significant difference between the stands in either M10 or M20 (table 3 and 4). The humus layer showed a significant decrease in carbon stock after harvesting (table 3 and 5), most evident in stand 11, 15, 16 and 20 (figure 5).

Table 3. Carbon stock (tonnes/ha) in the humus layer, mineral soil 0-10 cm (M10) and 10-20 cm (M20), total and separately for each layer in old and young stands at each site, and statistical significance of the difference in carbon stock (tonnes/ha) between old and young stands. H_0: A = B, H_1: A ≠ B. α in table, corrected according to Holm (1979). Carbon stock in the mineral soil is not corrected for stoniness.

Site	Total soil C A	Total soil C B	Humus A	Humus B	M10 A	M10 B	M20 A	M20 B
1	85.0	67.1	33.8	26.6	24.7	19.9	26.5	20.6
2	81.9	69.5	23.7	17.4	29.4	27.4	28.8	24.8
3	81.0	60.6	23.8	23.0	28.5	17.6	28.7	20.0
6	89.0	80.0	32.6	29.1	32.6	30.1	23.8	20.8
7	67.4	55.9	17.3	14.0	25.2	19.1	24.9	22.8
11	82.2	67.2	45.1	23.8	20.4	20.1	16.7	23.3
12	41.4	43.6	19.8	20.4	11.8	10.4	9.7	12.7
13	45.0	47.4	18.7	16.7	15.6	17.8	10.7	12.9
14	58.9	57.5	29.1	25.1	18.3	18.6	11.4	13.8
15	65.6	48.1	32.2	16.7	19.7	17.9	13.6	13.5
16	68.8	47.0	30.7	14.5	23.2	17.8	15.0	14.7
17	63.5	76.6	27.1	33.7	15.9	22.4	20.5	20.6
18	51.4	53.8	19.8	18.8	18.4	20.8	13.1	14.1
19	66.7	60.8	24.5	24.4	22.7	23.1	19.5	13.4
20	64.8	47.6	31.2	17.0	14.5	13.1	19.1	17.5
Average C stock (tonnes/ha)	67.5	58.8	27.3	21.4	21.4	19.7	18.8	17.7
p-value paired t-test	0.006		0.010		0.141		0.303	
Adjusted α	0.0125		0.017		0.025		0.05	

Total soil carbon stock (M10, M20 and humus) was reduced by 11.1 % after harvesting. Humus layer carbon stock decreased by 18.5 %, while the percentual decrease of carbon stock in M10 (5.1 %) and M20 (0.7 %) was not significant. (Table 4)

Table 4. Relative reduction of carbon stock after harvesting of the old-growth stands, in humus, mineral soil, total soil carbon stock, tree biomass and total ecosystem carbon stock. Standard deviation in parenthesis. H_0: $\mu = 0$, $H_1 = \mu \neq 0$. α in table, adjusted according to Holm (1979). n = 15.

	Reduction of C, %	p-value	Adjusted α
M20	0.7 (21.3)	0.901	0.05
M10	5.1 (18.8)	0.310	0.025
Soil total	11.1 (15.1)	0.013	0.017
Humus	18.5 (22.2)	0.006	0.0125

Thickness of the humus layer is significantly higher in old stands ($p = 0.041$, $\alpha = 0.05$), as well as the carbon content in percent ($p = 0.011$, $\alpha = 0.05$). Tree biomass did not show a significant effect on humus carbon stock (figure 6). It does however indicate an increase in humus carbon stock with increasing biomass, before it levels off when tree biomass carbon stock is around 30 tonnes/ha.

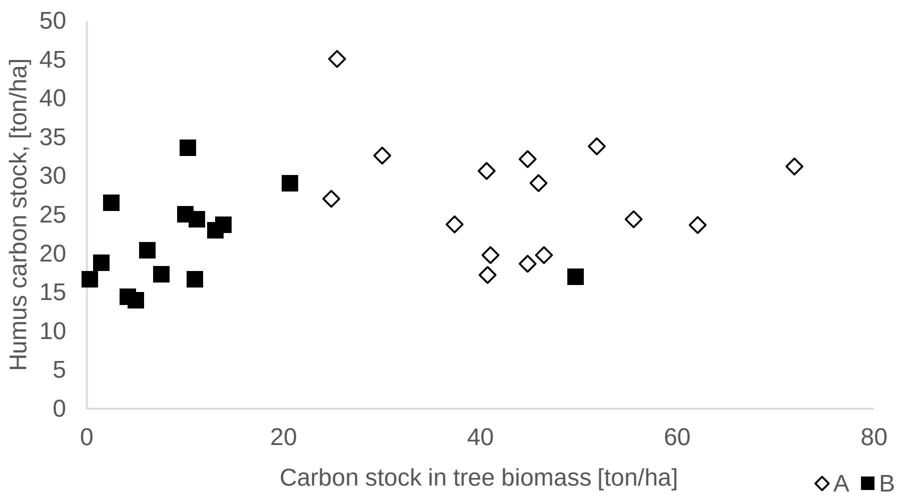

Figure 6. Carbon stock in the humus layer related to carbon stock in biomass, tonnes/ha.

4 Discussion

In this study, the harvesting effect on soil carbon stock is significant only in the humus layer. Mineral soil carbon stock is relatively stable after this one clear-cut. This is in line with soil carbon having a slow response (Leuschner, et al., 2014). Even if the mineral soil is not significantly affected by harvesting, the decrease in humus carbon stock is so strong that it causes a significant effect on total soil carbon stock. Humus carbon stock is not significantly affected by tree biomass, although indicating a positive relationship until it levels off. The humus layer is thinner in the younger stands, meaning that harvesting have likely affected the humus layer. Lack of litter fall during the clear-cut period might be one reason for the carbon stock difference. Litter is an important carbon source and can account for 70-80 % of soil carbon input (Liski, et al., 2002). The harvesting itself also affects the humus layer, but it can be rebuilt in a matter of decades after a new stand is established (Nave, et al., 2010; Ågren & Hyvönen, 2003; Pukkala, 2017). Peltoniemi, et al. (2004) showed that soil carbon stock decreased and reached a minimum 20 years after harvesting, before increasing again. The young stands in this study are between 14 and 54 years (at 1.3 m height). It is however not only the stand age that affects litter fall effect on soil carbon; a good regrowth of biomass is required. At some sites in this study tree regeneration was poor and biomass low. This was the case in two of the sites that showed most reduction in humus carbon stock (site 15 and 16). At the same time, site 1 and 18 also had poor tree regeneration and little biomass, but the humus carbon stock did not show much difference between young and old stands. This calls for a more detailed study of the organic layer and litter fall.

Carbon content in percent of dry mass in the humus layer is lower in the younger stands. This could be an effect of increased respiration after the disturbance (Hyvönen, et al., 2007; Jandl, et al., 2007). Parts of the carbon loss from the humus layer might also have been transported to the mineral soil (Achat, et al., 2015) through mixing of organic material into the mineral soil, and decomposition of harvest residues and roots of the harvested trees (Olsson, et al., 1996; Yanai, et al., 2000; Berggren Kleja, et al., 2008). Mineral soil carbon stock showed no significant difference after harvesting, which indicates that above ground disturbances has little effect on deeper soil layers, at least in this short-term perspective. If there were carbon losses from the mineral soil, it could have been balanced by carbon inputs from harvesting residues or mixing of organic material into the soil. This could explain the higher carbon stock in the mineral soil in some of the younger stands, also apparent in a study by Olsson, et al. (1996).

Similar results, with decreased carbon stock in organic layers but not the mineral soil, has previously been suggested by Olsson et. al (1996), Achat, et al. (2015) and Nave, et al. (2010). Johnson (1992) and Johnson & Curtis (2001) concludes no significant effect on soil carbon after harvesting. Long-term modelling studies have in contrast predicted decrease in soil carbon as an effect of forest management (Dean, et al., 2017; Harmon, et al., 1990; Liski, et al., 1998). Soil carbon can have a slow response (Leuschner, et al., 2014), and in empirical short-term studies like this one, the mineral soil carbon might not have responded to the disturbance yet. The young stands have only been harvested once and the soil carbon might respond differently after several rotation periods.

Even if carbon stocks show a significant decrease in the humus layer and not in the mineral soil, the variation between the stands was high. This makes it difficult to draw certain conclusions about the reasons of carbon stock decrease. Soil carbon stock can depend on other factors than harvesting, such as tree species (Berg & Meentemeyer, 2001; Vesterdal, et al., 2013; Stendahl, et al., 2010), soil texture (Olsson, et al., 1996) or history of forest fire (Liski, et al., 1998). These factors cannot be taken into account in this study since the stone and boulder content is not measured and can differ between sites, meaning that the soil carbon stock can be an over-estimation (Stendahl, et al., 2009). At the same time, the total carbon stock of the mineral soil is presumably underestimated since the mineral soil is sampled only to 20 cm depth. Even though most part of soil carbon should be in the top soil layers, Liski & Westman (1995) showed that 18-28 % of mineral soil C can be found below 1 m depth. Improvements to this study should therefore include measurements of stone and boulder content, sampling of deeper soil layers, and the previously mentioned litter fall. It would also be of interest to include the whole forest floor in the organic part of the soil, not just the humus layer. Further interesting studies could include sites with higher site productivity and comparison of old-growth forests with older, managed forests to find out if and when the humus layer is restored. Comparing carbon stocks in unmanaged forests to continuous cover forests could also be interesting. The maintained litter fall and less soil disturbance could preserve soil carbon better than in clear-cut forestry (Taylor, et al., 2008), while trees harvested would contribute to timber supply. To know more about how forest carbon stock influence atmospheric carbon levels, it would also be interesting to determine if the forests are carbon sinks, sources or neutral.

In this study, the sample plots in each stand are located quite near each other, with 20 meters between the plot centers. Four plots in each stands should give a good average value of carbon stock and tree biomass, but soil carbon can have a large spatial variability (Leuschner, et al., 2014). This could mean a risk of missed variation within the stands. The spatial variation is also a reason to study carbon stocks in a landscape perspective and not only at stand level.

The studied forests are located in an area with rather cold climate. Carbon balance acts differently in warmer climate (Berg, et al., 2007; Akselsson, et al., 2005; Ågren & Hyvönen, 2003), meaning that climate change affects carbon balance in forests and that the results. Warmer climate increase productivity and litter fall, and thus potential carbon input to the soil (Bergh, et al., 2003; Yanai, et al., 2000). Parts of the carbon from the increased litter production eventually enters deeper layers of the soil (Hyvönen, et al., 2007) but more carbon is also released to the atmosphere due to increased decomposition rates. (Stockman, et al., 2013; Ågren & Hyvönen, 2003). This climate change induced potential change in carbon balance is important to consider when planning future forest management. The climatic circumstances and low site productivity of this study area should also be taken into account regarding the transferability of the results to other regions.

The main focus regarding forests in climate change mitigation is usually the use of wood material replacing fossil products. Tree biomass carbon can be more effective than soil carbon in climate change mitigation, since it can be used in wood products (Lundmark, et al., 2014; Sathre & O'Connor, 2010). Younger forests grow faster and assimilate more carbon from the atmosphere, while old forests suffers a decline in productivity (Wardle, et al., 2004; Pukkala, 2017). It is argued that growth of young trees could compensate for potential losses of soil carbon due to harvesting (Egnell, et al., 2015). Use of wood products and substitution effects are important to consider in climate change mitigation, but it is not always applicable. At the sites in this study it can take a long time before carbon stock recovers after harvesting, given that the productivity is relatively low and regrowth after harvesting can be slow. Potential soil carbon losses, even a small percentual change, could affect atmospheric carbon levels (Ortiz, 2012). It would therefore be reasonable to leave forests of this type unmanaged to preserve soil carbon stock.

Conclusion

Old-growth forests store large amounts of carbon in biomass and soil, which makes them interesting in a climate change mitigation perspective. It is important to know how this carbon stock is affected by forest management. This study shows a decrease in soil carbon in old-growth boreal forests after harvesting. The difference is mainly driven by change in humus layer carbon stock, while carbon stock in mineral soil is less affected. The reduction in humus carbon stock causes a significant decrease in total soil carbon stock. The humus layer has not been restored at all sites after harvesting, possibly due to low site productivity. This indicates that it is better to leave forests with low site productivity unmanaged to preserve carbon stock. It is important to study in more detail what causes the decrease in humus layer carbon stock, and the reasons for the large variation between the sites. These forests have only been harvested once, a relatively short time ago, and carbon stocks might react differently after longer time of management. Soil carbon stock in old growth boreal forests is decreased after harvesting, but more studies are needed to understand causes of this decrease and to find the best way to manage or not manage old-growth boreal forests.

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Appendix 1. Functions used for calculating dry weight (living trees) and biomass (dead wood)

Table 1. Carbon content (%) in stem, branches and stump/roots for different tree species. *(Lind, 2001)*

	Stem	Branches	Stump & roots
Pinus sylvestris	48.8	51.2	48.8
Picea abies, broad-leaves	48.0	50.8	48.0

Marklunds biomass functions

Table 2. Marklund's biomass functions used to calculate dry weight of stem, living and dead branches, stump and roots of living species for different tree species. d = tree diameter at 1.3 m in cm, h = tree height in m. *(Marklund, 1988)*

	Function
Stem (with bark)	
T2	-2.6768 + 7.5939*d/(d+13) + 0.0151*h + 0.8799*ln(h)
G2	-2.1702 + 7.469*d/(d+14) + 0.0289*h + 0.6828*ln(h)
B2	-3.5686 + 8.2827*d/(d+7) + 0.0393*h + 0.5772*ln(h)
Living branches	
T14	-2.5413 + 13.3955*d/(d+10) + -1.1955*ln(h)
G12	-1.2063 + 10.9708*d/(d+13) + -0.0124*h + -0.4923*ln(h)
B11	-3.3633 + 10.2806*d/(d+10)
Dead branches	
T22	-5.8926 + 7.1270*d/(d+10) + -0.0465*h + 1.1060*ln(h)
G20	-4.6351 + 3.6518*d/(d+18) + 0.0493*h + 1.0129*ln(h)
B16	-6.6237 + 11.2872*d/(d+30) + -0.3081*h + 2.6821*ln(h)
Stump	
T28	-3.9657 + 11.0481*d/(d+15)
G26	-3.3645 + 10.6686*d/(d+17)
Roots > 5 cm	
T31	-6.3413 + 13.2902*d/(d+9)
G28	-6.3851 + 13.3703*d/(d+8)
Roots < 5 cm	
T34	-3.8375 + 8.8795*d/(d+10)
G31	-2.5706 + 7.6283*d/(d+12)

Näslunds smaller volume functions

Table 3. Näslund's smaller volume functions, used to calculate volume of dead wood on bark. All three functions are for northern Sweden. d = tree diameter in cm at 1.3 m height on bark, h = tree height in m. *(Näslund, 1941)*

	Function
Pinus sylvestris	$0.09314*d^2 + 0.03069*d^2h + 0.002818*dh^2$
Picea abies	$0.1202*d^2 + 0.01504*d^2h + 0.02341*dh^2 - 0.06590*h^2$
Betula spp	$0.03715*d^2 + 0.02892*d^2h + 0.004983*dh^2$