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Pine, spruce and birch logging residues on a clear-cut increase base cations concentrations in soil percolation water along with nitrate concentrations increase

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ABSTRACT

This study's aim was to determine the effect of logging residue piles of Scots pine, Norway spruce and silver birch on the base cation concentrations in percolation water below the rooting depth in a clear-cut. The second aim was to determine if the concentrations of nitrate and dissolved organic carbon were related to the concentrations of base cations in percolation water. A Norway-spruce-dominated stand was clear-cut, and logging residues were taken from spruce, pine, and birch trees from the adjacent and similar forest stand to the clear-cut. Piles containing 40 kg m^{-2} of fresh branches were constructed on the soil surface, covering a 60 cm × 60 cm area, i.e. the whole surface area of the lysimeter that was first installed. A zero-tension lysimeter collected soil percolating water through a logging residue pile and soil profile to a depth of 40 cm below the surface of the ground. Percolation water was collected for chemical analysis at 4–6-week intervals during 2016–2017 and the concentrations of calcium, magnesium and potassium were determined. Logging residues of spruce, pine, and birch caused increased concentrations of base cations in percolation water, and the highest concentrations were associated with birch residues. Dissolved organic carbon concentrations were always low and were not correlated with base cations. Logging residues are located to restrict parts of a clear-cut area in large piles, and this causes elevated concentrations of nitrate below the piles: this study showed that nitrate concentrations were related to the elevated concentrations of base cations.

1. Introduction

Forest biomass is increasingly utilized as a renewable bioenergy source to replace fossil fuels, as well as for producing other materials like plastics and composites (CCFM, 2018). Due to the growing demand for forest-based biomass, harvesting methods have evolved, and whole-tree harvesting (WTH) is sometimes employed instead of the more traditional stem-only harvesting (SOH). In SOH, only the tree trunks are harvested, leaving nutrient-rich logging residues, such as branches and tree tops, on-site (Vanguelova et al., 2010). In contrast, WTH involves harvesting both the tree stems and a major part of logging residues, resulting in an increased removal of nutrients from the forest (Palviainen and Finér, 2012). Modern harvesting practices often involve creating logging residue piles on the forest floor when stems are mechanically limbed on-site. Additionally, logging residues may be spread across the forest floor to improve soil-bearing capacity and prevent deep wheel tracks caused by off-road machinery (Ring et al., 2019). As a result, logging residues can be unevenly distributed, covering between 10 and 60 % of the soil surface (Nurmi, 1994; Rosen and Lundmark-Thelin, 1987).

The extraction of forest biomass, along with other processes that deplete nutrients from the already nutrient-limited boreal forest soils can lead to a decline in soil fertility. Base cations, calcium (Ca), magnesium (Mg), and potassium (K), are among the main nutrients in the soil and they have multiple functions, such as decreasing the acidity of the soil and affecting soil buffering capacity through cation exchange. In general, base cation cycles are driven by weathering of minerals, cation exchange, and importantly soil leaching, thus many forest ecosystems show a net loss of base cations. The original sources of base cations for the forest ecosystems are mineral weathering and atmospheric deposition (Starr et al., 2014). On the other hand, base cations are lost from the forest ecosystems in leaching and cuttings. Piirainen (2002) showed that the input of base cations to soil percolation water increased after a clear-cut in the upper soil layer due to leaching from logging residues and the

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organic layer, although the leaching in deeper soil was minimal. In addition, Thiffault et al. (2011) found that forest biomass harvesting has greater negative impact on base cation pools in the forest floor than in the underlying mineral soil layers. Ca, Mg, and K are stored in different tree compartments, and the losses in cuttings depend on which tree compartments are harvested. According to Ukonmaanaho et al. (2008), about half of Ca (kg ha^{-1}) in above-ground tree compartments is stored in stemwood and bark, and another half in living and dead branches and needles in mature spruce stands in southern Finland. For K and Mg about one third is stored in stemwood and bark and two thirds stored in living and dead branches and needles (Ukonmaanaho et al., 2008). When only stemwood and bark are harvested in final cutting, significant amounts of base cations are left on the forest floor in logging residues. However, after a final cut, fresh logging residue piles cover a restricted part of the soil surface of the clear-cut area due to modern harvesting techniques (Rosen and Lundmark-Thelin, 1987; Ring et al., 2015; Lindroos et al., 2016) forming large accumulations of nutrient-rich material on the forest floor.

The significance of clear-cutting and logging residues on leaching from forest ecosystems have been studied for nitrogen (N) (e.g. Rosen and Lundmark-Thelin, 1987; Mann et al., 1988; Kubin, 1998; Piirainen et al., 2002; Wall, 2008; Ring et al., 2015; Lindroos et al., 2016; Törmänen et al., 2020) and for base cations (e.g. Piirainen, 2002; Ring et al., 2015; Lindroos et al., 2016). Elevated dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) fluxes have been reported after harvest with clear-cut due to chipper debris in the upland sites in Ontario, Canada (Morris, 2009). Soil below logging residue piles has been found to be 'hot spots' for nutrient cycling on a clear-cut and increase nutrient concentrations below the piles (Lindroos et al., 2016; Smolander et al., 2019; Törmänen et al., 2020). Nitrate (NO_3-N) concentrations in percolation water increased strongly below Norway spruce logging residue piles soon after clear-cutting (Lindroos et al., 2016; Törmänen et al., 2020), and a similar phenomenon was also reported for Scots pine and silver birch residues (Törmänen et al., 2020). Lindroos et al. (2016) found base cation concentrations to increase below the logging residue piles of spruce. Unlike spruce and pine, birch is known to increase the base cation concentrations in soil and soil water in mature stands (e.g. Lindroos et al., 2011).

When leaching of nutrients is studied, an important factor to be considered is the ionic balance between cations and anions (e.g. Forsius et al., 1995). Increased concentrations of organic anions (Mosello et al., 2008; Lindroos et al., 2018) and NO_3 anion (Lindroos et al., 2016) may play a significant role in the presence of cations in rain and soil waters. The strongly increased concentrations of NO_3-N in soil percolate water, discussed above, raises a question about how this affects the leaching and presence of base cations in percolation water. Different tree species may also have a variable effect on soil and percolation water composition, and it has been shown in many studies that birch is accompanied by high pH and base saturation in the soil and high base cation concentrations in percolation water (e.g. Priha and Smolander, 1999; Lindroos et al., 2011; Smolander and Kitunen, 2011). The activities of carbon (C) and N cycling processes are often higher in birch soils than in coniferous soils (reviews by Augusto et al., 2015; Huuskonen et al., 2021). The decomposition rate of woody, and especially the foliage material of different tree species also differs (Palviainen et al., 2004). Yamada et al. (2015) found rapid decomposition of logging residues of Japanese cedar in the organic layer of forest soil and removal of K ions from the organic layer to the surface soil. There is still a lack of knowledge about the effects of logging residues of different tree species on base cation concentrations in soil percolation water in conditions prevailing in boreal forest soil. This study site has been intensively investigated in earlier studies (Törmänen et al., 2018; Törmänen et al., 2020; Törmänen and Smolander, 2022). The combination of the current study to earlier studies provide possibility to investigate complex relationships between different soil processes affecting nutrient status of soil percolation water. As a summary, higher base cation content in percolation water mostly signals nutrient losses (leaching), which can be harmful to soil fertility and plant nutrition as well as soil buffer capacity against acidification. It rarely indicates a beneficial nutrient return especially on clear cut areas where trees are harvested and understorey vegetation cover area is decreased, leading to smaller nutrient uptake by the vegetation.

The aim of this study was to determine the effect of logging residue piles of Scots pine, Norway spruce and silver birch on the base cation concentrations in percolation water below the rooting depth in a clear-cut. The second aim was to determine if the concentrations of NO_3-N and DOC were related to the concentrations of base cations in percolation water. The study was performed on the same logging residue experiment as an earlier study by Törmänen et al. (2020), which showed the effect of logging residues on soil percolation water N and DOC. We hypothesised that the logging residues of all three tree species would increase the base cation concentrations in percolation water, but the birch residues would favour this more than the coniferous species. We also hypothesised that a driving force for the increased concentrations of base cations would be the anions, NO_3- N, and organic anion (DOC). NO_3-N especially has previously been shown to leach at elevated levels below the piles (Lindroos et al., 2016; Törmänen et al., 2020).

2. Material and methods

The study was performed on a logging residue experiment on a clear-cut in southern Finland (lat. 60°N, long. 26°E). The annual precipitation of the area is 618 mm and the annual mean temperature is 4.6 °C. The effective temperature sum is 1300 °C (Rinne et al., 2017). The study site and experimental setup for the determination of chemical composition in percolation water below the logging residues of Norway spruce, Scots pine and silver birch have previously been described in detail by Törmänen et al. (2018, 2020). Briefly, a Norway-spruce-dominated stand was clear-cut in the autumn of 2014. A flat area was selected for the study area, and the soil was composed of sandy material and classified to be Haplic Arenosol according to IUSS Working Group WRB (2006). The site was classified as a mesic heath forest site type (*Vaccinium myrtillus* type, Cajander, 1949). In autumn 2016 without effect of logging residues, the average soil pH in the organic layer was 4.23. The average organic matter content (%) was 35.0, and C to N ratio 28.7 (Törmänen et al., 2018). For mineral soil layers soil pH, organic matter content (%) and C to N ratio was 4.33, 4.9, and 23.6, respectively (Törmänen et al., 2018). To study the base cation concentrations in percolation water below the rooting zone, an experimental setup with zero-tension lysimeters ($n = 12$) was established in the study area in the autumn of 2015. The lysimeters were constructed based on the lysimeter design described by Lindroos et al. (2016), and this zero-tension lysimeter type was applied in the study area as described in detail by Törmänen et al. (2020). Study site was well-suitable for all selected tree species used in our study. Logging residues were taken from spruce, pine and birch trees from the adjacent and similar forest stand to the clear-cut. All logging residues selected by hand to the piles consisted only of branches, with needles and leaves, taken from the approximately 80 years old trees. No small trees were included to the study material hence logging residues were comparable in size and corresponded to the logging residues left on practical harvesting. In 2016, the average C to N ratios for the logging residues of needles or leaves of pine, spruce and birch were 22.4, 31.5, and 18.5, respectively. The corresponding ratios for the branches of pine, spruce and birch were 58.9, 58.1, and 48.4 (Törmänen and Smolander, 2022). Piles containing 40 kg m^{-2} of fresh logging residues (Table 1, Supplementary material) were constructed on the soil surface, covering a 60 cm × 60 cm area, i.e. the whole surface area of the lysimeter that was first installed below the soil surface. Zero-tension soil column lysimeters with one outlet for water were installed parallel, with 0.5–1-m distance between each lysimeter and 0.05 m to the side of a soil excavation pit (depth 1.5 m). First, the soil was carefully removed from the pit and each soil horizon kept separated. Then, lysimeters i.e. wooden boxes (60 cm × 60 cm × 50 cm (height)), with the inside protected by a polyethylene cover, were installed at each excavated point. The soil was returned inside the lysimeters in the original horizontal order to mimic the actual soil conditions as described by Törmänen et al. (2020). Other logging residues were first removed from the study area. For each tree species, there were three replicate logging residue piles and a control without logging residues with three replicates. Control treatment correspond to the WTH method in operational forestry and size of logging residue piles (40 kg/m^2) i.e., the amount of logging residues left on top of the lysimeter per surface area correspond to the amount of logging residues left on piles in operational forestry.

Percolation water was collected for chemical analysis at 4–6 -week intervals in 7 samplings in 2016 and 2017 between March and November, i.e. when there was no snow in the area. In the laboratory, the samples were filtered (0.45 μm), and the concentrations of Ca, Mg, and K were determined by the inductively coupled plasma atomic emission spectrophotometer (iCAP 6500 Duo analyzer, Thermo Scientific, Cambridge, United Kingdom) according to the SFS-EN ISO 11885 standard (accredited method). Concentrations of NO_3-N and DOC in the same percolation water samples have been shared by Törmänen et al. (2020), and the relationships between NO_3-N or DOC here with base cations were determined.

Mean values and standard deviations were computed for each sampling. Since the data was not normally distributed, non-parametric statistical methods were used. Differences between concentrations between tree species and the control were studied by Friedman's non-parametric ANOVA and subsequent pairwise testing. In addition, the significance of differences between the pine treatment and control were studied for 2017 separately using the non-parametric sign -test for the Ca and Mg concentrations because it did not show statistical difference when comparing the whole dataset. Relationships between the concentrations of base cations, NO_3-N and DOC in percolation water were studied using correlation and regression analysis.

3. Results

The Ca concentrations in percolation water below the pine, spruce, or birch logging residues were close to those of the control treatment (no logging residues) in 2016 but started to increase in the final samplings (Fig. 1). During the whole study period (2016–2017), the Ca concentrations were significantly higher under birch and spruce residues than in the control (Fig. 1). The Ca concentrations were also significantly higher under pine residues than in the control in 2017 ($p < 0.05$, sign test). The Ca concentrations were significantly higher under birch residues than under pine residues between 2016 and 2017 (Fig. 1).

The Mg concentrations started to increase under logging residues in the final samplings in 2016 (Fig. 2). Throughout the study period (2016–2017), the Mg concentrations were significantly higher under birch and spruce residues than in the control (Fig. 2). The Mg concentrations were also significantly higher under pine residues than in the control in 2017 ($p < 0.05$, sign test). The Mg concentrations were significantly higher under birch residues than under pine residues between 2016 and 2017 (Fig. 2).

The K concentrations increased under logging residues in the final samplings in 2016 (Fig. 3). The K concentrations were significantly higher under logging residues of all tree species than those in the control for the whole study period (Fig. 3). There were no significant differences between the tree species in K concentrations.

The timing of the increased concentrations of base cations below the logging residues was very similar for the pine and birch treatments during 2016 and 2017. This was indicated by the significant positive correlations between the Ca, Mg, and K concentrations between the pine and birch treatments (Fig. 4). The timing of the increased concentrations for the spruce treatment differed from those of pine and birch, and no significant correlations were found between the base cation concentrations between spruce and pine/birch. All correlations and significances are given in Table 2 (Supplementary materials).

The combined data from all the treatments indicated that NO_3-N concentration in percolation water was positively and highly significantly correlated with the equivalent based sum of Ca, Mg and K (Fig. 5). On the other hand, DOC concentration was not correlated with the sum of the base cations (Fig. 6).

4. Discussion

It has been shown that the leaching of base cations increases after clear-cutting (SOH, i.e. logging residues left on the site) of spruce-dominated stands (Piirainen, 2002). The distribution of logging residue piles on the forest floor after clear-cutting has proved a key factor affecting the concentrations of base cations from spruce-dominated stands. Large logging residue piles of spruce branches and needles caused elevated concentrations of Ca, Mg, and K in percolation water below the piles during the second and third year after cutting in a tree-year-study (Lindroos et al., 2016). A similar effect of logging residues of spruce was found in our current study and the same effect was also associated with pine and birch residues. However, the timing for the elevated concentrations was similar for the pine and birch residues, while it differed for the spruce residues. Base cation concentrations started to increase after clear-cutting, and the highest values were found

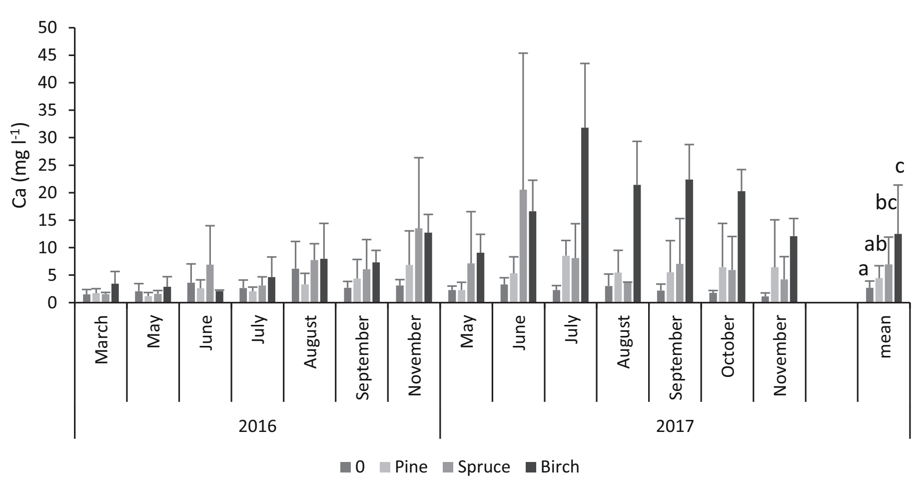

Fig. 1. Ca concentration (mean, S.D., $n = 3$ for each sampling occasion) in percolation water at a depth of 40 cm in the mineral soil below the pine, spruce and birch logging residues (40 kg m^{-2}) and no logging residues (0 kg m^{-2}). Mean and S.D. are indicated for the whole study period, and different letters indicate the significant differences at $p < 0.05$ (Friedman non-parametric ANOVA with pairwise testing).

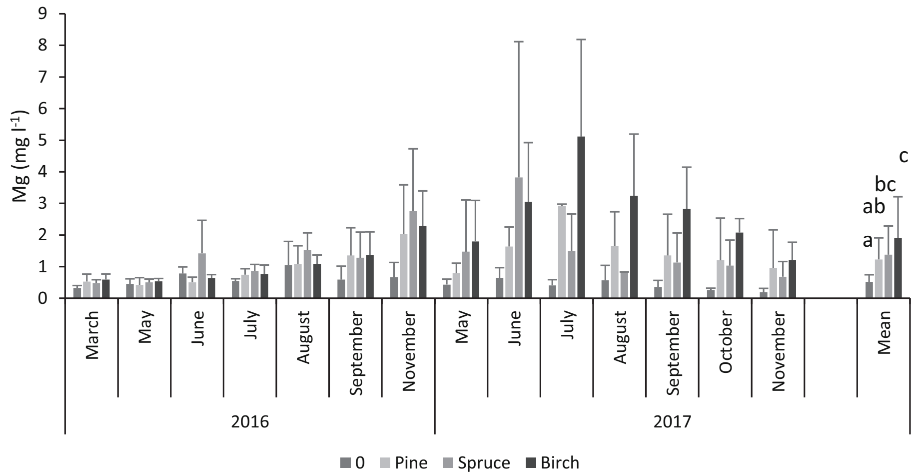

Fig. 2. Mg concentration (mean, S.D., n = 3 for each sampling occasion) in percolation water at a depth of 40 cm in the mineral soil below the pine, spruce and birch logging residues (40 kg m^{-2}) and no logging residues (0 kg m^{-2}). Mean and S.D. are indicated for the whole study period, and different letters indicate the significant differences at $p < 0.05$ (Friedman non-parametric ANOVA with pairwise testing).

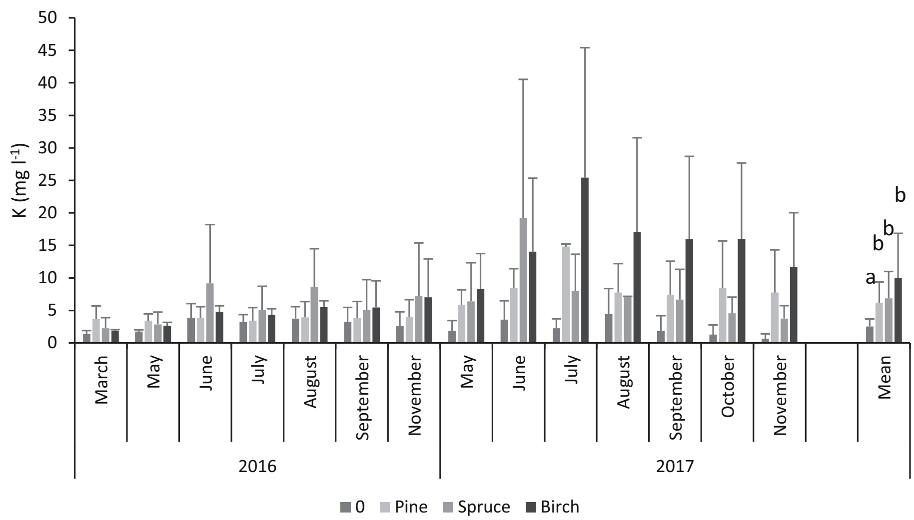

Fig. 3. K concentration (mean, S.D., n = 3 for each sampling occasion) in percolation water at a depth of 40 cm in the mineral soil below the pine, spruce and birch logging residues (40 kg m^{-2}) and no logging residues (0 kg m^{-2}). Mean and S.D. are indicated for the whole study period, and different letters indicate the significant differences at $p < 0.05$ (Friedman non-parametric ANOVA with pairwise testing).

in the second year in this two-year study. In control plots, ground vegetation took up nutrients, but how this affected the concentrations in percolation water is unknown.

In current study, birch residues caused the highest base cation concentrations in percolation water. Logging residues consist of green foliage and wood compartments. In this two-year study, the chemical effect of different tree species on soil originates predominantly from foliage decomposition, because the wood compartments have a considerably slower decomposition rate and lower nutrient concentrations as reported in earlier studies (Palviainen et al., 2004; Smolander et al., 2008). According to Smolander et al. (2008), the mass loss of spruce needles was above 30 % in the first two years, while that of the main branches was about 10 %. The decomposition rate, particularly at the beginning, also depends on tree species (Prescott et al., 2000). In general, during the first decomposition stages higher nutrient concentrations and more easily leached and decomposable water-soluble compounds make it easier for leaf litter to decompose and release nutrients than is the case for needle litter with surface layer waxes and a high concentration of lignin and other polyphenolic compounds (Johansson, 1995; Prescott et al., 2000; Kiikkilä et al., 2012, 2013). Palviainen et al. (2004) showed that the mass of decomposing foliage after two years decreased in the order birch > pine > spruce; for branches, the mass loss of pine was largest, but the differences between tree species were very small. Changes in soil processes due to differences in residue quality affect the composition of soil percolation water, but we cannot distinguish the direct and indirect effects of the residue piles. In addition to the chemical composition of logging residues, soil processes are affected by the changes in soil physical conditions, moisture, and temperature caused by the residues (Törmänen et al., 2018).

The ionic balance between the cations and anions has proved a key regulating factor in water systems (e.g. Forsius et al., 1995; Mosello et al., 2008). In the soil waters of boreal forests, dissolved organic anions play an important role in fulfilling the anion deficit (e.g. Lindroos et al., 1995, 2018). The NO_3^- is known to be a very mobile anion in soil waters of boreal forest soils and clear-cutting may promote an increase in net nitrification rate in the soil and subsequently the NO_3-N concentrations in the soil and percolation water (Smolander et al., 2001). Plant-available N is a limiting factor for the forest growth in boreal upland forests, and net nitrification in undisturbed soils is low (Högberg et al., 2017). NO_3-N leaching is therefore usually minimal from the boreal

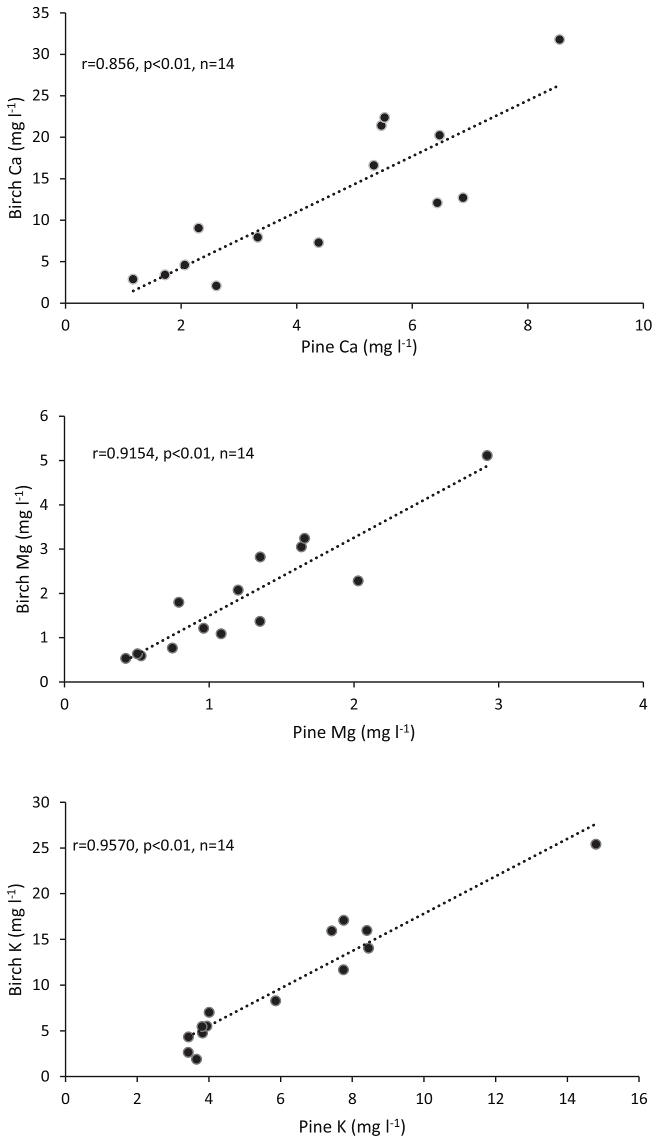

Fig. 4. Relationship between the Ca, Mg and K concentrations in percolation water between treatments with pine and birch logging residues.

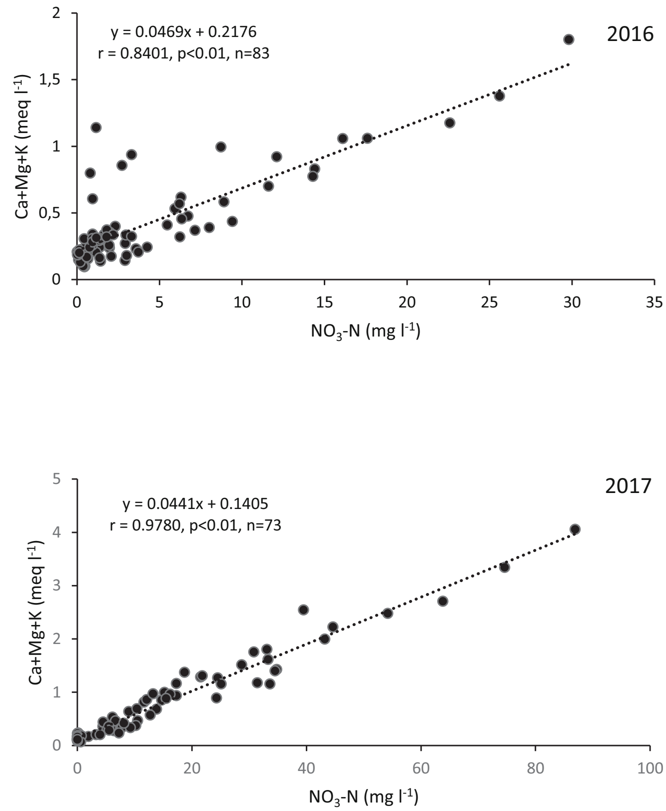

Fig. 5. Relationship between the sum of Ca, Mg and K concentrations and NO_3-N concentration in percolation water in the combined data from all the treatments.

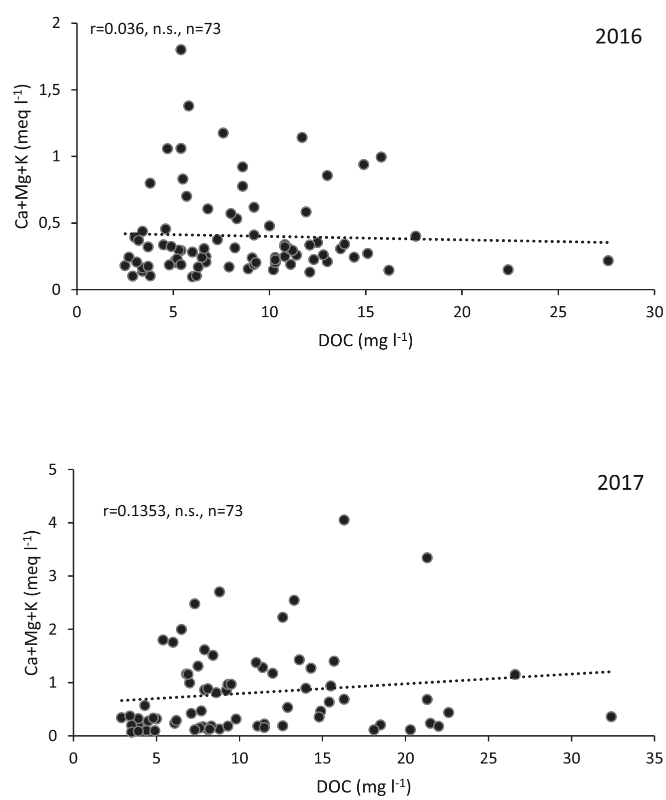

Fig. 6. Relationship between the sum of Ca, Mg and K concentrations and DOC concentration in percolation water in the combined data from all the treatments.

forest soils (Mustajärvi et al., 2008). However, leaching is possible on some sites after clear-cutting. If nitrification causes elevated concentrations of NO_3-N in soil water, this supports the presence of cations, as shown in a study in a black alder stand in western Finland (Lindroos and Aro, 2019). The logging residues of all tree species already caused increased NO_3-N concentrations below the residue piles one year after the establishment of the piles (Törmänen et al., 2020) in the experiment used in our current study. This phenomenon was strongly related to the increased concentrations of Ca, Mg, and K in the percolation water analysed in our current study, and one explanatory factor for the increased concentrations of base cations from 2016 to 2017 is undoubtedly the increased NO_3-N concentrations caused by stimulated nitrification (Törmänen et al., 2018; Törmänen et al., 2020) and the ionic balance between the NO_3^- and base cations. Also, Titus et al. (1997) found that concentrations of Ca and Mg in soil water were related to increased concentrations of NO_3-N following harvesting in white birch stands in Newfoundland. In the current study, for practical reasons logging residue piles were established one year after harvesting operations. We cannot exclude the fact that this may have affected element concentrations in percolation water but we can assume that the trends and tree species differences were the same as would have been on a fresh clear-cut.

Logging residues have been shown to increase the DOC concentration in soil solution (Lindroos et al., 2018). However, podzolic soils are known to precipitate dissolved organic matter into the B horizon. Our study site is located on acidic Haplic Arenosol but shows early stages of morphological features of developing B horizon due to ongoing podzolic processes. Precipitation of dissolved organic matter to B horizon leads to a low DOC concentration in percolation water below the rooting zone (Lindroos et al., 2008). Such a situation also proved evident in our current study, as indicated by the low DOC concentrations in comparison to that measured under the organic layer of another site (see Lindroos et al., 2008). Our DOC concentrations were also comparable to DOC concentrations measured under the B horizon in previous studies (Lindroos et al., 2008; Törmänen et al., 2020). There was a poor relationship between increased concentrations of base cations and DOC. The leaching of dissolved organic matter did not seem to be an important regulating factor for the concentrations of base cations below the logging residue piles in our experiment.

In this study lysimeters were installed carefully and avoiding any additional disturbance for soil. Returning of all soil material back to lysimeters may still have affected water infiltration, leaching fluxes and soil processes although DOC concentrations were on the same level as in earlier studies where soil was not disturbed as described above (Lindroos et al., 2008). In addition, we can assume that this effect was similar for all treatments and rather small. To assess the effects of logging residue piles from different tree species, plots were set up on the same clear-cut area with uniform parent material. This minimized variation in major soil-forming factors, allowing soil property differences to be linked primarily to the biological impact of pine, spruce, and birch residues. On the other hand, care should be taken generalizing these results to other soil conditions for example if site have till soil material or occur in more fertile soils.

5. Conclusions

In conclusion, logging residues of spruce, pine, and birch increase the base cation concentrations in the soil percolation water. Logging residues concentrated to restrict parts of a clear-cut area in large piles causes elevated concentrations of NO_3-N, and this increases the concentrations of base cations. There were tree-species-specific differences, and the highest concentrations of base cations were associated with birch residues. These results are important from the point of view of practical forestry to understand the importance of the logging residues for composition of soil percolation water and further the nutrient dynamics of forest soil after clear cutting. In practical forestry, large logging residue piles, shown in several studies to act as "hot spots" for soil processes, should be avoided. They may lead to increased leaching of base cations and subsequent nutrient depletion, undesirable especially on nutrient-limited boreal forests. Instead, residues should be spread more evenly on the forest floor to secure nutrient return.

CRediT authorship contribution statement

Antti-Jussi Lindroos: Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Tiina Törmänen:** Writing – review & editing. **Aino Smolander:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Funding information

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Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2025.e01005.

Data availability

Data will be made available on request.

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