

Research paper

Piling up Norway spruce logging residues alters soil organic matter in clear cuts

Aino Smolander^{*}, Veikko Kitunen, Antti-Jussi Lindroos

Natural Resources Institute Finland, Latokartanonkaari 9, FI-00790 Helsinki, Finland

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ABSTRACT

The aim of the study was to assess the impacts of piling up Norway spruce logging residues on the dynamics of forest soil organic matter composition in the years following final felling and to discuss possible consequences for soil C and N cycling. We focused on the content of dissolved organic carbon (DOC), phenolic compounds, and terpenes in the humus layer to determine whether they controlled changes in C- and N-cycling, as residue piles have previously been observed to be a hot spot for N-cycling and losses. We monitored the dynamics for four years in a logging residue experiment that included plots with residue piles (40 kg/m²) and control plots without residues (0 kg/m²). We also sampled two other field experiments six years after additions of different residue amounts (0, 10, 40 kg/m²). Overall, logging residues strongly affected humus layer properties, with the temporal variation depending on the compound group. Within months logging residues increased the concentrations of K₂SO₄-extractable DOC and condensed tannins, and both effects endured for years. There was a sharp increase in the concentration of volatile monoterpenes due to residues, but it lasted only for a year. The increase in di- and triterpenes occurred later, showing that diterpenes and triterpenes were enriched in time in the humus layer. The amount of microbial biomass C and rates of C and net N mineralization and nitrification were positively correlated with DOC concentration. There were also some strong and positive correlations of microbial biomass C and N and C mineralization with higher terpenes, especially with triterpenes. While, in the residue treatment net N mineralization and nitrification rates were negatively correlated with monoterpenes, indicating their important role in controlling N-cycling in situations with N excess as well. Logging residues caused similar changes in the two other field experiments, but the responses were not always proportional to the residue amounts added. In conclusion, piling up Norway spruce logging residues changes the dynamics of forest soil organic matter composition for years and creates hotspots for soil C- and N-cycling. The overall result of the uneven residue distribution is a strong spatial variation in soil, evident from the beginning to several years.

1. Introduction

Forest soils store almost half of the organic C in terrestrial ecosystems, and the proportion of soil C stock of the ecosystem C stock is highest in boreal forests (Mayer et al., 2020). It is important to identify the soil conditions and forest management practices that best promote C accumulation to mitigate climate change. It is not only the amount of organic input entering the soil but also its composition that control the long-term changes in the sequestration of C into the soil (Tupek et al., 2019).

Final felling leads to a temporary decrease in forest soil C stock (Lindroos et al., 2022), but C accumulation in the soil depends on harvest intensity. In stem-only harvesting, all logging residues are left on

the site. In whole-tree harvesting, currently a relatively common harvesting method in Europe, a major part of logging residues is harvested in addition to tree stems to fulfill the demands for tree biomass for bioenergy production, although it is recommended that a portion be retained on the site (Titus et al., 2021). Consisting of fresh branches and stem tops, the residues differ from normal tree litter fall entering the soil surface: The foliage remains green and nutrient-rich - not senescent, as is the case with litter input due to biological annual cycle. The residues also contain large amounts of fine and coarse wooden debris and bark. Logging residues thus provide soil with relatively fast to very slowly degrading material. Residues are not evenly distributed over the harvest area in both harvesting intensities. The harvesting method is adapted so that logging residues are piled during the timber processing and only the

^{*} Corresponding author.

E-mail address: aino.smolander@luke.fi (A. Smolander).

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residues needed to improve the soil bearing capacity are left on the strip roads (Routa et al., 2013). The variation is large but residue piles cover approximately 20 % of the soil surface (Dr. Juha Laitila, personal communication, Ring et al., 2015). This results in a large portion of the soil surface receiving no residues.

Logging residues constitute a large C and nutrient stock (Clarke et al., 2021). In final fellings of Norway spruce, the amounts of logging residues were on average 20–60 Mg/ha, containing 150–300 kg/ha of N (Hakkila et al., 1998). However, as logging residues are not evenly distributed, the pulse of fresh organic matter per area unit is much higher under the residues. Foliage is degraded fastest, but there is a long lag for the coarse woody debris before it is a part of soil organic matter (Hyvönen et al., 2000; Palviainen et al., 2004). Logging residue piles also change soil physical conditions like temperature and moisture (Rosen and Lundmark-Thelin, 1987; Törmänen et al., 2018; Webster et al., 2021), which also control soil processes, such as decomposition, leaching and gas exchange.

In the first years after final felling, logging residue piles have been shown to stimulate soil N-cycling. Under coniferous residue piles, net N mineralization and especially nitrification are strongly enhanced (Adamczyk et al., 2016; Törmänen et al., 2018; Smolander et al., 2019), and N losses via leaching or gaseous emissions may increase for a few years (Rosen and Lundmark-Thelin, 1987; Wall, 2008; Ring et al., 2015; Lindroos et al., 2016; Clarke et al., 2017; Smolander et al., 2019; Törmänen et al., 2020). Logging residues from *Pinus radiata* plantations increased recalcitrant C pools in soil organic matter (Huang et al., 2011), but very little information is generally available about the response of soil organic matter composition to the residues.

Special groups of organic compounds belonging to plant secondary compounds may - according to results from laboratory experiments - strongly affect C- and N cycling (Schimel et al., 1998; Kraus et al., 2003; Smolander et al., 2012; Adamczyk, 2021). These groups of compounds occur in large concentrations in coniferous logging residues (Obst, 1998), and harvesting intensity affects both the quantity and quality of them entering the soil. Terpenes consist of thousands of different compounds, all of them hydrocarbons derived from a variety of isoprene units and classified as mono-, sesqui-, di-, tri-, tetra-, and polyterpenes. Condensed tannins are polyphenols that can form complexes with proteins and some other organic N-containing compounds. Some long-term changes in the abundance of tannins and terpenes in soil were observed due to logging residue harvest (Smolander et al., 2008, 2010, 2013; Adamczyk et al., 2016). However, the dynamics of how the logging residue input changes soil organic matter composition after being incorporated in the soil, is not understood.

Condensed tannins have been shown to affect N cycling processes in many ways, e.g., by affecting enzyme activities and forming complexes with organic N compounds (Smolander et al., 2012; Adamczyk et al., 2017). Recent studies also point to the important role they play in C sequestration in forest soils (Adamczyk et al., 2019; Adamczyk, 2021). Several volatile monoterpenes have been shown to affect soil C- and N-cycling and enzyme activities; the inhibition of nitrification is perhaps the best recognized impact (White, 1994; Paavola et al., 1998; Smolander et al., 2006; Uusitalo et al., 2008; Asensio et al., 2012; Adamczyk et al., 2015a). Di- or triterpenes, e.g., abietic acid and β -sitosterol, were also shown to have inhibitory potential in enzyme activities and to affect N-cycling processes and fungal/bacteria ratio (Adamczyk et al., 2011, 2013, 2015a). The exposure of soil to coniferous secretory resin, a mixture of mono- and higher terpenes or terpenoids (Back and Ekman, 2000), or to resin volatiles showed similar effects to pure terpenes (Lenoir et al., 1999; Uusitalo et al., 2008). Despite the knowledge gathered from laboratory experiments, the importance of terpenes and tannins in controlling soil processes in field conditions is unknown.

The most productive forest sites in Finland and Sweden are dominated by Norway spruce, and logging residue harvesting is mainly carried out after the final felling of such areas (Routa et al., 2013). Our aim was to increase understanding of how spruce logging residues affect the dynamics of soil organic matter composition in the following years after final felling, and to discuss possible consequences for soil C and N cycling. We focused on how residues affected the concentrations of dissolved organic carbon (DOC), water-soluble phenolic compounds, volatile monoterpenes, and higher terpenes in the humus layer organic matter. We monitored the dynamics for four years in one field experiment and related the concentration of the above-mentioned compounds to microbial biomass C and N, and rates of C and net N mineralization and nitrification (data partly from Smolander et al., 2019). Two other field experiments were also sampled six years after logging residue treatments to determine the significance of different residue amounts. We hypothesize that 1) soil organic matter composition under the logging residue piles differs from that in soil which did not receive residues, 2) logging residue causes temporal changes in soil organic matter composition, and 3) the abundance of the organic compounds studied and C- and N-cycling activities in soil are related.

2. Materials and methods

2.1. Study sites

All the study sites were logging residue experiments established on clear cuts in Southern Finland (Smolander et al., 2019). The Latokartano experiment was originally a Norway-spruce-dominated stand. The site represented the *Vaccinium myrtillus* type (MT), applying the Finnish forest type classification (Cajander, 1949). The soil texture was till (unsorted material), and the soil type was Cambic Podzol or Cambisol (IUSS Working Group WRB, 2006). The organic layer was mor, i.e., poorly decomposed 'raw humus'. The stand was clear cut in July 2012. A controlled field experiment using a randomized block design was established in June 2013, with two treatments corresponding to 0 and 40 kg/m² of fresh logging residues. Four replicate blocks of 2 m × 3 m were randomly placed in the area and then divided into two 3m² plots (2 m × 1.5 m). The adjacent spruce trees were cut, and fresh spruce branches and tops with green foliage were used to build up the residue piles on the one of the study plots. The other was left untouched to serve as a control treatment.

Two other field experiments, the Evo and Mysmalm experiments, were both on the *Vaccinium myrtillus* site type (MT). They were originally Norway spruce stands with sorted sand as the soil texture, and the soil type was Haplic Arenosol (Lindroos et al., 2016; IUSS Working Group WRB, 2006). The latter two experiments had three logging residue treatments (0, 10, and 40 kg/m² of fresh spruce logging residues) established six years ago, each on two replicate plots with a size of 1m². The 10 kg/m² treatment corresponds to the logging residue amount if the residues are distributed evenly on the soil surface, whereas 40 kg/m² or even more is common in modern harvesting technology leaving residues as piles on the soil surface.

2.2. Soil sampling

Samples were taken from the humus layer of both logging residue and control treatments. In Latokartano, sampling was done first twice a year, in the spring and fall, and later only in the fall. The first sampling was done just before the residue piles were built, and the sampling continued for four years. The first soil sampling (0 months) in both control plots (0 kg/m²) and residue plots (40 kg/m²) was undertaken in June 2013 just before logging residue piles were established. The next samplings were performed in October 2013 (4 months), May (11

months) and October 2014 (16 months), October 2015 (28 months), and September 2016 (39 months). The Evo and Mysmalm experiments were sampled only once, in June 2014, six years after the establishment.

Five soil cores were systematically taken with a steal auger (diam. 58 mm). The humus layer (F + H) was carefully separated, and the five replicates per plot were combined in gastight plastic bags into one composite humus layer sample. The composite samples were placed in a cold box, brought to the laboratory, and stored at 2–3 °C before analysis. In the 2013–2015 samplings in Latokartano, logging residue piles were lifted to take the samples. In 2016, the ground vegetation had grown through the piles, and the soil samples were taken through the piles. This was also the case in the two older experiments.

2.3. Soil analysis

Pretreatments were performed as previously described (Smolander et al., 2013, 2019). Soil samples were sieved (6 mm mesh size), dry matter content (105 °C overnight) and organic matter content (loss-on-ignition at 550 °C) were determined, and part of the fresh sieved samples dried at 40 °C and finely ground.

The concentration of total water-soluble phenolic compounds was determined from 0.5 g of the dried and ground sample using the spectrophotometric Folin Ciocalteu assay (Box, 1981), as previously described (Kanerva et al., 2008). The standards were prepared from commercial tannic acid (Merck). The concentration of condensed tannins was determined from 0.5 g of a dried and ground sample using a spectrophotometric, modified acid-butanol assay (proanthocyanidin assay) (Waterman and Mole, 1994), as described by Kanerva et al. (2008). The average standard curve made from condensed tannins extracted and purified from silver birch leaves and Norway spruce needles, as described by Kanerva et al. (2006), was used for calibration.

For monoterpene determination, the fresh humus layer samples were crushed mechanically in a mortar with liquid nitrogen the following day immediately after sieving, and the monoterpenes were immediately extracted essentially according to Asensio et al. (2008), modified by Smolander et al. (2013). Briefly, 3 g of humus material was extracted with 10 ml pentane spiked with an internal standard (chlorodecane) and shaken in a mechanical shaker for 1 h. The suspension was then centrifuged (15 min, 10,000 rpm, 5 °C). The supernatant was taken, and the extraction was repeated. The combined supernatant was stored in a freezer until gas chromatography–mass spectrometry (GC–MS) analysis.

Sesqui-, di-, and triterpenes in the humus layer samples were essentially determined as previously described (Smolander et al., 2013). The concentrations of sesqui-, di-, and triterpenes were determined from 1 g of dried and ground sample after acetone extraction by GC–MS.

The microbial biomass C and C mineralization rate was measured from the fresh sieved humus-layer samples, as previously described (Smolander et al., 2013). Briefly, the amount of C in the microbial biomass was measured with the fumigation-extraction method. The dissolved organic C (DOC) in the K₂SO₄ extracts from unfumigated soil was used to describe the humus layer DOC. The aerobic mineralization of C was estimated by measuring CO₂-C production with a gas chromatograph in an incubation experiment at a constant moisture (60 % WHC) and average temperature during summer months (14 °C, Törmänen et al., 2020). This was done twice during the incubation: About one and two weeks after the start of the incubation, the bottles were closed with a gas-tight septa, and the CO₂ evolved was measured after 24 h.

The soil parameters were calculated on a soil organic matter basis (mg or g/kg o.m.) to describe the quality of the organic matter.

2.4. Statistical analysis

A non-parametric Wilcoxon signed rank test was applied to analyze whether the differences in the mean values between logging residue treatments were significant in the Latokartano experiment. Pearson correlation coefficients were determined to study whether microbial biomass and activities were correlated with the organic matter composition. Data for microbial biomass N and net N mineralization and nitrification rates, determined from the same samples, were obtained from Smolander et al. (2019).

For the Evo and Mysmalm field experiments, where there was only one sampling (six years after the establishment of the residue piles), the non-parametric Kruskal-Wallis test was applied to determine significant differences between the residue amounts. Since these field experiments had only two replicate plots the combined data from both experiments was used for the analysis.

3. Results

3.1. Early-stage changes in soil organic matter

Logging residues strongly affected temporal variation and concentrations of organic compounds in the Latokartano experiment (Figs. 1–2).

Logging residues significantly increased the K₂SO₄-extractable DOC concentration in the humus layer in all except one sampling (Fig. 1). Residues increased the concentration of total water-soluble phenolic compounds in the first summer sampling, i.e., four months after the establishment of the piles. The concentration of condensed tannins was

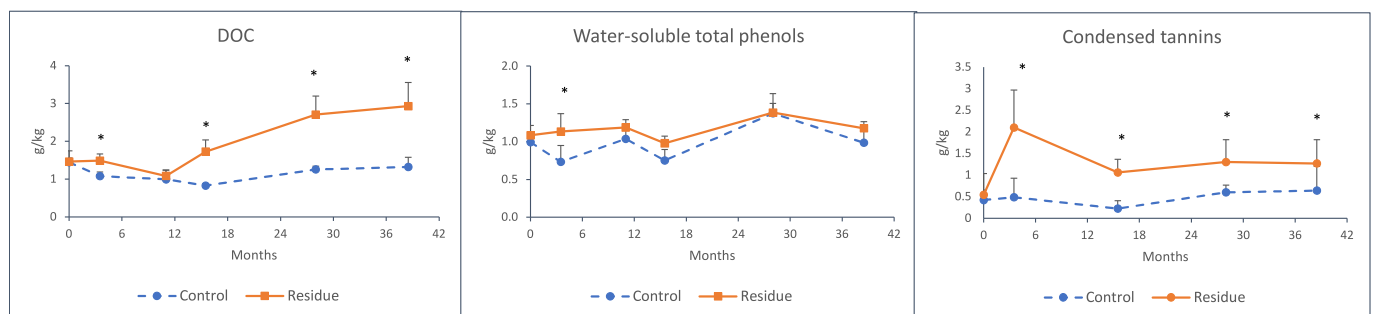


Fig. 1. Effects of Norway spruce logging residues on dissolved organic matter (DOC), water-soluble total phenols and condensed tannin concentrations in the humus layer organic matter in the Latokartano field experiment. The first soil sampling (0 months) in both control plots (0 kg/m²) and residue plots (40 kg/m²) was undertaken in June 2013 just before logging residue piles were established. The next samplings were performed in October 2013 (4 months), May (11 months) and October 2014 (16 months), October 2015 (28 months), and September 2016 (39 months). Mean (+standard deviation) for four replicate plots. Significant differences ($p < 0.068$, non-parametric Wilcoxon Signed Rank test) between control and residue treatments are marked with *.

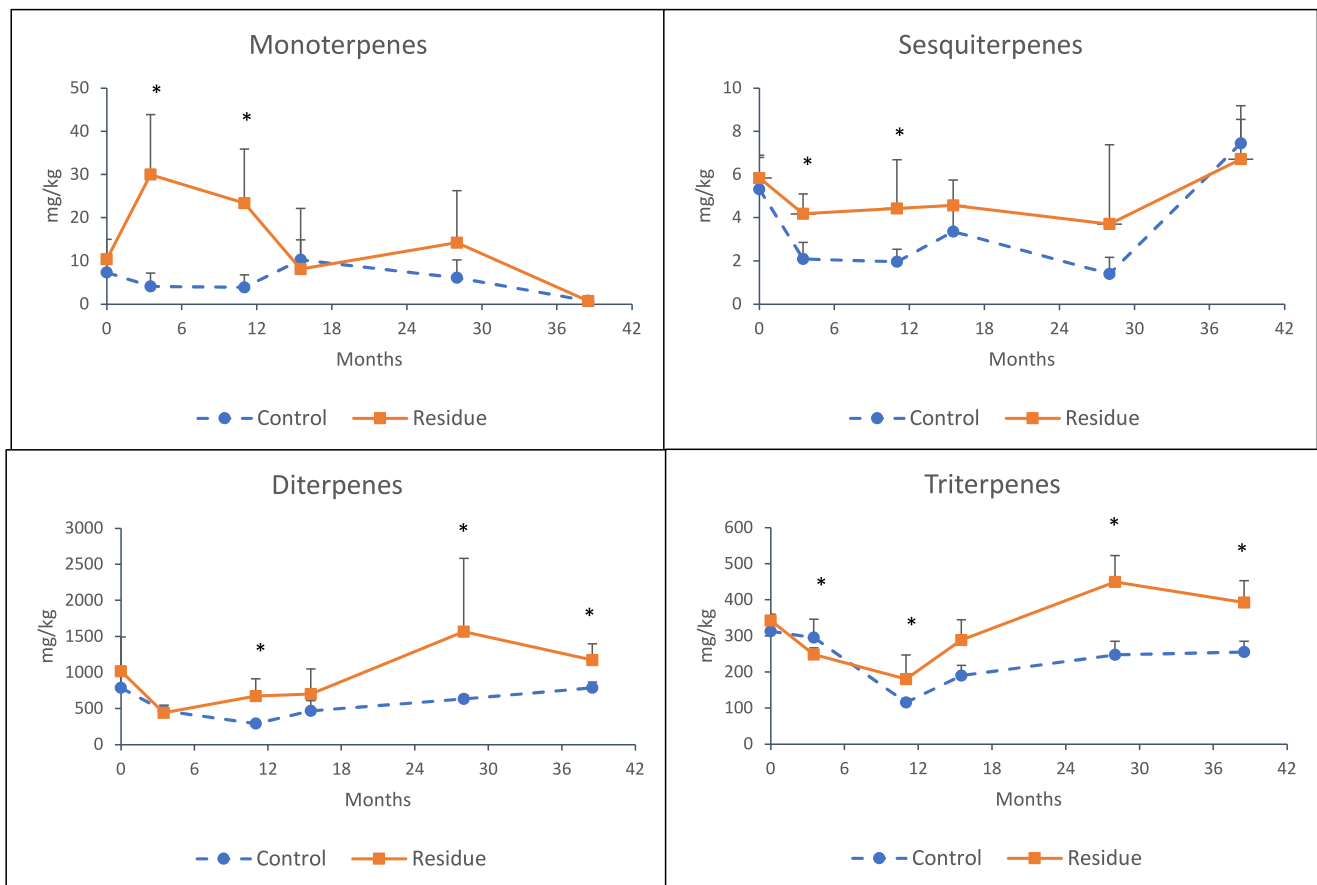


Fig. 2. Effects of Norway spruce logging residues on the concentrations of different terpenes in the humus layer organic matter in the Latokartano experiment. For explanations, see Fig. 1.

increased due to residues from the first sampling and stayed at a higher level thereafter.

Logging residues significantly increased the concentration of monoterpenes and sesquiterpenes in the first two samplings (Fig. 2). Logging residues increased the concentration of diterpenes and triterpenes later, after a year had elapsed from the establishment of the piles.

No major differences were observed in the distribution of different terpene species in each terpene group, i.e., the proportion changed little due to residue treatment or its different decay stages over time (Fig. 3). There were few exceptions regarding monoterpenes: Under residues, the proportion of camphene especially appeared to decrease in the last two samplings, while that of α - and β -pinene appeared to increase. Sesquiterpenes consisted of numerous different sesquiterpenes - for example, cubenene, longifolene, and cadinene, none of them dominant (results not shown). The most abundant diterpene was always dehydroabietic acid (Fig. 3). Triterpenes consisted mostly of sterols, β -sitosterol being the most abundant.

Overall logging residues did not affect the amount of C in the microbial biomass, although in the last sampling, it was lower under residues (Fig. 4). Residues generally stimulated the rate of C mineralization from the second year, but the difference was significant only in the last two years.

The amount of microbial biomass C, and C and net N mineralization and nitrification rates were all positively correlated with the concentrations of K_2SO_4 -extractable DOC (Table 1). Microbial biomass C and N, and C mineralization were also positively correlated with sesqui-, di-, and triterpenes, but the significant correlation was not always strong. When examining correlations only in the residue treatment, both net N mineralization and nitrification were positively correlated with DOC and negatively with monoterpenes (Table 1, Fig. 5). There were also a few strong and positive correlations of microbial biomass and C mineralization with higher terpenes, especially triterpenes (Table 1, Fig. 5).

3.2. Later-stage changes and effects of different amounts of logging residues

Logging residues increased the concentration of DOC; the 40 kg treatments differed significantly from 0 and 10 kg treatments (Fig. 6). Water-soluble total phenolic compounds were more abundant in the 40 kg treatment than in the control treatment. Logging residues did not significantly affect diterpenes, whereas triterpenes were more abundant in the 40 kg residue treatment than in the control. The amount of microbial biomass C did not differ between treatments (Fig. 6). C mineralization rates did not consistently follow the amounts of residues;



Fig. 3. Development of percentage distribution of different terpene species in mono-, di-, and triterpenes in the control and residue plots in the Lato-kartano experiment.

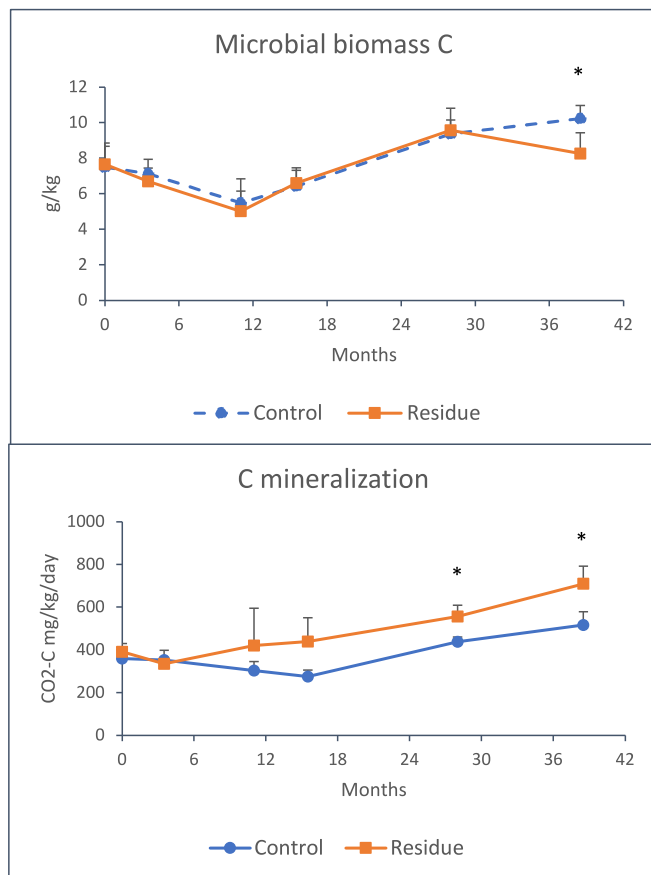


Fig. 4. Effects of Norway spruce logging residues on the amount of microbial biomass C and the rate of C mineralization in the humus layer organic matter in the Latokartano experiment. For explanations, see Fig. 1.

Table 1

Pearson correlation coefficients of soil microbial biomass, and the rates of C and net N mineralization and nitrification with the concentrations of organic compound groups. Correlation for whole Latokartano data and for residue and control plots separately.

Concentration	Microbial biomass C	Microbial biomass N ^a	C mineralization	Net N mineralization ^a	Net nitrification ^a
All plots (n = 48)					
DOC	0.43**	ns	0.75**	0.58**	0.64**
Total water-sol. phenols	0.41**	ns	0.39**	ns	ns
Condensed tannins (n = 40)	ns	ns	ns	ns	0.32*
Monoterpenes	ns	ns	ns	-0.38**	ns
Sesquiterpenes	0.33*	0.30*	0.48**	ns	ns
Diterpenes	0.42**	0.35*	0.52**	ns	ns
Triterpenes	0.50**	0.42**	0.60**	ns	ns
Terpenes total	0.46**	0.38**	0.57**	ns	ns
Control plots (n = 24)					
DOC	0.61**	0.54**	0.64**	0.53**	ns
Total water-sol. phenols	0.49*	ns	ns	ns	ns
Condensed tannins (n = 20)	ns	ns	ns	ns	ns
Monoterpenes	ns	ns	ns	ns	ns
Sesquiterpenes	0.48*	0.50*	0.46*	ns	ns
Diterpenes	0.60**	0.64**	0.52**	ns	ns
Triterpenes	0.46*	0.50*	0.43*	ns	ns
Terpenes total	0.62**	0.66**	0.54**	ns	ns
Residue plots (n = 24)					
DOC	0.68**	0.55**	0.73**	0.55**	0.57**
Total water-sol. phenols	0.50*	ns	ns	ns	ns
Condensed tannins (n = 20)	ns	ns	ns	ns	ns
Monoterpenes	ns	ns	ns	-0.62**	-0.52**
Sesquiterpenes	ns	ns	0.44*	ns	ns
Diterpenes	0.54**	0.51*	0.45*	ns	ns
Triterpenes	0.72**	0.69**	0.57**	ns	ns
Terpenes total	0.60**	0.56**	0.49**	ns	ns

Correlation significant at the 0.05 level marked with * and at 0.01 level marked with **.

^a Data from Smolander et al. (2019).

however, the 40 kg treatment was significantly higher than the control.

The distribution of different terpene species in all residue amounts appeared relatively similar (Fig. 7), although in Mysmal, the proportion of dehydroabietic acid, the most abundant diterpene, seemed higher under residues than the control, and that of pinifolic acid seemed lower. β -sitosterol was the most abundant triterpene.

4. Discussion

As hypothesized, humus layer concentrations of organic compounds under the logging residue piles differed largely from that in soil which did not receive residues, and the concentrations also changed over time. We can consider several explanations for these differences occurring between residue treatments. In control plots the growing ground vegetation took N and other nutrients up but these plots also continuously received new root exudates and litter from the vegetation. In the residue plots, the pile of spruce branches covered the ground vegetation and soil surface, and it took several years for ground vegetation to develop through the piles. Under the piles, a portion of needles and other fine material was soon deposited on the soil surface and faced different temperature and moisture conditions, while it took time for a portion of them to enter the soil surface because they were stuck to branches. The decomposition rate depends on the residue material: In another field experiment, over five years, the accumulated mass loss was about 60 % for spruce needles, 50 % for lateral branches covered with needles, 40 % for needleless lateral branches, and only 20 % for thick main branches (Smolander et al., 2008). In addition, the ground vegetation remaining under the piles started to degrade.

In accordance with our hypothesis, piling up logging residues caused temporal changes in organic matter composition, which were related to changes in C- and N-cycling activities. A simultaneous increase in the concentration of DOC (K_2SO_4 -extractable) and C mineralization was expected because on several forest sites, C mineralization has been shown to be correlated with water-extractable DOC (e.g., Sjöberg et al., 2003; Zhao et al., 2008; Smolander and Kitunen, 2011). The results

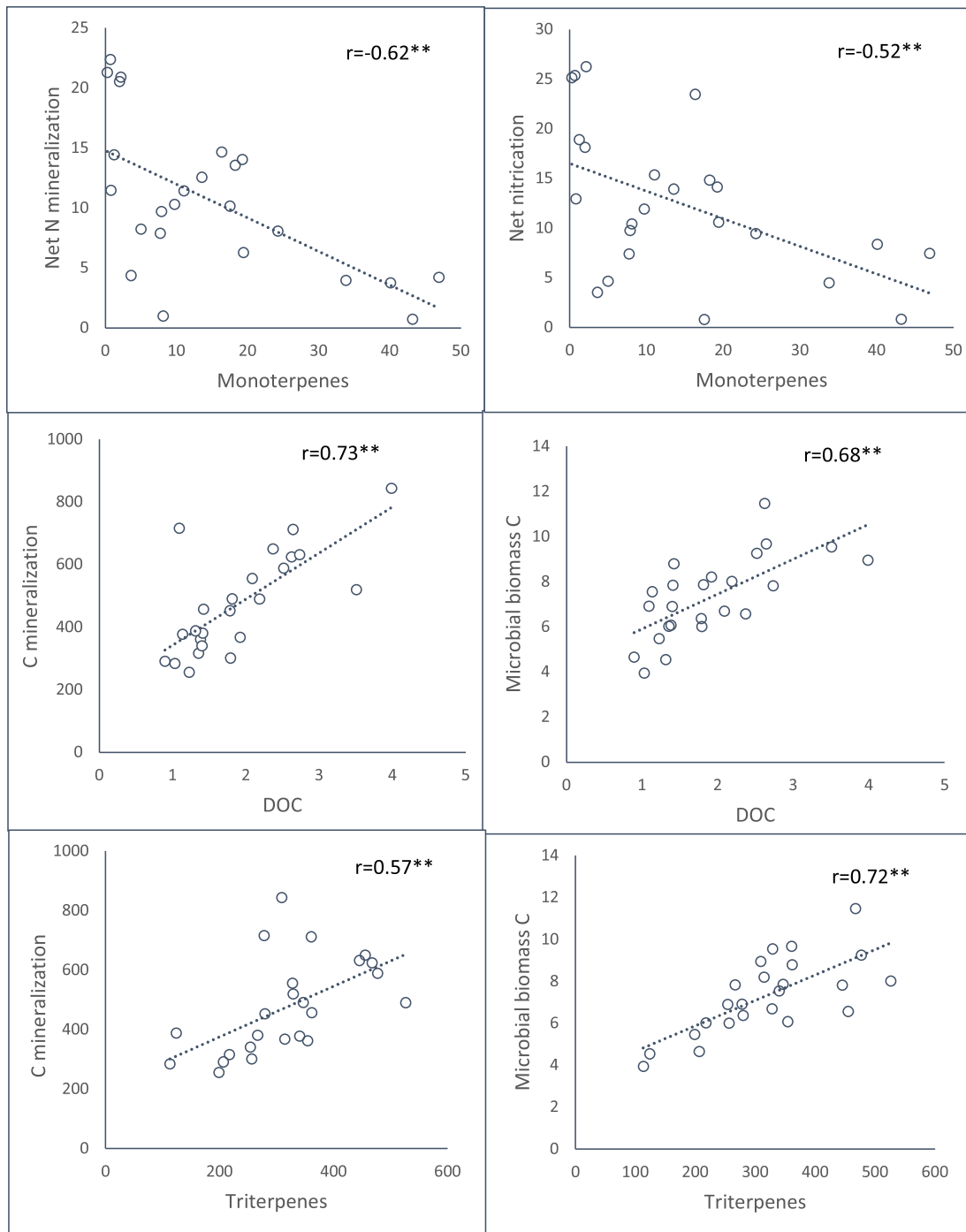


Fig. 5. Relationships of microbial biomass C, C mineralization, net N mineralization and nitrification with DOC, monoterpenes, and triterpenes in the Latokartano logging residue experiment. A correlation significant at the $p < 0.05$ level is marked with *, and at the 0.01 level with **.

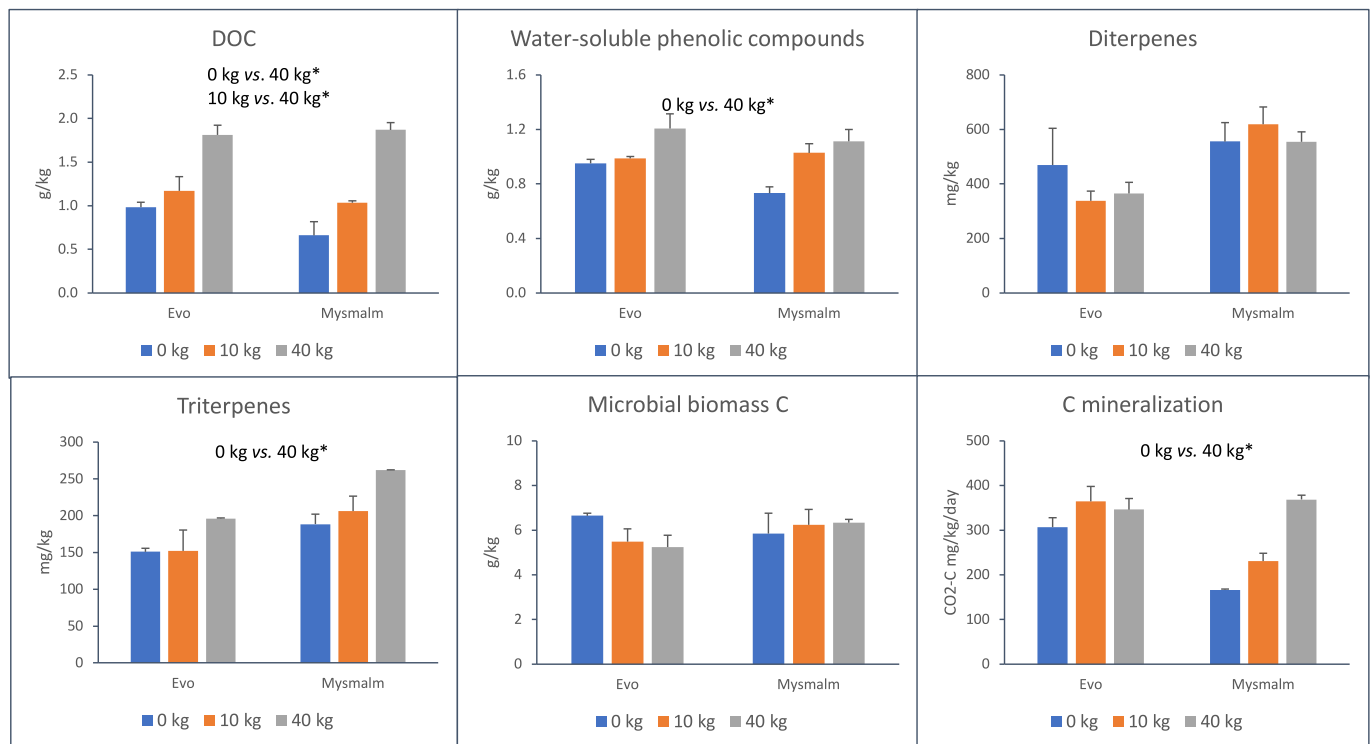


Fig. 6. Properties of the humus layer organic matter in the Evo and Mysmalm field experiments six years after the establishment of the residue treatments of 0, 10, and 40 kg/m². Mean (+standard deviation) for two replicate plots in both experiments. Significant differences between logging residue amounts in the combined data of both field experiments are marked in the figures ($p < 0.05$, the non-parametric Kruskal-Wallis test).

point to the close relationship between the activity of heterotrophic soil microbes and dissolved soil organic matter. The results also indicate a more active microbial population under residues, which is in accordance with the increased enzyme activity observed in the humus layer under residues (Adamczyk et al., 2015b). In the first months, easily degradable dissolved organic matter, including N-containing compounds and part of the phenolic compounds, is leached from the surface of spruce needles (Kiikkilä et al., 2012). Meanwhile, most terpenes are very poorly soluble, and the majority probably is incorporated in the soil much later, after the decaying residue starts to be part of the humus layer. An exception is monoterpenes and some sesquiterpenes due to their high volatility—they may reach the soil and soil microbial population mainly through the vapor phase and be absorbed by soil particles.

Logging residues strongly increased the concentration of condensed tannins in soil organic matter, in the first summer probably due to their solubility, and their concentration also remained higher over the years. Although the effect of condensed tannins is well recognized in laboratory experiments, the lack of correlation with N-cycling activities in this study and previously reported for mature stands (Smolander et al., 2012), points to the difficulty of demonstrating their real role in field conditions with various other interactions. The soil also simultaneously received a large pulse of extra N from the residues (Wall, 2008). Possibly with excess amounts of nitrogen, other factors become more important in controlling N-cycling activities. For total water-soluble phenolic compounds, an indirect relationship with N-cycling processes is suggested, their concentration describing the stage of degradation rather than any direct effect (Kanerva et al., 2008; Smolander et al., 2012).

In time, diterpenes and triterpenes were enriched in the humus layer of residue plots. Diterpenes consisted of the common resin acids of conifers, such as abietic, dehydroabietic, pimaric, and isopimaric acids (Ekman and Holmbom, 2000). Dehydroabietic acid was enriched in Scots pine needle litter during a 19-month decomposition experiment, meaning that it degraded at a lower rate than other resin acids (Kainulainen and Holopainen, 2002), but we observed no clear increase in

its proportion in the humus layer diterpenes. As in other studies of leaf/needle or soil material (Smolander et al., 2012), β -sitosterol was the most abundant triterpene.

Contrary to higher terpenes, the concentration of monoterpenes in organic matter first showed a sharp increase in residue plots but thereafter decreased, resulting in a very small concentration after four years. Monoterpenes were abundant in forest floor fluxes from Scots pine- and/or Norway spruce-dominated stands (Aaltonen et al., 2013; Mäki et al., 2019), and the importance of litter as a source of volatile organic compounds (VOC) has been emphasized (Peñuelas et al., 2014). In accordance with our results, in plant, soil, and emission studies, a decrease in monoterpene content has been shown from fresh conifer foliage to senescent foliage and further to decaying foliage (Wilt et al., 1993b; Ludley et al., 2009), and from litter to the humus layer and the mineral soil (White, 1991; Wilt et al., 1993a; Asensio et al., 2008; Kanerva et al., 2008; Smolander et al., 2013; Smolander and Kitunen, 2021). Accordingly, Haapanala et al. (2012) observed high levels of monoterpene emissions from logging residues after logging but the emissions decreased rapidly within a few months. The loss of monoterpenes from the logging residue probably occurred through gradual diffusion into the surrounding atmosphere (Wilt et al., 1993b) and into the humus layer, which thus acted as a sink for volatiles (Ramirez et al., 2010; Aaltonen et al., 2013). The compound list consisted of the same compounds as reported for spruce (Manninen et al., 2002). The small changes in relative concentrations of individual monoterpene compounds in time are explained by their different volatility and degradability by the soil microbial population (Wilt et al., 1993a; Smolander et al., 2006; Asensio et al., 2008; Ramirez et al., 2010).

The monoterpene concentration in the humus layer was higher under the residues than in the control but so were net N mineralization and net nitrification rates determined from the same humus layer samples (Smolander et al., 2019). This seems to contrast with the results from laboratory experiments in which exposure to individual monoterpenes and coniferous resin volatiles has inhibited net N mineralization and



Fig. 7. Percentage distribution of different terpene species in di- and triterpenes in 0, 10, and 40 kg/ha logging residue treatments in the Evo and Mysmalm field experiments.

nitrification (White, 1994; Ward et al., 1997; Paavolainen et al., 1998; Smolander et al., 2006; Uusitalo et al., 2008; Smolander et al., 2012; Adamczyk et al., 2015a). However, when focusing on the dynamics in the residue plots in more detail, we may get a different picture. The concentration of monoterpenes was already highest three months after the pile establishment, when the rates of net N mineralization and nitrification had yet to increase (Smolander et al., 2019). Later, when the concentration of monoterpenes decreased until it was negligible in the fourth summer, nitrification was very intense. Moreover, the negative correlation with nitrification in residue plots with large amounts of monoterpenes - and no correlation in control plots with low amounts of monoterpenes - indicates that inhibition may occur above some threshold values. In mature forest stands, a similar figure was obtained, with a loose negative correlation of monoterpenes in both the humus layer and soil atmosphere with net N mineralization (Smolander et al., 2012). Moreover, in a ponderosa stand, net nitrification in mineral soil was inversely correlated with monoterpene concentration in the litter layer (White, 1991).

Higher terpenes such as abietic acid (diterpene), colophony (a mixture of diterpenes), and β -sitosterol have also been shown to affect soil N-cycling in laboratory experiments (Adamczyk et al., 2011, 2013, 2015a). However, the effect seemed less dramatic than for monoterpenes, and we did not detect any linear relationship with N-cycling

activities. Positive correlations of higher terpenes, especially triterpenes, with microbial biomass and C mineralization accord with results previously obtained in mature spruce stands (Smolander et al., 2012).

Recent results suggest that condensed tannins may play a considerable role in the long-term stabilization of C into forest soils due to their interactions with fungi (Adamczyk et al., 2019; Adamczyk, 2021). The concentration of tannins in humus layer organic matter remained higher throughout the experiment. Logging residues may perhaps increase soil C stock, not only by increasing C input to soil as such but by being stabilized due to condensed tannins. Diterpenes and triterpenes were also enriched in soil organic matter and possibly also play a role in C stabilization. Under the residues, the simultaneous increase in nutrients, including N, DOC and these two groups of plant secondary compounds, may lead to interesting interactions for the soil microbial population, including both inhibitory and stimulatory effects.

In the Evo and Mysmalm field experiments six years after logging residue treatment, similar phenomena to those in the Latokartano experiment were observed, i.e., an increase in DOC and triterpenes and stimulation of C mineralization. Moreover, the composition of di- and triterpenes also resembled that in the Latokartano experiment. This indicates that the response of humus layer properties to spruce logging residues may be generalized to other similar sites. However, the responses were not always proportional to the residue amounts added, as

Webster et al. (2021) also concluded for soil respiration and nutrient concentrations in soil solutions.

In conclusion, piling up Norway spruce logging residues changes the dynamics of forest soil organic matter composition for years and creates hotspots for soil C- and N-cycling with elevated risk for C and N losses. The overall result of the uneven residue distribution is a strong spatial variation in soil, evident from the beginning to several years.

CRedit authorship contribution statement

Aino Smolander: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Veikko Kitunen:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Antti-Jussi Lindroos:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

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