Leaching of Organic Carbon and Plant Nutrients at Clear Cutting of Scots Pine Stand on Arenosol

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Armolaitis, K., Stakėnas, V., Varnagirytė-Kabašinskienė, I., Gudauskienė, A. and Žemaitis, P. 2018. Leaching of Organic Carbon and Plant Nutrients at Clear Cutting of Scots Pine Stand on Arenosol. *Baltic Forestry* 24(1): 50-59.

Abstract

The study was undertaken to assess the chemical changes in soil at a clear cutting of Scots pine (*Pinus sylvestris* L.) stand on Arenosol in South-Western Lithuania. The study determined the changes of organic carbon and plant nutrients in mineral topsoil and soil solution between and under skid trails, composed of logging residues, during the first 4 years after clear cutting.

The obtained data showed that, in general, significantly higher mean concentrations of NO_3-N + NO_2-N and NH_4-N and, to a lesser extent, K_2O and P_2O_5 were found under than between skid trails. However, higher concentrations of total organic carbon (TOC) were found up to 10 cm depth of mineral soil between skid trails. After 3 years mean concentration of NO_3-N + NO_2-N significantly increased only in 0-10 cm depth of mineral soil between skid trails but decreased up to the depth of 40 cm under skid trails. Mean concentrations of TOC increased between and, especially, under skid trails. Meanwhile, the mean concentration of P_2O_5 decreased under skid trails and the concentration of K_2O, both between and under skid trails, in mineral topsoil up to 10–20 cm depth.

In soil solution of fresh clear cutting, mean concentrations of NH_4-N, NO_3-N + NO_2-N, total N (TN), K^+, Ca^{2+} and Mg^{2+} significantly increased under than between skid trails and decreased in the 4-year-old clear cutting both between and under skid trails. However, in fresh clear cutting, mean concentration of dissolved organic carbon (DOC) did not differ between and under skid trails but increased under skid trails in the 4-year-old clear cutting. There, mean concentrations of TN, K^+, Ca^{2+} and Mg^{2+} were also significantly higher under skid trails.

Keywords: clear cutting, skid trails, mineral topsoil, soil solution, organic carbon, plant nutrients.

Introduction

Intensive forest management, especially felling, causes disturbance of forest ecosystem, affects soil physical, biological and chemical properties. Clear cutting is the dominant treatment for extraction of merchantable timber and forest regeneration. However, in Nordic and Baltic countries the use of logging residues, consisting of tops, branches and needles, for energy production is also high and expected to increase in the future (Thiffault et al. 2011, Helmisaari et al. 2014, Rytter et al. 2015, 2016, Lundmark et al. 2013, 2017). Otherwise, the logging residues can be left with different spatial distributions, modifying the effects of residue removal. Usually, in the clear cuttings, the skid trails are often covered by logging residues.

Significant physical, biological and chemical changes are observed in the clear cuttings of mature stands (Gundersen et al. 2006, Nave et al. 2010). When clear cutting operation is performed, the nutrient consumption by vegetation significantly decreases (Finér et al. 2003, Palviainen 2005, Gundersen et al. 2006). However, more intensive sunlight and increased atmospheric precipitation cause the higher temperature and humidity which, in turn, accelerates mineralization of organic matter and nitrification process in the mineral soil (Smolander et al. 2001, Gundersen et al. 2006, Sasnauskienė 2013). Furthermore, dissolved organic carbon (DOC) and potassium (K^+), nitrate (NO_3^-), phosphate (PO_4^{3-}), calcium (Ca^{2+}) ions are leached from forest floor and logging residues (Palviainen et al. 2005, Gundersen et al. 2006, Schelker et al. 2012). For these reasons, the leaching of above-mentioned compounds into the ground water and forest streams may increase (Gundersen et al. 2006, Väänänen et al. 2006, Laudon et al. 2009, Löfgren et al. 2009).

In the mineral soil of clear cuttings, the fastest decomposition of organic matter and nutrient release can be expected to occur during the first three years after felling operation (Palviainen et al. 2004). Subsequently, the initial level of NO_3^- leaching could be recovered after 4–5 years, however the increased leaching of organic carbon and other nutrients into the ground water could last for 10–20 years (Ahtiainen and Huttunen 1999, Palviainen et al. 2005, 2014, Gundersen et al. 2006, Nave et al. 2010).

We conducted a 4-year study in a clear cutting of Scots pine stand aiming to assess the impacts of skid trail logging residues on the soil and soil solution chemistry. Logging residues were defined as the branches and debris left on site after harvest of merchantable timber. The aim of the study was to examine the effect of logging residues, left in composed skid trails of clear cutting, on organic carbon (OC) and the nutrients (the compounds of N, P, K, Ca and Mg) release. More specifically, the study objectives were focused to determine the changes of OC and plant nutrient concentrations between and under skid trail in (1) mineral soil in the 1 and 4-year-old clear cuttings and (2) soil solution during the first 4 years after clear cutting.

Material and Methods

Study area and site

The study was carried out in Dubrava forest of Dubrava Experimental and Training Forest Enterprise in South-Western part of Lithuania (54°49' N, 24°05' E) in 2013–2016. The soils in Dubrava forest (mean elevation is 75–76 m a.s.l.) were developed from glaciolacustrine deposits after the last Nemunas (Riss-Wurm, Weischselian) glaciation. Amount of atmospheric precipitation and mean air temperature during the study period as well as standard climatic norms (SCN) taken from nearby Kaunas meteorological station (1981–2010) are shown in Table 1. The SCN for air temperature was 7.0 °C and the SCN for precipitation was 638 mm. During the period of 2013–2016, the mean air temperature exceeded the SCN by 0.6–1.6 °C. However, the amount of precipitation during vegetative periods of 2013, 2014 and 2016 slightly differed and it was significantly by 1.7 times lower than SCN in 2015 (Table 1). Furthermore, it caused no soil solution samples during the vegetative period of 2015.

Table 1. The amount of atmospheric precipitation and mean air temperature during 2013-2016 at Kaunas meteorological station

Year	Precipitation, mm		Mean temperature, °C	
	Annual	V-IX months	Annual	V-IX months
2013	700	400	7.7	16.7
2014	666	345	8.2	16.0
2015	551	197	8.6	15.8
2016	845	422	7.6	16.0
*SCN**	*638*	*339*	*7.0*	*14.6*

**SCN* – Standard climatic norm (1981-2010) was taken from Kaunas meteorological station.

Study site was established in a 1-year-old clear cutting (plot area 0.2 ha) of mature Scots pine (*Pinus sylvestris* L.) stand. Prior to harvesting, the Scots pine stand volume was 332 m^3 per ha and it was dominated (90% of the volume) by mature Scots pine (Table 2). The soil in the clear cutting was classified as Arenosol (WRB 2014) and forest site – as Nb – oligotrophic mineral soil of normal moisture, according to the Lithuanian classification (LR AM/LMI/VMT 2006).

Table 2. Characteristics of Scots pine stand before clear cutting and adjacent mature Scots pine stand (Intensive monitoring plot 6M, Lithuania) in 2012

Plot	Plot area, ha	Age, years	Species composition	Total stem volume, m^3 ha^{-1}	Stocking level
Scots pine stand before clear cutting	0.2	89	90% *Pinus sylvestris* L. 10% *Betula pendula* Roth	332	0.8
Adjacent mature Scots pine stand	1.2	97	70% *Pinus sylvestris* L. 20% *Picea abies* (L.) H. Karst. 10% *Betula pendula* Roth	408	0.8

At study site, conventional stem-only harvesting was carried out in autumn of 2012. In the clear-cutting site, skid trails (strip roads) were composed of logging residues (tree tops < 8 cm diameter, branches and needles).

Logging residues sampling and chemical analysis

During the harvesting, the logging residues were stacked into skid trails of about 4 meters width, leaving an average distance of 22 meters between the skid trails. The skid trails occupied about 16% of the clear cutting. According to Petrauskas et al. (2010), the branches and tree tops comprised about 17% of total stem volume in the mature coniferous stands of 0.8 stocking level. Therefore, it was calculated that the mean mass of logging residues amounted 15.70 kg m^{-2} in the skid trails while it was only 0.72 kg m^{-2} between skid trails (Table 3). Based on earlier study (Armolaitis et al. 2013), the needles, which were stacked together with branches, comprised about 20% or 3.14 kg m^{-2} in skid trail. The studied treatment was described by the amounts and distribution of logging residues, which may be found in clear cutting area after conventional stem-only harvesting in Lithuania (LR AM 2015).

Table 3. Mass of logging residues, fallen needles and forest floor in skid trails and between skid trails at fresh (2012) and 4-year-old (2016) clear cuttings of Scots pine stand

Year of assessment	Location	Mass of branches with needles in logging residues, kg m^{-2}	Mass of needles in logging residues, kg m^{-2}	Mass of forest floor, kg m^{-2}
2012	Skid trails	15.70	3.14	6.26 ± 0.98
2012	Between skid trails	0.72	0.14	6.26 ± 0.98
2016	Skid trails	10.90 ± 1.00*	0.00	7.06 ± 0.40

*Mean ± *SE*.

In spring of 2016, the absolute dry mass (dried to constant mass in an oven at 105 °C) of retained logging residues in the skid trails and forest floor under skid trails were measured according with the following procedure: the logging residues and forest litter, consisting of decomposed logging residues and former forest floor, were collected randomly from 1 m^2 plots in the skid trails, in 3 replicates.

Chemical analyses of logging residues and forest floor were performed in the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry. The following parameters were determined: total organic carbon (TOC) by dry combustion at 900 ºC with a CNS analyzer (ISO 10694); the concentrations of total nitrogen (TN) using the Kjeldahl method (ISO 11261); inorganic N by the spectrometric method (ISO 11261) in 1M KCl extraction: NH_4-N by sodium phenolate and sodium hypochlorite, and NO_3-N and NO_2-N by sulphanilamide; mobile potassium (K_2O) and mobile phosphorus (P_2O_5) by the Egnér-Riehm-Domingo (A-L) method (Egnér et al. 1960); exchangeable cations of Ca^{2+} and Mg^{2+} were determined in a 0.1 M $BaCl_2$ extraction (ISO 11260).

Soil sampling and chemical analysis

The first soil sampling was carried out in the 1-year-old clear cutting (in September of 2013) and was repeated after three years (2016) when clear cutting was 4-year-old. Composite soil samples (each at 6 systematically distributed points with minimal 6–8 m distance between the points) were collected from the 0–10, 10–20 and 20–40 cm depth mineral surface layers in 3 replicates between and under skid trails, separately. The samples of soil mineral layers were taken with a metallic auger of 3 cm diameter.

Selected soil chemical parameters (TOC, TN, NH_4-N, NO_3-N + NO_2-N, mobile K_2O and P_2O_5, exchangeable cations of Ca^{2+} and Mg^{2+}) were determined according to the above-mentioned chemical methods with the exception of pH_{KCl}, which was determined in 0.01 M KCl suspension (ISO 10390).

Soil solution sampling and chemical analysis

Soil solution was sampled at the depth of 20 cm by tension lysimeters with P80 ceramic suction cup (Nieminen et al. 2016), which were installed in May 2013. In clear cutting, in total 12 lysimeters were installed: 6 lysimeters were installed under skid trail (with logging residues) and 6 lysimeters were installed between skid trail (without logging residues). Soil solution was collected by applying 80 kPa vacuum by hand pumping two weeks before collection. Soil solution was sampled for two times per vegetation period (June and August-September) in 2013, 2014 and 2016 (soil solution was not found in dry vegetative period of 2015, see Table 1).

Chemical analyses of soil solution were performed in the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry. The following soil solution chemical parameters were determined: pH using the potentiometry method ISO 10523; dissolved organic carbon (DOC) using the method described in ISO 8245; dissolved total nitrogen (TN) using the method described in ISO 11905-1; NH_4-N using the method described in EN ISO 11732; total NO_3-N + NO_2-N by photometry method EN ISO 13395; total phosphorus (TP) and phosphate phosphorus (PO_4-P) by EN ISO 6878; potassium cations (K^+) by ISO 9964-2; cations of Ca^{2+} and Mg^{2+} by EN ISO 7980 method.

Calculations and statistical analysis

The equation (Delaney et al. 1996) was applied to calculate the relative percentage change of concentrations of OC and nutrients in mineral soil between and under skid trails during three years:

$$\text{Relative percentage changes in concentration} = \frac{B_n - A_n}{A_n} \times 100\%,$$

where: A_n is the concentrations at the 1-year-old clear cutting; B_n is the concentrations at the 4-year-old clear cutting.

Mean values of soil solution chemical compounds in the clear cutting were compared with the corresponding mean values obtained in adjacent Scots pine stand (belonging to the Intensive Forest Monitoring plot 6M in Lithuania), during the vegetative periods of 2013–2016.

The data were analysed for differences in mean concentrations of chemical parameters in soil and soil solution between and under skid trails using one-way ANOVA followed by the Tukey post hoc tests. All statistical analyses were carried out using the STATISTICA software package, and $p < 0.05$ was considered to indicate a statistical significance. Throughout the study, the means are presented with the standard error (± SE) of the mean.

Results

Organic carbon and nutrients in logging residues

The mass of logging residues had decreased in average by 1.4 times during 4-year period after clear cutting (Table 4). However, mean stocks of total C and total N in logging residues stacked in skid trails decreased by 1.7 and 2.5 times, respectively.

There were no overall trends common to all measured chemical parameters (total C, total N, NO_3-N + NO_2-N and NH_4-N, P_2O_5, K_2O, Ca^{2+}, Mg^{2+}) in the logging residues and forest floor 4 year after clear cutting (Table 4). Meanwhile, the stock of NO_3-N + NO_2-N in forest floor by 26.5-fold exceeded the stock in logging residues. Mean stock of total C was by 2.1 times and K_2O was by

1.8 times higher in logging residues than in forest floor. Contrary to total C, mean stocks of total N and NH_4-N were by 2.6 and 3.3 times, respectively, and the stocks of Ca^{2+} and P_2O_5 were by 2.2–2.4 times and Mg^{2+} was by 1.3 times lower in logging residues than in forest floor.

As could be seen in Table 4, during 4-year period after clear cutting, mean stock of total N in logging residues, stacked in skid trail, decreased by 2.5 times.

Table 4. Mean biomass and stocks of total carbon (total C), total N, total nitrate + nitrite (NO_3-N + NO_2-N) and ammonium (NH_4-N) nitrogen, mobile compounds of phosphorus (P_2O_5), potassium (K_2O), calcium (Ca^{2+}) and magnesium (Mg^{2+}) in logging residues (branches and needles) and forest floor of skid trails 4 years after clear cutting

Compartments of skid trail	Mass, kg m^{-2}	Total C, kg m^{-2}	Total N	NO_3-N + NO_2-N	NH_4-N	P_2O_5	K_2O	Ca^{2+}	Mg^{2+}
			g m^{-2}						
Logging residues	10.9 ± 1.0* (15.7)**	4.8 ± 0.4 (8.1)	37.8 ± 11.2 (94.3)	0.2 ± 0.1	4.6 ± 2.3	18.2 ± 4.4	104.6 ± 18.8	217.7 ± 47.2	42.6 ± 3.8
Forest floor	7.1 ± 0.4 (6.3 ± 1.0)	2.3 ± 0.2	99.9 ± 4.7	5.3 ± 0.3	15.2 ± 2.0	42.9 ± 2.5	58.8 ± 3.9	477.7 ± 60.4	54.4 ± 6.5

* Mean ± *SE*.
** The values given in brackets show calculated initial data in 2012.

As logging residues, i.e. tops, branches and needles, containing high stocks of nutrients, are compacted in skid trails, the nutrient release from these logging residues could be significant. The atmospheric precipitation intensifies the release of mineral nutrients from the skid trails to the soil (Wall 2008). In addition, logging residues could stimulate decomposition of soil organic matter (Adamczyk et al. 2016). Moreover, the main part of organic carbon from the logging residues in skid trails could be emitted to the atmosphere due to microbial processes in dead wood (Stakėnas et al. 2011).

Soil organic carbon and nutrients

In the fresh 1-year-old clear cutting, there were no detectable differences ($p > 0.05$) in pH_{KCl} and mean concentrations of exchangeable Ca^{2+} and Mg^{2+} both between and under skid trails within each sampled 0–10, 10–20 and 20–40 cm surface mineral layers (Table 5). Significantly higher ($p < 0.05$) concentrations of total organic carbon (TOC), total nitrogen (TN) and mobile P_2O_5 were recorded only in 0–10 cm mineral topsoil. There, mean TOC concentration was by 30% and mean TN concentration was by 45% higher between skid trails than under skid trails. In opposite, mean concentration of P_2O_5 had increased in average by 49% under skid trails.

In the fresh clear cutting much higher differences or the increase of mobile mineral nitrogen compounds (NH_4-N, NO_3-N + NO_2-N) and mobile K_2O in mineral soil were found under skid trails than between skid trails without logging residues (Table 5). The concentrations of NH_4-N in soil under skid trails were in average by 2.3 and 1.7

Table 5. Mean pH value and mean concentrations of selected chemical parameters in surface mineral layers of Arenosol at a fresh 1-year-old clear cutting of Scots pine stand (2013)

Depth, cm	Location	pH_{KCl}	TOC, g kg^{-1}	Total N, g kg^{-1}	NH_4-N, mg kg^{-1}	NO_3-N + NO_2-N, mg kg^{-1}
0-10	under skid trails	3.6 ± 0.1	17.4 ± 0.7	0.85 ± 0.03	**7.95 ± 2.62**	**9.26 ± 5.14**
	between skid trails	3.6 ± 0.2	**22.6 ± 1.2**	**1.23 ± 0.28**	3.41 ± 0.64	0.31 ± 0.16
10-20	under skid trails	4.1 ± 0.1	8.4 ± 0.6	0.49 ± 0.03	**5.17 ± 1.41**	**6.05 ± 2.38**
	between skid trails	4.1 ± 0.1	8.8 ± 0.5	0.50 ± 0.13	2.97 ± 0.42	1.40 ± 0.36
20-40	under skid trails	4.4 ± 0.1	3.5 ± 0.2	0.30 ± 0.05	1.36 ± 0.22	**6.12 ± 1.06**
	between skid trails	4.4 ± 0.3	4.1 ± 0.2	0.24 ± 0.01	1.06 ± 0.03	1.17 ± 0.38

Depth, cm	Location	P_2O_5	K_2O	Ca^{2+}	Mg^{2+}
		mg kg^{-1}			
0-10	under skid trails	**146 ± 9**	**160 ± 9**	247 ± 26	66 ± 3
	between skid trails	98 ± 6	66 ± 8	301 ± 82	68 ± 1
10-20	under skid trails	185 ± 27	**75 ± 2**	186 ± 16	55 ± 7
	between skid trails	149 ± 6	39 ± 5	205 ± 29	62 ± 7
20-40	under skid trails	124 ± 24	**48 ± 4**	166 ± 11	54 ± 4
	between skid trails	107 ± 17	23 ± 2	199 ± 20	62 ± 6

Notes. Mean ± *SE* of composite soil samples ($n = 3$) (sampling was carried out in September, 2013). Significantly higher ($p < 0.05$) concentrations are shown in bold.

times higher ($p < 0.05$) in the 0–10 and 10–20 cm mineral soil layers, respectively, than between skid trails. However, exceptionally significant differences were obtained for the concentrations of NO_3-N + NO_2-N, and, to a lesser extent, for K_2O. Significant increase of these nutrients under skid trails was found in all sampled layers up to the 40 cm depth. There, if to compare with the sites between skid trails of clear cutting, mean concentrations of K_2O were in average by 1.9–2.4 times, while sum concentrations of NO_3-N + NO_2-N were by from 4.3 to 5.2 times (in 10–20 and 20–40 cm depths, respectively) and even up to 30-fold (0–10 cm) higher.

Usually NH_4-N comprised the largest part of mineral nitrogen in mineral forest soils (Vaičys et al. 1997, Gundersen 2006). From data presented in Table 5 it could be calculated that NH_4-N concentrations in soil between skid trails amounted 55–85%, while under skid trails they were only 22–46% of total concentrations of soil mineral nitrogen (NH_4-N + NO_3-N + NO_2-N). It could be suggested that the nitrification in the soil under skid trails was about by 2 times more intensive than between skid trails in the fresh 1-year-old clear cutting.

Soil chemical analyses were repeated after 3 years period when clear cutting site was 4 years old. It was found that soil pH had not changed significantly ($p > 0.05$) both between and under skid trails (data are not shown). The relative percentage changes of concentrations of determined other soil chemical parameters are presented in Figure 1.

As these can be seen in Figure 1, the concentrations of observed mineral soil chemical parameters changed demonstrating different patterns between and under skid trails in the 4-year-old clear cutting. First of all, it could be pointed out that during 3-year period the concentration of NO_3-N + NO_2-N increased in average even 14-fold between skid trails up to a depth of 10 cm reflecting the intensification of nitrification process. Contrary, mean concentrations of NO_3-N + NO_2-N have

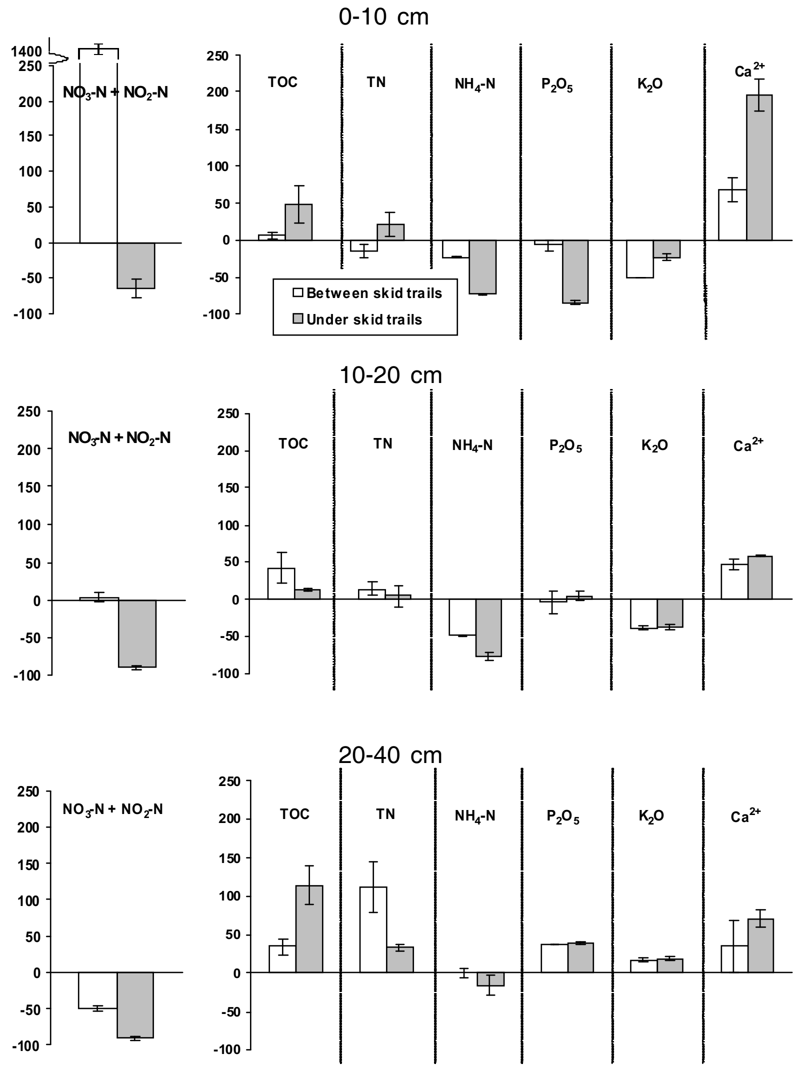

Figure 1. Relative percentage changes (taken as reference value: 100% or zero in the Figure) of mean concentrations of the NO_3-N + NO_2-N, total organic carbon (TOC), total nitrogen (TN), NH_4-N, P_2O_5, K_2O and Ca^{2+} in the mineral 0–10, 10–20 and 20–30 cm surface layers of Arenosol at the 1-year (2013) and 4-year-old (2016) clear cuttings of Scots pine stand in 2016 in comparison with the values obtained in 2013. For values greater than the reference value, the relative change is a positive number and for values that are smaller, the relative change is negative. Bars show standard error of mean

decreased by 65–92% up to the depth of 40 cm under skid trails. Meanwhile NH_4-N mean concentrations decreased both between (by 23–48%) and under (by 73–76%) skid trails up to a depth of 20 cm.

Relatively not so high percentage changes were found for soil TOC and TN (Figure 1). Between skid trails, the TOC mean concentrations did not change up to the depth of 10 cm but significantly ($p < 0.05$) increased by 34–42% in 10–20 and 20–40 cm mineral soil layers. However, under skid trails TOC concentrations increased more significantly, in average by 48% at a depth of 0–10 cm and more than 2 times at a depth of 20–40 cm. The relative changes of TN concentrations were minor both between and under skid trails up to a depth of 20 cm (increase/decrease mean changes did not exceed 14–21%). However, TN concentrations increased in average by 2.1 times between skid trails and by 33% at 20–40 cm mineral soil layer under skid trails. In a meta-analysis covering more than 400 studies, Nave et al. (2010) concluded that overall harvesting operations and particularly large clear-cutting systems result in a significant reduction in the soil C storage of the forest floor with little change to mineral soil C. James and Harrison (2016) found a significant overall reduction in forest soil C following harvest that occurs in both the O horizon and mineral soil. The experiment from Sweden showed that clear-cutting resulted in significant accumulation of mineral N in soil during the first year after stem harvesting, and this accumulation was significantly higher than plant N uptake and N leaching (Bergholm et al. 2015).

Mean concentrations of Ca^{2+} evenly increased (by 34–68%) in all sampled layers up to a depth of 40 cm between skid trails. Under skid trails, it increased by 3 times at a depth of 0–10 cm and by 58–71% at the depths of 10–20 and 20–40 cm. Meanwhile, no changes between skid trails or the decrease of P_2O_5 mean concentrations by 84% under skid trails and the decrease of K_2O concentrations by 38–50% both between and under skid trails were found up to a depth of 20 cm (Figure 1). However, mean concentrations of these mobile compounds increased by 37–38% (P_2O_5) and 17–19% (K_2O) at a depth of 20–40 cm between and under skid trails.

The above-mentioned data showed no detectable difference in soil pH between logging residues treatment in surface mineral soil layers, and this result was consistent with the data obtained by Ring et al. (2015). Nevertheless, our data showed that logging residues left on the skid trails affected the increase of the concentrations of TN, NO_3-N + NO_2-N, NH_4-N, mobile K_2O and P_2O_5 in surface mineral soil compared with concentrations of these plant nutrients between skid trails already at the fresh 1-year-old clear cutting. These findings seem to be consistent with other research (Palviainen et al. 2005, Laudon et al. 2009, Löfgren et al. 2009, Schelker et al. 2012). Otherwise, after the clear cuttings, in the sites without logging residues the decomposition of soil organic matter and nutrient release is often found accelerated (Staaf and Olsson 1994, Piirainen et al. 2009, Finér et al. 2016).

Soil solution carbon and nutrients

The data obtained during vegetation period on the fluctuation/dynamics of soil solution chemistry at a depth of 20 cm between and under skid trails in the clear cutting during 1, 2 and 4 years after harvesting and in the adjacent Scots pine stand (mean data of 2013, 2014 and 2016) are presented in Figure 2. Obtained data allow us: (1) to compare soil solution chemistry between and under skid trails in the fresh 1-year-old clear cutting; (2) to evaluate the soil solution chemistry changes in clear cutting during three years; and (3) to assess these changes comparing with the data obtained in the adjacent Scots pine stand.

Initial data showed that the mean pH of soil solution did not differ significantly ($p > 0.05$) and pH 4.6 ± 0.4 between skid trails and pH 4.1 ± 0.1 under skid trails in the fresh 1-year-old clear cutting (Figure 2) were observed. In soil solution, total N (TN, in average 61 mg L^{-1} between and 139 mg L^{-1} under skid trails), NO_3-N + NO_2-N (33 and 91 mg L^{-1}), dissolved organic carbon (DOC, 59 and 40 mg L^{-1}), K^+ (23 and 62 mg L^{-1}), Ca^{2+} (22 and 48 mg L^{-1}) and Mg^{2+} (5 and 13 mg L^{-1}) were dominant among determined chemical parameters. Meanwhile, the mean concentrations of NH_4-N did not exceed 10 mg L^{-1}, while total P (TP) and PO_4-P in average amounted 0.1 and 0.04-0.05 mg L^{-1}, respectively, both under and between skid trails.

In the fresh 1-year-old clear cutting there were no detectable differences ($p > 0.05$) in pH and in mean concentrations of DOC, TP and PO_4-P between and under skid trails (Figure 2). Meanwhile, the concentrations of NH_4-N were in average by 7.7 times, K^+ and NO_3-N + NO_2-N were by 2.7–2.8 times and the concentrations of Ca^{2+}, TN and Mg^{2+} were in average by 2.2–2.5 times higher ($p < 0.05$) under skid trails than between skid trails without logging residues.

During entire 1-4-year period after the harvesting the concentrations of all determined chemical parameters, with exception of DOC, diminished in soil solution between skid trails (Figure 2). The decrease of mean concentrations to the stable level (in comparison to the 1-year-old cutting) for the NH_4-N by 33 times, and for Mg^{2+} and Ca^{2+} and PO_4-P by 2.1–3.1 times were determined already in the 2-year-old clear cutting. However, the minimal concentrations of TN, NO_3-N + NO_2-N and K^+ decreased by about 23, 17 and 8 times, respectively, and as to TP by 45% were found between skid trails in the 4-year-old clear cutting.

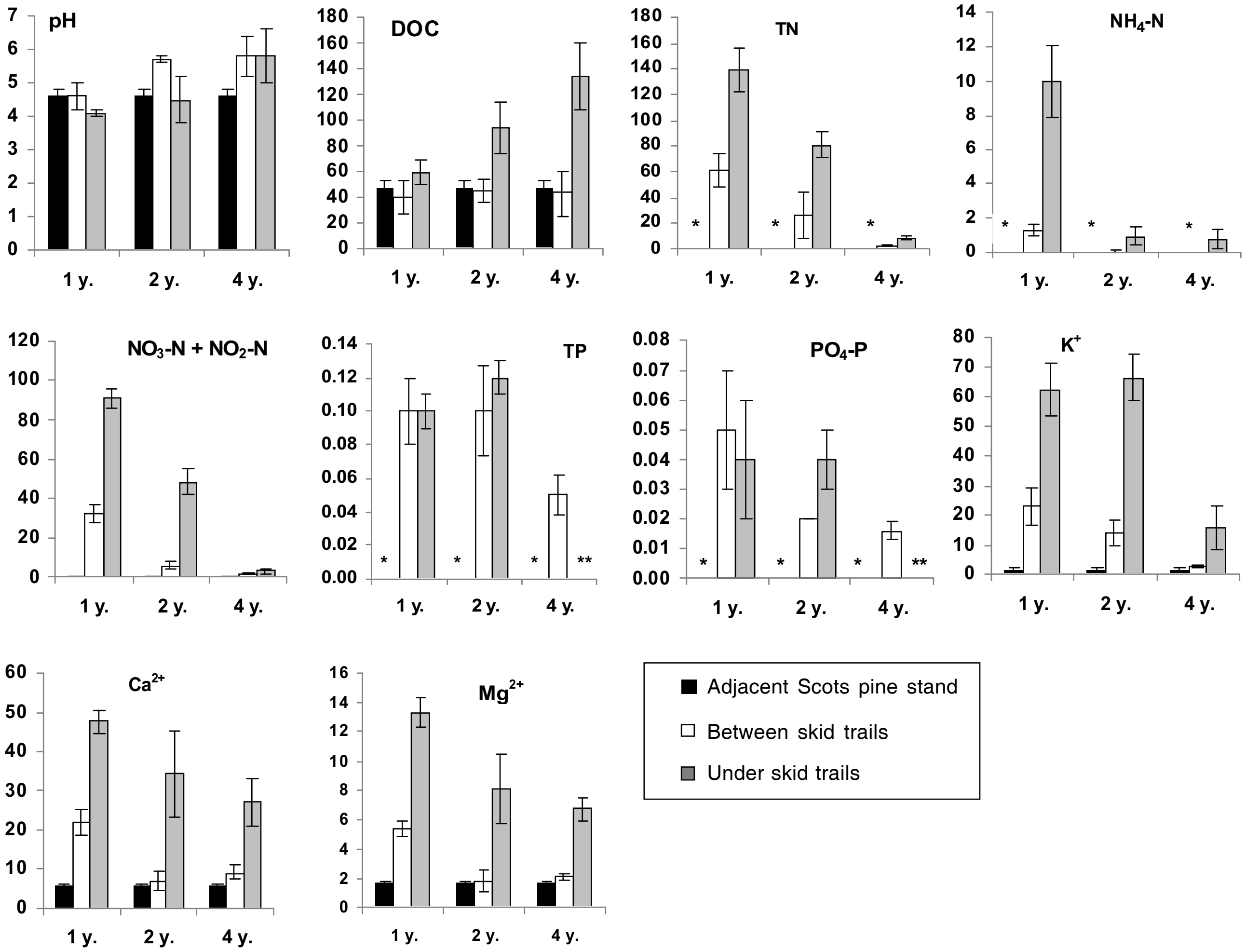

Figure 2. Dynamics of mean pH values and mean concentrations (mg L^{-1}) of dissolved organic carbon (DOC), total nitrogen (TN), ammonium nitrogen (NH_4-N) and nitrate + nitrite (NO_3-N + NO_2-N) nitrogen, total phosphorus (TP) and phosphate phosphorus (PO_4-P), cations of potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) in soil solution at the depth of 20 cm during vegetation periods in the 1, 2 and 4-year-old clear cuttings (soil solution was not found in the 2-year-old clear cutting) and average (sampled in the period of 2013-2016) pH values and mean concentrations of some chemical compounds (DOC, NO_3-N + NO_2-N, K^+, Ca^{2+} and Mg^{2+}) at the adjacent Scots pine stand on Arenosol. Bars show standard error of mean. *Notes: * No data is available because the chemical compound was not detected in adjacent Scots pine stand; ** No data was available due to the lack of soil solution*

In soil solution, under skid trails the mean concentrations of DOC tended to increase and were by 2.3 times higher in the 4-year-old than in the 1-year-old clear cutting. Meanwhile mean concentrations of NH_4-N decreased 11-fold already in the 2-year-old clear cutting. However, the concentrations of NO_3-N + NO_2-N and TN drastically decreased in average 31 and 16-fold, respectively, while the mean concentrations of K^+ decreased 4-fold, Ca^{2+} and Mg^{2+} about 2-fold under skid trails in the 4-year-old clear cutting. It is worth to mention that in the 4-year-old clear cutting the mean concentrations of TN and NO_3-N + NO_2-N in soil solution did not differ ($p > 0.05$) between and under skid trails, while the mean concentration of K^+ was 5.6-fold higher and the concentrations of DOC, Ca^{2+} and Mg^{2+} were by 3.0–3.2 times higher under skid trails.

The precise numbers that were given by Lindblom (2009) showed that 25% of N, 53% of P, 87% of K, 42% of Ca and 49% of Mg could be released from logging residues during the first three years after first thinning of Scots pine stand. Our study confirmed that mineral N (NH_4-N and NO_3-N + NO_2-N), also K^+, TN, Ca^{2+}, Mg^{2+}, to a lesser extent PO_4^{3-} and, in addition, DOC were mainly released from the logging residues on the skid trails, and could be leached into ground water especially from fresh 1–2-year-old clear cuttings of previous Scots pine stand. Increased NH_4–N concentration in the soil stimulates formation of nitrates, which could be easily lost through runoff or leaching (Ring et al. 2003, Titus et al. 2006, Bergholm et al. 2015). Meanwhile Mg^{2+}, Ca^{2+}, TP and K^+ have been found to leach readily from logging residues of conifers (Johansson 1994, Wall 2008), but the response in deep soil water is also affected by the mobility of these elements in the soil (Piirainen et al. 2004). Stevens et al. (1995) showed that mobile PO_4^{3-}-P and K^+ were leached from logging residues left on harvest site, only K^+ concentration increased in the deep soil water.

As can be seen from Figure 2, if to compare with adjacent Scots pine stand, between skid trails mean concentrations of DOC, Ca^{2+} and Mg^{2+} in soil solution already did not differ in 2-year-old clear cutting, while NO_3-N + NO_2-N and K^+ concentrations were at the same level as in Scots pine stand – in 4-year-old clear cutting. However, even in 4-year-old clear cutting under skid trails mean concentrations of K^+ were still about 9-fold higher, Ca^{2+} and Mg^{2+} were by 4–5, and DOC was by about 3 times higher than in the Scots pine stand.

There are a number of published studies that describe the duration of leaching processes after clear cuttings of forest stands. The leaching of mineral N after clear cuttings could last for five years, with a peak after 1–2 years (Huber et al. 2004, Hedwall et al. 2013). Otherwise, the stimulated vigorous ground vegetation in the clear cuttings could decrease mineral N leaching up to pre-harvest level already after 4–5 years (Ahtiainen and Huttunen 1999, Palviainen et al. 2005, 2014, Gundersen et al. 2006).

Conclusions

The logging residues compacted on the skid trails at the clear cutting of Scots pine stand affected the chemistry of mineral topsoil and soil solution of Arenosol during the studied 4-year period.

The data of mineral topsoil chemical composition showed that in the fresh 1-year-old clear cutting no significant differences ($p > 0.05$) in pH_{KCl} and mean concentrations of Ca^{2+} and Mg^{2+} both between and under skid trails were found up to a depth of 40 cm of mineral soil. Significantly higher ($p < 0.05$) mean concentrations of mobile mineral nitrogen compounds (NO_3-N + NO_2-N and NH_4-N), to lesser extent increased concentrations of K_2O and P_2O_5 were found under skid trails than between skid trails. Meanwhile, significantly higher concentrations of total organic carbon (TOC) and total nitrogen (TN) were found up to a depth of 10 cm of mineral soil between skid trails than under skid trails. After 3 years, along the decrease of NH_4-N, the mean concentration of NO_3-N + NO_2-N significantly increased only in a depth of 0–10 cm of mineral soil between skid trails but decreased up to a depth of 40 cm under skid trails. Mean concentrations of Ca^{2+} and TOC increased between and especially under skid trails. The decreased mean concentration of P_2O_5 under skid trails and the decreased concentration of K_2O both between and under skid trails in mineral topsoil up to a depth of 10–20 cm were followed by decrease of these mobile compounds at a depth of 20–40 cm.

The data of soil solution collected at 20 cm depth showed that in the fresh clear-cutting site the mean concentrations of DOC, TP and PO_4-P did not differ between and under skid trails. Meanwhile, the concentrations of NH_4-N, NO_3-N + NO_2-N and total N (TN) as well as K^+, Ca^{2+} and Mg^{2+} were by several times higher under than between skid trails. In the 4-year-old clear cutting, the concentrations of these nutrients diminished both between and under skid trails, except for DOC concentration. The mean concentrations of TN and NO_3-N + NO_2-N in soil solution did not differ between and under skid trails, while the mean concentrations of K^+, DOC, Ca^{2+} and Mg^{2+} were higher under skid trails.

In comparison with the adjacent Scots pine stand, the mean concentrations of DOC, Ca^{2+} and Mg^{2+} in soil solution between skid trails of the clear cutting did not differ already in the 2-year-old clear cutting, while the concentrations of NO_3-N + NO_2-N and K^+ did not differ in the 4-year-old clear cutting. However, the mean concentrations of K^+, Ca^{2+} and Mg^{2+} and DOC were significantly higher under skid trails of the 4-year-old clear cutting than in the Scots pine stand.

Above-mentioned data led us to the assumption that logging residues could be extracted for forest fuel in sandy Arenosols in order to avoid enhanced leaching of organic carbon and nutrients, especially mineral nitrogen.

Acknowledgement

The research was part of the Project "Study of impact of clear cuttings on biodiversity dynamics in forest ecosystems" (No. SIT-1/2015) of the National Research Programme "Sustainability of agro-, forest and water ecosystems" (2015–2018) funded by the Lithuanian Research Council.

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