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How different approaches to logging residues handling affected retention of nutrients at poor-soil Scots pine site after clear-cutting? A case study

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Abstract: Biomass nutrient loss and retention were studied at nutrient-poor forest site dominated by Scots pine where two methods of logging residues handling after clear-cutting were compared. The experiment was conducted on nutrient-poor pine-oak forest site on deep sandy-gravel unconsolidated sediments at the altitude of 255 m. There were three treatments established such as (*i*) control – no harvesting, (*ii*) whole-tree harvesting with ca. 10% of the slash retained unintentionally on site as processing residues and (*iii*) stem-only harvesting when small-diameter wood and slash were left on site. The third treatment was found to retain much larger amounts of nutrients in logging residues representing 16% of total above-ground dry mass which accounted for 58% of N, 32% of P, 56% of K, 22% of Ca and 28% of Mg left on site.

Keywords: biomass removal; nutrients; Scots pine; Norway spruce; allometry; whole-tree and stem-only harvesting

To understand nutrient cycles in forest ecosystems, the source and processes in which nutrients are taken, used, retained, returned and released to be reutilized after retransformation into available form are essential (see e.g. Binkley 1986; Attiwil, Adams 1993). The simplified models from semi-natural forests describe usually both import and export fates of nutrients; these are returned right to and/or not far from the source such as e.g. forest floor (see Uhlig, Blackenburg 2019). In managed forests, from which substantial amounts of nutrients are removed when a crop is harvested, different concepts of nutrient management are needed (see Binkley 1986). One can infer that for keeping forest nutrition sustainable, forest soil fertility is expected to be maintained if nutrient export via harvested trees does not exceed the nutrient availability levels recharged by fluxes from weathering minerals (Uhlig, Blackenburg 2019; Casetou-Gustafson et al. 2019, 2020), inputs via deposition and also pools of nutrients stored in organic layers of soil temporarily (Bormann, Likens 1967; Palviainen, Finér 2012; Akselsson et al. 2019; Uhlig, Blackenburg 2019). After clear-cutting, the nutrients are exported through removal of harvested trees and additional loss was attributable to uptake by regenerating vegetation (e.g. decrease in Ca pool) and leaching (e.g. decrease in Mg, Cu and Mn pools); there was shown also further decrease in nutrient pools along with increasing age of stands (Richardson et al. 2017).

Scots pine (*Pinus sylvestris* L.) forests are renewed using a clear-cutting forest system frequently; this approach also represents the most common

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forest harvesting practice worldwide (see Mayer et al. 2020). The pine above-ground biomass, which large amount is removed when using clear-cutting, is ca. 80% roundwood with sawlog top minimum diameter of 7 cm (Bílek et al. 2016; Węngiel et al. 2018). Urban et al. (2015) estimated the pine stems accounted for 75% of the total stand biomass volume. The above-ground and below-ground biomass might account for ca. 80% and 20% respectively in the mature Scots pine stand (Urban et al. 2015). Over decades of the last century and also at the beginning of 2000s, the logging residues were considered to be rather a woody waste that increased forest renewal costs. Nowadays, handling of logging residues, and its impact on site nutrition are in focus since these parts of trees have become merchantable for bioenergy purposes (Eisenbies et al. 2009; Kimsey et al. 2011; Hazlett et al. 2014; Egnell 2016; Jurevicz et al. 2016; Knust et al. 2016; de Jong et al. 2017; Nilsson et al. 2018; Węngiel et al. 2018; Kabrick et al. 2019; Kurvits et al. 2020). The removals of biomass including those compartments that are rich in nutrients rises an issue of a site nutrition sustainability. Particularly, this is a matter of higher bark and foliage nutrient concentrations compared to those in wood (Kreutzer 1979; Akselsson et al. 2019). From this point of view, it was a whole-tree harvesting that was reported as particularly risky (Šrámek et al. 2009; Wall 2012; Egnell; Ulvcrona 2015; Knust et al. 2016; Węngiel et al. 2018) as it increased the nutrient export from forests (Palviainen, Finér 2012). The species-specific effects as nutrient removals from pine stands were found lower compared to spruce and birch ones and were also attributable to stem-only harvesting and harvested stem m^3 from whole-tree harvesting (Palviainen, Finér 2012). In order to maintain the soil fertility or if nutrients are even depleted, return of nutrients through soil conditioners such as wood ashes is often recommended (see Souček, Špulák 2006; Prietzel et al. 2008; Remeš et al. 2016; de Jong et al. 2017; Mayer et al. 2020). This way of nutrient return is, however, needed to be safe for environment i.e. absence or low-level content of harmful substances (Ozolincius et al. 2006) is necessary, which increases difficulty and costs of such measure.

There are many methods developed to estimate risks of soil degradation resulting from above-ground biomass removal; they were based both on terrestrial and remote-sensing mapping. Despite that, it is still necessary to study particular tree species, stand types and site conditions in the field (Kimsey et al. 2011). For example, nutrition sustainability can be assessed using a nutrient budget approach which is a nutrient stability ratio of nutrient removed during harvest to post-harvest nutrient reserve (see Hazlett et al. 2014). It was also hypothesized that decreasing nutrient availability increases nutrient use efficiency; which might be, however, at the expense of reduced productivity (Turner 2020). Woody biomass removal is expected to threat the poor sites particularly. Such sites are the most common ones where Scots pine is grown as dominant commercial species in Europe (Durrant et al. 2016). On deep alluvial sands of the study area, mixture of Scots pine with Norway spruce in understory represents the most common forest stand type (Peřina 1960).

The objective of our study was to estimate amounts of nutrients in compartments of aboveground biomass of mature Scots pine stands to compare nutrient pools in logging residues both removed and left on site according to biomass processing method after clear-cutting. This approach addressed a following research question: How large might be above-ground biomass nutrient export and/or pools left on the study site forest when using different slash-processing methods after clear-cutting?

MATERIAL AND METHODS

Study site. The investigation was conducted in the municipal estate of Hradec Králové City in north-eastern Bohemia, the Czech Republic. The dominant species of the almost 4 000 ha urban forest area is Scots pine with 67% share (Městské lesy Hradec Králové 2000). The experiment design consisted of three treatments such as Control, Clear-cut 1 (C-c-1) and Clear-cut 2 (C-c-2, see Table 1) at the altitude of 255 m. Nutrient-poor pine-oak forest site developed on sandy-gravel soil, which is the uppermost layer of unconsolidated pleistocene sandy-gravel alluvial sediment; ground water table level depth is 4–8 m (source: local ground water probes). The soils are nutrient-poor podzols typical of low contents of N, P, K and Ca (for example the concentrations in shallow A-layer are ca. 3 mg·kg^{-1} of N (nitrate form), 30 mg·kg^{-1} of P, 48 mg·kg^{-1} of K, 120 mg·kg^{-1} of Ca and 38 mg·kg^{-1} of Mg), raw thick surface humus and very low contents of nutrients in mineral soil placed deeper than 80 cm (Peřina 1960).

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Table 1. Description of plots/treatments

Treatments	Stand age (years)	Area (ha)	Biomass processing
Control	85	1.3	no harvest – all biomass left on site
Clear-cut 1 (C-c-1)	98	1.1	sawlogs, smallwood and slash biomass removed, ca. 10% of the slash were left on site as processing residues (i.e. whole-tree harvesting)
Clear-cut 2 (C-c-2)	90	0.6	sawlogs removed, smallwood and slash left on site (i.e. stem-only harvesting)

Control – stand left on site; C-c1 and C-c2 – stands removed using a clear-cutting; sawlog top (see Domke et al. 2013) represents a merchantable bole below minimum top diameter of 7 cm – all thinner parts of tree including stumps are considered to be logging residues

These sites were, therefore, considered to be prone to nutrient depletion if logging residues are removed excessively without adequate nutrient return. Average air temperature of the area was 7.3 °C and average annual precipitation totaled 612 mm (long-term normals for the period of 1981–2010).

Prior to harvesting, all trees were measured using Field-Map technology (see fieldmap.cz) on the three plots in 2017. The set of devices included: laser distance meter with electronic compass (TruePulse 360B, Laser Technology, Inc., USA), electronic caliper (Masser BT, Masser Oy, Finland), GPS device (SX Blue II, Geneq, Canada), tablet (Toughpad FZ-G1, Panasonic, Japan) and other geodetic equipment. The measured parameters were trunk foot coordinates and DBHs of all live trees with DBH exceeding 7 cm inclusive. Heights were approximated using height curve method for Scots pine and Norway spruce, respectively. Totally, 2 704 trees were measured.

Tree sampling. Trees were sampled in 2017. Totally 17 spruce above-ground parts representing lower story were taken in order to investigate dimensions and dry mass of particular biomass compartments such as foliage, live branches, dead branches, stem bark and stem wood. Nutrients in needles, and both live and dead branches were analyzed as mixed samples of every sampled tree. Stem bark and stem wood were sampled from breast-height (1.3 m above ground) part of each tree with DBH exceeding 5 cm (8 sample trees). Thereafter, five Scots pine trees with dimensions close to mean stem values of the C-c-1 and C-c-2 treatments were sampled. Lower number of pine trees was taken in agreement with the land owner. Stem disks from 2-m sections, all live branches and samples of dead branches were taken. Contents of nutrients (N, P, K, Ca and Mg) in the plant dry mass of every compartment of both species were analyzed (Zbíral 2001).

Biomass allocation. Both live weight/DBH and dry mass/DBH linear regressions were computed for all biomass compartments and species. Based on the particular sampled biomass compartments, a regression equation was calculated for relationship of DBH and dry mass of spruce; the most fitting approximation was found to be a polynomial regression. Correlation coefficients exceeded 0.9 except for live and dry branches (Table 2).

Table 2. Regression relationships between DBH (x) and dry mass of particular biomass compartments (y) of spruce with correlation coefficients

Biomass compartment	Model	Correlation coefficient
Stem	$y = 0.1915x^2 - 0.3209x + 0.3117$	$R^2 = 0.981$
Stem wood	$y = 0.1724x^2 - 0.3134x + 0.2462$	$R^2 = 0.981$
Stem bark	$y = 0.0191x^2 - 0.0075x + 0.0655$	$R^2 = 0.959$
Live branches	$y = 0.0734x^2 - 0.1419x + 0.1688$	$R^2 = 0.866$
Dry branches	$y = 0.0090x^2 + 0.0112x + 0.1312$	$R^2 = 0.666$
Needles	$y = 0.0476x^2 + 0.0037x + 0.0189$	$R^2 = 0.916$
All dry mass	$y = 0.3215x^2 - 0.4479x + 0.6306$	$R^2 = 0.985$

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Table 3. Regression relationships between DBH (x) and dry mass of particular biomass compartments (y) of pine with correlation coefficients; thin branches include leaved part with diameter below 0.5 cm

Biomass compartment	Model	Correlation coefficient
Stem	$y = 34.213e^{0.0863x}$	$R^2 = 0.870$
Stem wood	$y = 31.868e^{0.0863x}$	$R^2 = 0.849$
Stem bark	$y = 2.4689e^{0.0831x}$	$R^2 = 0.913$
Thick branches	$y = 0.9020e^{0.1099x}$	$R^2 = 0.775$
Thin branches	$y = 0.1501e^{0.1483x}$	$R^2 = 0.901$
Needles	$y = 1.4222e^{0.1012x}$	$R^2 = 0.763$
All dry mass	$y = 35.662e^{0.0895x}$	$R^2 = 0.877$

As for the low number of pine samples, the relationships between DBH and biomass compartments were fitted the best exponentially. The correlation coefficients showed weaker relationships compared to spruce polynomial model; the weakest ones were found for both needles and thick branches as $r^2 = 0.763$ and 0.775, respectively (see Table 3).

Nutrient pools. Nutrient pools in particular stands were based on the structure of the stand part in every treatment, regression relationships between tree species DBH and dry mass of tree biomass compartments and also on mean contents of nutrients in the biomass compartments. For those few spruces which DBHs exceeded 25 cm, a regression approach for compartment biomass estimation was borrowed from Vejpustková et al. (2017). Scots pine regression models were applied also for Weymuth pines, which in individual treatment accounted for 4% of G maximally (Table 4).

The computed nutrient pools in compartments served for determination of nutrient removal by clear-cutting and of nutrient pools in logging residues left according to method of biomass processing after clear-cutting.

Statistical analyses. The statistical analyses were performed in R (R Core Team 2019). To compare nutrient concentrations in each tree compartment, non-parametrical Kruskal-Wallis test with multiple comparison by kruskalmc (pgirmess package; see Siegel, Castellan 1988) was used. The differences were considered to be significant if $P \leq 0.05$.

RESULTS

Stand structure

The densest stand was that one where the C-c-1 treatment was established after logging; the highest share of spruce was found there (see Table 4). Except for few overstory trees, spruces developed a sparse subcanopy layer. The C-c-1 basal area was ca. 5% higher compared to the other treatments; 90% of basal area shared Scots pine in all treat-

Table 4. Forest stand characteristics in the three treatments

Treatment	Species code	Number of trees (N)	Number of trees (%)	Mistletoe (%)	DBH (cm)	Height (m)	Max. height (m)	Basal area (m²)	Basal area (%)
Control	SP	658	77.8	22.1	26.7	24.8	27.0	38.7	93.2
	WEP	11	1.3		19.9	22.6	26.2	0.4	1.0
	NS	177	20.9		10.8	9.7	32.1	2.4	5.9
	Total	845	100.0		23.3	21.6	32.1	41.5	100.0
C-c-1	SP	679	68.7	15.7	27.0	25.1	28.0	40.3	92.8
	NS	309	31.3		11.0	10.4	18.9	3.1	7.2
	Total	988	100.0		22.0	20.5	28.0	43.5	100.0
C-c-2	SP	648	75.1	19.8	26.7	26.4	28.3	38.0	91.2
	WEP	73	8.5		16.7	23.9	28.2	1.8	4.4
	NS	142	16.4		11.9	11.0	24.6	1.8	4.4
	Total	863	100.0		23.5	23.7	28.3	41.6	100.0

SP – Scots pine; WEP – Weymouth pine; NS – Norway spruce; ; C-c-1, C-c-2 - for description of treatments see Table 1

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Table 5. Nutrient concentrations in individual compartments of spruce and pine (% of dry mass), the same letters indicate a statistically homogeneous group of compartments for particular nutrient (in rows; Kruskal-Wallis), branches were analysed in bark

NS	Stem wood		Stem bark		Live branches		Dry branches		Needles	
Nutrient	X	Sx	X	Sx	X	Sx	X	Sx	X	Sx
N	0.046[a]	0.017	0.436[bc]	0.131	0.594[cd]	0.083	0.430[ab]	0.058	0.937[d]	0.081
P	0.004[a]	0.005	0.066[bc]	0.020	0.075[cd]	0.018	0.035[ab]	0.011	0.125[d]	0.028
K	0.028[a]	0.010	0.238[cd]	0.074	0.208[bc]	0.050	0.050[ab]	0.037	0.392[d]	0.079
Ca	0.068[a]	0.025	1.254[d]	0.517	0.303[bc]	0.046	0.370[cd]	0.049	0.257[b]	0.067
Mg	0.012[a]	0.004	0.069[c]	0.024	0.053[bc]	0.008	0.034[ab]	0.009	0.066[c]	0.016

SP	Stem wood		Stem bark		Thick branches		Thin branches (< 0.5 cm)		Needles	
Nutrient	X	Sx	X	Sx	X	Sx	X	Sx	X	Sx
N	0.034[a]	0.019	0.210[ab]	0.102	0.253[ab]	0.041	0.817[bc]	0.036	1.436[c]	0.089
P	0.011[a]	0.008	0.001[a]	0.025	0.015[ab]	0.007	0.090[bc]	0.039	0.142[c]	0.013
K	0.020[a]	0.008	0.048[ab]	0.123	0.150[ab]	0.023	0.392[bc]	0.021	0.572[c]	0.034
Ca	0.070[a]	0.009	0.340[b]	0.204	0.251[ab]	0.029	0.252[ab]	0.052	0.236[ab]	0.068
Mg	0.011[a]	0.001	0.012[a]	0.001	0.037[ab]	0.006	0.066[b]	0.008	0.084[b]	0.020

NS – Norway spruce; SP – Scots pine; X – mean; Sx – standard deviation

ments. Despite some differences, all treatments were considered comparable.

Nutrient contents

Needles of both pine and spruce were higher in N, P, K and Mg, whereas bark was higher in Ca (for pines insignificantly). The live branches of spruce were higher in N and P compared to dry ones. The significance of the differences in nutrient contents of pine individual compartments were less frequent as a consequence of lower number of samples (Table 5).

Nutrient pools and nutrient removal

Aboveground tree dry mass computed by the regression relationship approach ranged from 283 to 294 tons per ha in the three plots (Table 6). Nutrient share of species in individual treatments was mostly proportional to their basal areas. Higher dry

Table 6. Tree species dry mass and biomass nutrient pools in the three treatments

Treatment	Species	Dry mass		N		P		K		Ca		Mg	
		(t·ha^{-1})	(%)	(kg·ha^{-1})	(%)	(kg·ha^{-1})	(%)	(kg·ha^{-1})	(%)	(kg·ha^{-1})	(%)	(kg·ha^{-1})	(%)
Control	SP	271.1	95.9	318.6	90.8	54.5	92.8	147.6	91.8	301.1	92.5	53.9	93.9
	WEP	2.7	1.0	2.9	0.8	0.5	0.9	1.4	0.9	2.9	0.9	0.5	0.9
	NS	9	3.2	29.3	8.4	3.7	6.3	11.8	7.3	21.4	6.6	3	5.2
	total	282.8	100.0	350.8	100.0	58.7	100.0	160.7	100.0	325.5	100.0	57.4	100.0
C-c-1	SP	281.8	96.0	322.9	88.7	55.9	91.5	150.1	90.0	312.1	91.6	55.6	93.1
	NS	11.6	4.0	41.2	11.3	5.2	8.5	16.6	10.0	28.4	8.3	4.1	6.9
	total	293.5	100.0	364.1	100.0	61.1	100.0	166.7	100.0	340.6	100.0	59.7	100.0
C-c-2	SP	264.3	93.5	286.4	89.0	50.9	90.9	134.3	90.0	291.2	91.0	51.4	91.9
	WEP	11.6	4.1	11.6	3.6	2.2	3.9	5.4	3.6	12.5	3.9	2.2	3.9
	NS	6.8	2.4	23.7	7.4	3	5.4	9.5	6.4	16.5	5.2	2.3	4.1
	total	282.7	100.0	321.8	100.0	56	100.0	149.3	100.0	320.1	100.0	55.9	100.0

SP – Scots pine; WEP – Weymouth pine; NS – Norway spruce

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Table 7. Participation of nutrient pools in stem wood, stem bark and smallwood with slash biomass (entitled as slash) on aboveground biomass pools (i.e. 100%) in the three treatments

Treatment	N (%)			P (%)			K (%)			Ca (%)			Mg (%)		
	wood	bark	slash	wood	bark	slash	wood	bark	slash	wood	bark	slash	wood	bark	slash
Control	28.2	10.5	61.3	62.9	1.0	36.1	34.6	5.8	59.6	57.0	19.5	23.6	66.0	4.0	30.0
C-c-1	28.1	10.7	61.2	62.4	1.2	36.5	34.6	6.0	59.4	56.3	19.8	23.8	65.7	4.2	30.1
C-c-2	31.0	11.4	57.6	66.8	0.9	32.4	37.6	6.1	56.4	58.5	19.5	22.0	68.5	4.0	27.5

C-c-1 – Clear-cut 1; C-c-2 – Clear-cut 2

mass of the C-c-1 was reflected proportionally in higher nutrient contents. The other source of differences in aboveground nutrient totals was the diameter distribution of individual tree species in particular treatment (Table 3).

In all the treatments, smallwood and slash constituted the highest nutrient pool of N and K whereas wood contained maximum of P, Ca and Mg accumulated in the aboveground biomass (Table 7). With respect to its amount, nutrient pools in bark were much lower with exception of Ca, which content differed for only ca. 2% from slash.

The C-c-1 treatment including slash removal for bioenergy purposes was impoverished for almost whole aboveground biomass and its nutrient pools. The nutrient removal accounted for 364 kg of N, 61 kg of P, 167 kg of K, 341 kg of Ca and 60 kg of Mg in 294 tons of dry mass per ha removed from the site. There were likely left mere 10% of slash unintentionally on the soil surface (processing residues – raking loss), which totalled 5 tons of dry mass with 22 kg of N, 2 kg of P, 10 kg of K, 8 kg of Ca and 2 kg of Mg per ha remaining at the site only.

As for the C-c-2 treatment, logging residues were windrowed and left on site amounting 16% of dry mass with for 58% of N, 32% of P, 56 % of K, 22% of Ca and 28 of % Mg of whole aboveground biomass (Table 8).

DISCUSSION

Impact on stands

C-c-2 stem-only removal left significantly more nutrients compared to common practice in C-c-1 treatment. It is likely that the rate of biomass removal would also affect forest growth. For example, productivity of Norway spruce was found to respond more sensitively to the nutrient loss due to slash and stump harvest than Scots pine as the dominant height was found lower in spruces whereas it remained unchanged in pines (Egnell 2016). Spruce is not, however, the main crop species at our study site. It dominates understory and, as such, is an important source of pole wood, and both pre- and post-harvesting slash. Although mixture of Scots pine and Norway spruce were not found to be more productive compared to the best performing monocultures, the mixed stands performed equally well in many cases (Blaško et al. 2020). In our experiment, individual spruces released from understory due to broken pine canopy showed their performance capability on the site as they grew even as tall as the dominant pine overstory.

Negative or positive impact on site

The largest negative effects on site were found after whole-tree and stump harvesting operations (Mayer et al. 2020). Also Akselsson et al. (2019)

Table 8. Dry mass and nutrients in aboveground biomass and logging residues left on individual plots (treatments) after clear-cutting and timber hauling on C-c-1 and C-c-2 and share of initial biomass

Treatment	Dry mass		N		P		K		Ca		Mg	
	(t·ha^{-1})	(%)	(kg·ha^{-1})	(%)	(kg·ha^{-1})	(%)	(kg·ha^{-1})	(%)	(kg·ha^{-1})	(%)	(kg·ha^{-1})	(%)
Control	282.8	100.0	350.8	100.0	58.7	100.0	160.7	100.0	325.5	100.0	57.4	100.0
C-c-1	5.0	1.7	22.3	6.1	2.2	3.6	9.9	5.9	8.1	2.4	1.8	3.0
C-c-2	45.0	15.9	185.2	57.6	18.1	32.4	84.1	56.4	70.5	22.0	15.4	27.5

C-c-1 – Clear-cut 1; C-c-2 – Clear-cut 2

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pointed out the risk of nutrient depletion at a site if trees such as Norway spruce and Scots pine are removed completely. This can be prevented using our C-c-2 stem-only harvesting which left 16% of the dry slash representing more than half of N and K, almost one third of P and Mg and more than one fifth of Ca allocated in the whole above-ground biomass. At analogous nutrient-poor sandy sites, Bílek et al. (2016) reported similar values for N (54–56%) and even higher ones for P (56–58%) and K (38 to 45%) in the smallwood and slash biomass of Scots pine which represented 14 – 24% of the total above-ground biomass. If considering also below-ground biomass parts, leaving needles, branches, stumps and coarse roots on the site can account for 74% N, 67% P, 72% K, 51% Ca and 62% Mg of biomass pools in Scots pine-dominated managed forests in the same area of interest (Novák et al. 2017) as our study site is placed. There were also studies such as that one by Jurevics et al. (2016) in which stump and/or slash harvest had no general medium-term effects on the total forest C pool which is in narrow relationship to other accumulated nutrients. Also Palvianen, Finér (2012) reported a smaller effect of whole-tree harvesting compared to stem-only harvesting on differences in nutrient export from pines compared to spruces and birches. Moreover, increased soil nitrate losses in percolating water under the piled logging residues of birch were reported compared to spruce and pine piles (Törmänen et al. 2020). Nilsson et al. (2018) found only small differences in nutrient removal levels when using so called fresh-stacked and dried-stacked methods though more needles were left on site in case of using the latter one. Raking and immediate export of slash after clear-cutting, which was conducted for our study purpose, did not allow needles to be left in sufficient amount on the site.

Logging residues left on the site contribute to the nutrient reserves through progressive decomposition. It is not, however, the mere amount of nutrient left on site which matters as there were proved significant differences in decomposition rates among the biomass parts in the order needles > twigs and fine roots (Eldhuset et al. 2017) which means the coarser biomass residue the slower breakdown rate. Progressive decomposition due to differently recalcitrant biomass compartments left after the clear-cutting is likely to be prolonged if the slash is windrowed as in the C-c-2 treatment. It is the way how a long-term source of nutrients is formed for use by the next forest generation. Progressive release of nutrients is beneficial also for it spans period of root development of the new forest trees to be ready to accept nutrient flux on the area of clear-cutting (Andersen et al. 2008). Laiho and Precott (2004) reported previously that coarse woody debris (CWD) contributes between 3–73% of above-ground litter input which accounts for less than 20% of N, P, K and Ca of the above-ground nutrient input. This should not demean importance of CWD at dry sites especially where CWD is likely to enhance nutrition by retaining moisture (Laiho, Prescott 2004) and bark of decomposing CWD is also long-term source of C and N (Romashkin et al. 2018).

From the ecosystem nutrition point of view, also natural disturbances such as bark beetle outbreaks can be viewed positively as there can be expected increased nutrient return (e.g. Cigan et al. 2015) from both the foliage fallen and the bark peeled off. And also, when stands of dead lodgepole pine were salvage cut after pine beetle outbreaks, Rhoades et al. (2020) found no negative effect of whole-tree harvesting on soil moisture, soil nitrogen supply or pools relative to uncut stands. For improvement of the managed forests nutrition, one can hardly rely on these natural processes. If needed, nutrient losses can be recompensed to some extent using an artificial fertilization. For example both production (Mavimbela et al. 2018) and soil characteristics (Prietzel et al. 2008) improvements were found after fertilization of the depleted pine sites. For sustainable nutrition maintenance, operations such as debarking of logs before skidding were reported to be an efficient soil improving measure since the bark is high in nutrients (see e.g. Kreutzer 1979; Akselsson et al. 2019). Despite the high nutrient concentrations, nutrient pools in dry matter of bark are lower relative to nutrient pools in other biomass compartments (see Table 7). Scots pine bark of the smallwood, which was left on the C-c-2 treatment in windrows, is likely to serve as earlier nutrient source compared to more recalcitrant wood. It is mechanically disintegrated sooner, falls on the ground and contact with forest floor helps improve the nutrient return. If stem bark of our stands was left on the site, it would increase Ca return particularly, which along with other nutrients return would be beneficial for the future forest ecosystem nutrition. This operation is, however, increasing the logging costs and is not likely

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to be applied. This favors the C-c-2 scenario at our nutrient-poor study site where 16% of the dry aboveground biomass in slash left on site returned more than half of N and K, almost one third of P and Mg and more than one fifth of Ca allocated in the whole above-ground biomass. And also, harvesting of stumps and roots is no longer applied, which seems to leave quite large amounts of biomass nutrients from slash and below-ground compartments accounting for one half to two thirds of the total stand biomass nutrient pools (see Novák et al. 2017) at the studied sites.

CONCLUSION

Based on the analyses of the nutrient distribution and pools in the aboveground biomass of Scots pine forest with Norway spruce in understory at the nutrient poor site, it can be concluded that:

(*i*) despite individual differences in nutrient concentrations of pine and spruce compartments, species representation in stand basal area was closely related to its share in aboveground biomass and in nutrient pools allocation;

(*ii*) needles and stem bark of Norway spruce were much higher in nutrients than stem wood, whereas Scots pine bark was lower in P compared to stem wood;

(*iii*) given the dry matter distribution, the highest pools of P, Ca and Mg were accumulated in stem wood; smallwood and slash accumulated most N and K, the least basic nutrient amounts were stored in stem bark;

(*iv*) in comparison with whole-tree harvesting approach (ca. 10% of the slash left), stem-only harvesting method increased amount of aboveground biomass left on site for more than 14%, which represents 51%, 29%, 50%, 20% and 25% higher pools of N, P, K, Ca and Mg in the biomass accumulated, respectively;

(*v*) leaving stem bark biomass on the site would account for 11%, 1%, 6%, 20% and 4% more N, P, K, Ca and Mg, respectively, to be decomposed for the next forest generation nutrition.

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