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Effect of harvest intensity and soil moisture regime on the decomposition and release of nutrients from needle and twig litter in northwestern Ontario

Joel Symonds[1], Dave M. Morris[2]* and Martin M. Kwiaton[2]

[1] *Faculty of Natural Resource Management, Lakehead University, 955 Oliver Rd, Thunder Bay, ON P7B 5E1, Canada*
[2] *Ontario Ministry of Natural Resources, Centre for Northern Forest Ecosystem Research, c/o Lakehead University, 955 Oliver Rd, Thunder Bay, ON P7B 5E1, Canada (*corresponding author's e-mail: dave.m.morris@ontario.ca)*

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A four-year fine litter decomposition study was established at black-spruce dominated forest sites following harvesting that included a range of biomass removals (uncut stand, stem only, full-tree, and full-tree + bladed). The current study was designed to address the following questions: (1) does an increase in biomass removal alter the decomposition rates and nutrient release in fine litter, and (2) do these patterns differ across site types that vary in soil moisture regime? Orthogonal contrasts revealed that: (1) conditions following harvesting (all biomass removal treatments combined) slowed the decomposition of both needle and twig material as compared with that of the uncut controls, (2) removal of the forest floor further reduced needle decomposition as compared with the other harvest treatments, and (3) decomposition rates did not differ between stem-only and full-tree harvest treatments. The wet mineral sites showed a more rapid rate of decomposition within the first two years.

Introduction

The boreal forest region in Ontario alone covers 43 million ha, with nearly 90% being considered as productive/commercial forest. A significant portion of the 22 million m^3 of roundwood harvested annually in Ontario comes from the boreal forest region (OMNR 2008). In Ontario, and elsewhere, the forest sector is undergoing a significant shift from primarily producing traditional wood products (i.e., lumber, pulp and paper), to a broadening array of bio-products, such as fuel for energy, specialty chemicals, and polymers. This growth in the bioeconomy sector, and the use of forest biomass as feedstock, is being driven by: (1) the demand for and cost of energy; (2) the need for climate change mitigation; (3) the need for economic renewal, innovation, and development particularly in small, northern and aboriginal communities; and (4) an interest in natural, renewable, and biodegradable source materials for products (Puddister *et al.* 2011). An important feedstock source, particularly in the boreal forest, is roadside slash generated by full-tree (also referred as whole-

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tree) harvesting systems, where the entire aboveground portion of the tree is removed and processed at roadside. For several decades, concerns have been raised that these removals, and the associated nutrients, may affect long-term site productivity (*see* reviews by Dyck *et al*. 1994, Richardson *et al*. 2002, Röser *et al*. 2008).

Site productivity in forest systems is maintained by the decomposition and release of nutrients from recycled litter or fine logging debris and soil organic matter (Aber and Melillo 1991). Microbial populations are the primary agents responsible for breaking down organic material into its inorganic form available for plant uptake (Chapin *et al*. 2002). However, since the rate at which microbial populations decompose organic matter in northern forests is slow, there is often an accumulation of litter in the forest floor which can actually limit site productivity (Prescott *et al*. 2000a).

In a review of literature pertaining to litter decomposition in northern forest soils, Berg (2000) reported that decomposition rates can range from 36.5% per year for fresh litter to 0.004% per year for more completely decomposed material. Many studies have confirmed that climate (temperature and precipitation) and substrate quality are the two main controlling factors of litter decomposition rate (Meentemeyer 1978, Vogt *et al*. 1986, Johansson *et al*. 1995, Moore *et al*. 1999, Berg 2000, Trofymow *et al*. 2002, Heim and Frey 2004, Pare *et al*. 2006, Santruckova 2006). Clear-cut harvesting alters soil temperature and moisture (Ballard 2000), and can change microbial community structure (Staddon *et al*. 1997) resulting in changes to the rates of litter decomposition and nutrient release. Findings, however, from these litter decomposition experiments have yielded mixed results, in part, due to increased fluctuations in microclimate conditions (i.e., high diurnal temperature changes, and periodic desiccation of surface soils) that can negate the positive effects on litter decomposition. Significant differences in litter decomposition and nutrient release rates following clearcut harvesting have been observed for some litter material types but not for others (Prescott *et al*. 2000b). In some cases, these differences have been shown within the first year but not in later stages (Duchesne and Wetzel 2000).

In light of the growing interest to intensify harvesting of forest biomass as a primary feedstock for the bioeconomy sector, there is a need to better understand how increased biomass removal will affect nutrient dynamics and decomposition rates in northern boreal forest systems. The current study was designed to address three questions. Firstly, does an increase in biomass removal alter the decomposition rates and nutrient release in the forest floor material (senesced needles and fine twigs)? Our prediction is that there will be a decline in decomposition rates along the gradient of increased biomass removal (hypothesis I). Secondly, do these patterns differ across site types that vary in soil moisture regime (moderately dry, moist, wet)? Here we predict lower decomposition rates at both the moderately dry and wet sites following harvesting, the result of either midsummer drought conditions (moderately dry site) or periods of saturated soil conditions (wet site) (hypothesis II). Finally, we predict that these differences in decomposition rates will diminish over time as substrate quality becomes a more determinant factor (hypothesis III).

Material and methods

Study site descriptions

The study area is situated on the eastern edge of Rowe's (1972) Upper English River Section within the Boreal Forest Region approximately 60 km northwest of Thunder Bay, Ontario (49°04´N, 89°15´W). The monthly temperature profile for the study area is characteristic of a climate with cold, dry winters and relatively short, moderately warm, moist growing seasons. Based on 20-year climatic averages, the mean annual temperature is 2.0 °C, and the mean annual precipitation is slightly under 670 mm yr^{-1} (60% falls as rainfall during the frost-free period). During the study, average growing-season air temperature (1 May–30 October) varied only slightly between the study years (11.6–12.2 °C), and precipitation was relatively consistent averaging 370 mm, although the rainfall in 1998 was higher (495 mm) than during the other three years. A total of 12 900 m^2 fixed-area plots, treated as replicates, were selected to represent modal conditions of three discrete vegetative communities commonly occurring along a topographic sequence in northwestern Ontario.

Site Type 1 (UM = upland, mineral) represents a spruce-pine/feathermoss site type occupying an upland, well-drained, moderately dry site (Dystric Brunisol profile [Agriculture Canada Expert Committee on Soil Survey 1987]), with a relatively thin (7–10 cm) fibrimor humus layer. The stand was dominated by black spruce (80%) and jack pine (20%) with a scattered occurrence of trembling aspen. The stand was approximately 100 years of age with a mean stand density of 1740 stems ha^{-1} and a basal area (BA) of 32.7 m^2 ha^{-1} (mean height = 15.1 m, mean diameter at breast height (DBH) = 14.2 cm). Site Type 2 (WM = wet, mineral) is representative of a moderately productive swamp occupying a poorly-drained, wet mineral site (rooting zone has periodic contact with the water table) dominated by black spruce. Mean stand age was 110 years with a stand density of 1200 stems ha^{-1} and a BA of 22.7 m^2 ha^{-1} (mean height = 14.6 m, mean DBH = 12.8 cm). The soil profile consists of thin, silty loam, mineral soil layers, overtopped by a relatively thick (20–30 cm) fibric peatymor humus (Terric Fibrisol profile [Agriculture Canada Expert Committee on Soil Survey 1987]). Site Type 3 (LP = low, peatland) represents low productivity, treed wetlands that have developed on organic substrate and are dominated by slow-growing black spruce with a minor component of larch. The mean stand age was 80 years with a stand density of 3480 stems ha^{-1} and a BA of 17.4 m^2 ha^{-1} (mean height = 6.9 m, mean DBH = 7.0 cm). Typically, the sphagnum-dominated forest floor has hummocky microtopography with deep, often water-filled hollows. The soil is representative of a classic organic profile common throughout northwestern Ontario, consisting of a thick (greater than 2 m) fibric peatymor humus (Humic Fibrisol profile [Agriculture Canada Expert Committee on Soil Survey 1987]).

Harvest treatments

In 1995, experimental harvests of varying intensities were conducted on 36, 30 × 30-m plots (three plots randomly assigned to three harvest treatments and an uncut control for each of the three site types). The harvest treatments included: (1) a stem-only (SO) harvest in which trees were delimbed at the stump, (2) a full-tree (FT) harvest in which trees were forwarded and delimbed at the roadside, and (3) a full-tree harvest followed by a winter shear blading (FTB) using a D8 bulldozer to remove the forest floor, roots, and stumps. This treatment resulted in the complete removal of the O horizon at the UM site, and the upper 20–25 cm at the WM and LP sites. In addition, three plots were identified within a large uncut portion of the stand to represent the reference-state condition (RS).

Litter bag deployment/retrieval

A total of 432 litter bags were filled with up to 5.0 g dry weight of litter material, resulting in 144 needle, twig (< 6 mm in diameter), and composite (twigs and needles mixed together) bags. A systematic grid (3 × 4 m) was established in the centre of each 30 × 30-m treatment plot, and randomly assigned a litter type and collection date. The collection periods included: six months (192 days), one year (343 days), two years (694 days), three years (1078 days), and four years (1450 days). Time 0 subsamples for each litter type and site type, were also retained for nutrient analysis. Bags were placed 1-m apart, and pinned to the forest floor underneath the fresh logging debris (if present) at each site in the autumn of 1995. Statistical analysis of the decomposition and nutrient data showed that there were no differences between the composite and pure litter bags, so the data from the composite bags were pooled together with the pure needle and pure twig data to increase the number of replicates.

Upon retrieval, the bags were picked clean of foreign debris (e.g., moss, fine roots), oven-dried at 60 °C, the contents removed and cleaned a second time, weighed, ground through a Wiley mill (20 mesh), and stored awaiting nutrient analysis. Total Kjehdahl Nitrogen (TKN) was determined using a modification of the classic Kjeldahl method (Kalra and Maynard 1991), and analyzed with a Technicon Instruments AutoAnalyzer II. Total phosphorus (P_{tot}), potassium (K), magnesium (Mg), and calcium (Ca) were determined with a Varian Vista Pro inductively coupled argon plasma spectrometer (ICP-AES) using a mixed acid (H_2SO_4, HNO_3, $HCLO_4$) digest (Grimshaw *et al*. 1989). All samples were analyzed in duplicate (QA), and NIST (National Institute of Standards and Technology) standard reference material (Pine 1575) was incorporated as a QC check every ten samples.

Statistical analysis

The litter decomposition experiment was treated as a $3 \times 4 \times 6$ completely randomized design (CRD), with site type, harvest treatment, and time as fixed factors. In this case, time was not considered a repeated measure as individual bags (each with unique weights of material — approx. 5 g dry weight, but precise weights were recorded) were randomly (*a priori*) assigned to a particular collection date, and placed at a unique location on each plot in a systematic grid. In this way, each bag experienced different forest floor/microclimate conditions as compared with the other deployed bags, providing a different expression of the within plot (experimental unit) variation for each collection date. ANOVA was performed using the PROC GLM procedure of SAS/STAT software (SAS Institute Inc. 1987). Response variables included: relative mass loss (% of initial mass), and relative nutrient content (% of initial content). Post-hoc examinations of the main effects were dealt with differently depending on the factor. Harvest treatment (qualitative factor) effect was examined using a series of orthogonal contrasts (Snedecor and Cochran 1989, Lane 1999). The contrasts and associated ecological questions that were addressed included: (L_1) is there a significant change in the rate of mass or nutrient loss resulting from timber harvesting (RS *versus* harvested)? (L_2) is there a significant change in the mass or nutrient loss when both the overstory and the organic matter on the forest floor are removed during harvesting (FTB *versus* FT, SO)? and (L_3) is there a significant change in the mass or nutrient loss when different amounts and sizes of slash remain at the site after harvesting (SO *versus* FT)? The expressions for these contrasts are summarized in Table 1.

The post-hoc Student-Newman-Keuls (SNK) multiple range test was used to examin the effect of site type (qualitative) on relative mass loss and nutrient content. As the main factor, time since deployment represented a quantitative factor, trend analysis was used to examine the shape of the response curves (Mize and Schultz 1985).

Results

Mass loss patterns

Mass loss trends within the first year were similar between needle and twig litter material (Fig. 1). There was a rapid loss of both needle and twig mass (approximately 20%) within the first six months, but then between six months and one year there was little change in mass. Percentage of twig mass loss was slightly lower than that of the needle mass loss during the first year but a clear divergence between the two materials was found at year two (ANOVA: $F_{1,134} = 14.35$, $p = 0.002$). By year two, decomposition of the twig material seemed to stabilize and no change in mass loss was recorded over the remainder of the experiment. Needle material however, continued to decompose and lose mass at a consistent, near

Table 1. Orthogonal contrasts for the effect of harvest type on litter mass and nutrient loss. λ subscripts are: 1 = Reference State (RS), 2 = Stem Only (SO), 3 = Full-Tree (FT), 4 = Full-Tree + Bladed (FTB).

	Contrast	Treatment coefficient				
		λ_1	λ_2	λ_3	λ_4	$\Sigma\lambda$
L_1	Unharvested *vs*. Harvested	–3	1	1	1	0
L_2	Forest Floor Removed *vs*. Retained	0	1	1	–2	0
L_3	Coarse & Fine Slash Retained *vs*. Coarse Slash Only	0	1	–1	0	0

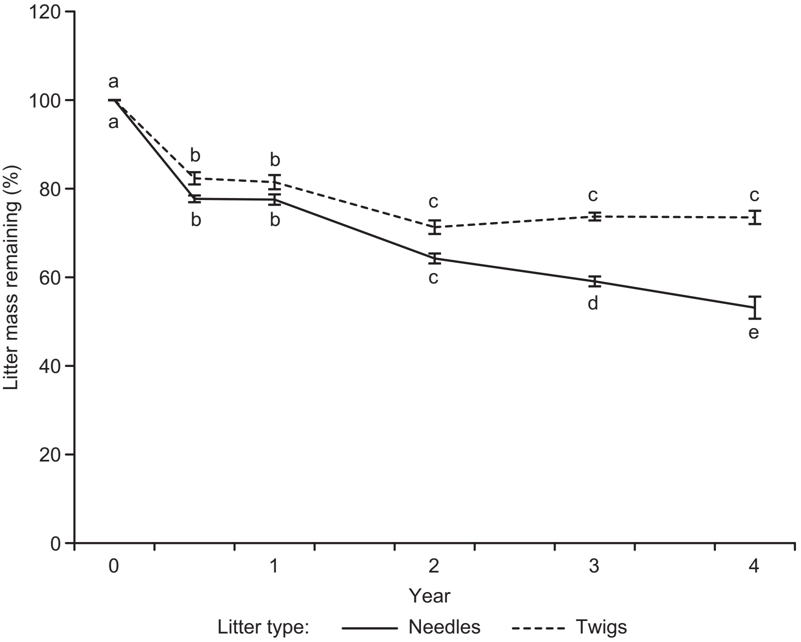

Fig. 1. Mean ± SE needle (black spruce and jack pine) and twig mass remaining (%) from all sites and harvest treatments. Different letters indicate statistically significant differences (post-hoc test) at $p < 0.05$.

linear rate during the entire sampling period. By year four, the percentages of original mass remaining were approximately 50% and 75% for needles and twigs, respectively (ANOVA: $F_{1,130} = 39.08, p < 0.001$). It should be noted that since black spruce and jack pine needles were found to lose mass at a similar rate, the results from these two species were pooled together.

Harvest treatment was found to significantly affect the rate of mass loss for needle material by year three (ANOVA: $F_{3,68} = 4.61, p = 0.006$). By year four, the difference between needle mass remaining in the non-harvested RS (40%) and in the FTB (65%) treatments was even more evident (Fig. 2). ANOVA results show harvest treatment did not have a significant effect on the rate of mass loss for fine twig material (ANOVA: $F_{3,303} = 2.67, p = 0.09$).

Site moisture regime (UM, WM, and LP) was found to have an effect on needle litter decomposition (ANOVA: $F_{2,78} = 15.46, p < 0.001$). Within the first two years, mass loss was found to occur more quickly at the WM sites, however by year three the WM mass loss rate slowed and soil moisture regime no longer had any significant influence (Fig. 3).

Orthogonal contrast results (Table 2) indicate that harvesting (L_1) significantly slowed the rate of mass loss of needle material (ANOVA: $F_{1,404} = 5.82, p = 0.02$), and slightly slowed twig decomposition as well (ANOVA: $F_{1,303} = 4.45, p = 0.049$). Removal of the forest floor was found to slow needle mass loss only slightly (ANOVA: $F_{1,404} = 4.22$, $p = 0.049$), but had no effect on twig material (ANOVA: $F_{1,303} = 2.14, p = 0.161$). Orthogonal contrast results also indicated that there were no differences between sites where both the coarse and fine slash material were retained (SO) and sites where the fine slash was removed but the coarse retained (FT) for needle

Table 2. Orthogonal contrast results for the effect of harvest type on litter mass loss.

	Contrast	Needles		Twigs	
		F	$p > F$	F	$p > F$
L_1	Unharvested *vs.* Harvested	5.82	0.020	4.45	0.049
L_2	Forest Floor Removed *vs.* Retained	4.22	0.049	2.14	0.161
L_3	Coarse & Fine Slash Retained *vs.* Coarse Slash Only	0.02	0.884	0.01	0.994

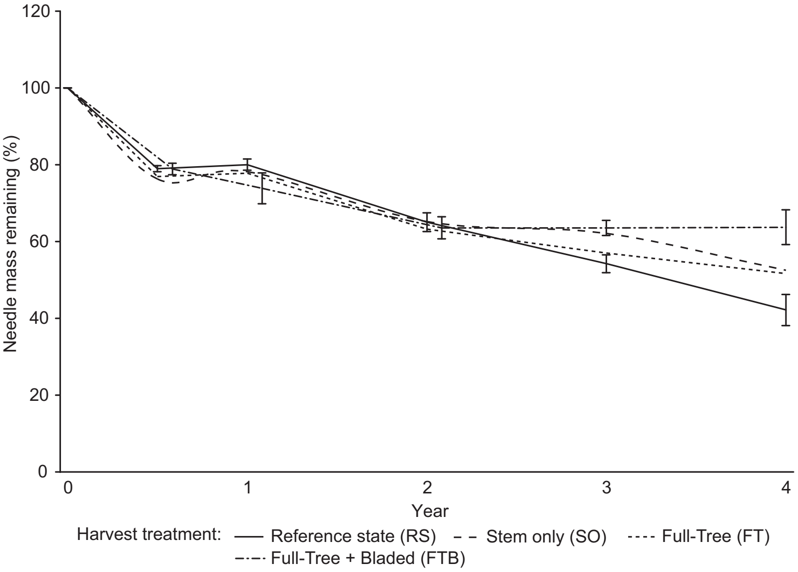

Fig. 2. Mean ± SE needle mass remaining (%) by harvest treatment. The FTB error bars were offset slightly to avoid overlap with other treatments.

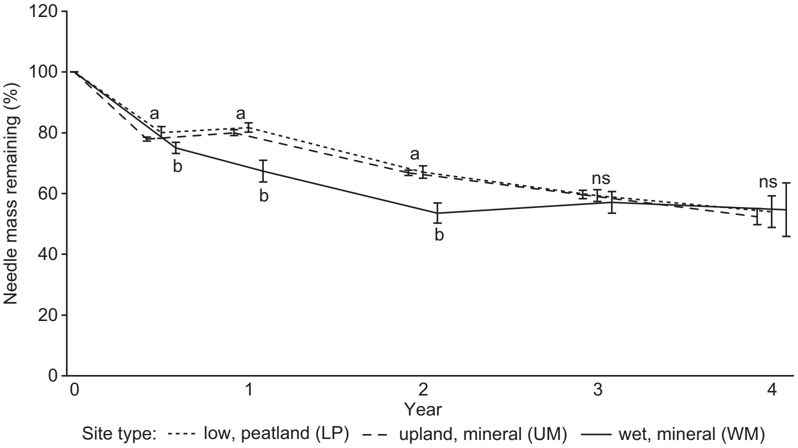

Fig. 3. Mean ± SE needle mass remaining (%) by site type. Different letters indicate statistically significant differences (post-hoc test) at $p < 0.05$ between WM and the other site types. UM error bars were offset to the left and WM error bars were offset to the right to avoid overlap with other site types.

(ANOVA: $F_{1,404} = 0.02$, $p = 0.884$) and twig (ANOVA: $F_{1,303} = 0.01$, $p = 0.994$) material, respectively.

Nutrient dynamics

Table 3 summarizes the initial (Time 0) nutrient concentrations and C:N ratios for the needle and twig litter collections done at each site prior to the initiation of the litter decomposition study. Differences in the chemical signatures between the litter types are evident. For example, base cation (K, Ca, Mg) concentrations are higher, and N and P concentrations are lower in the needle material as compared with those in the twig samples. These low N and P values are presumably the result of retranslocation prior to needle shed (Morris 2000). These low values, in turn, result in high C:N ratios (> 110) increasing the chance of N immobilization during the initial phase of decomposition.

Harvest treatment had no effect on nutrient (N, P, K, Ca, Mg) content at any point in time for either the needle or twig material. Similarly, there was no statistical difference between the three soil moisture regimes. However, N and P levels at the WM sites were consistently lower than those at the UM and LP sites. Time since deployment did have a significant effect on all nutrients (Table 4), however, trends varied temporally (i.e. by year) for each element.

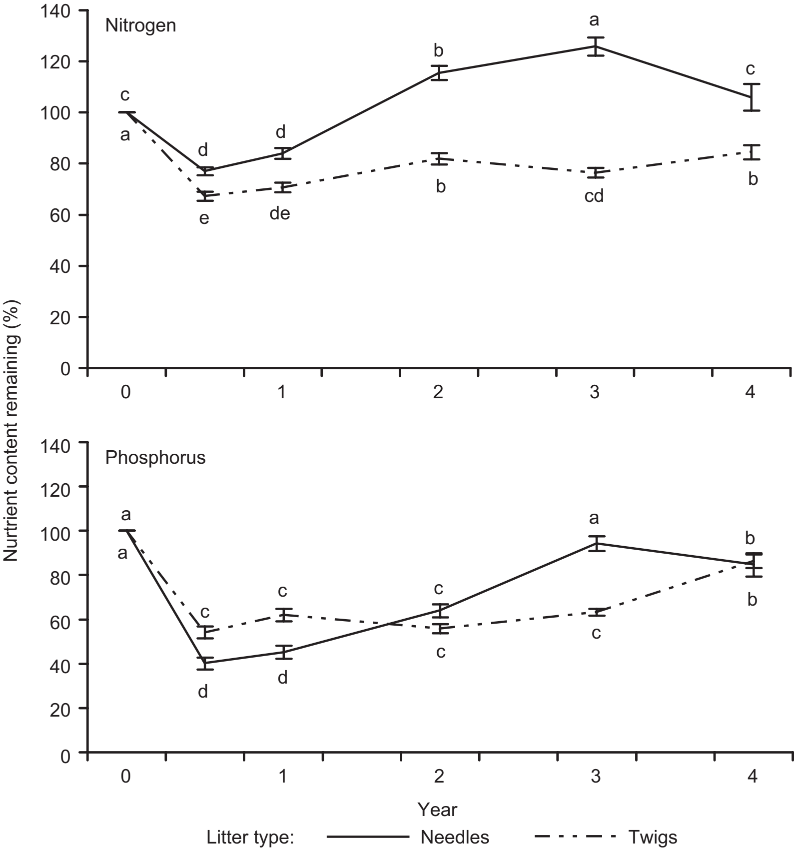

Fig. 4. Mean ± SE nitrogen and phosphorous content (%) remaining for needle and twig material. Different letters indicate statistically significant differences (post-hoc test) at $p < 0.05$ by year.

The N and P content of both the needle and twig material were found to decrease very rapidly within the first six months (e.g., needle P decreased by 60%) (Fig. 4). Nitrogen and P contents then gradually increased over the rest of the four-year study, with the exception of twig N, which remained stable from six months onward (Fig. 4). By year two, the N content of the needle material exceeded the original level. This increase (N immobilization) is likely due to the high initial C:N ratios (> 110) in the needle litter (Table 3). Nitrogen and P in the needle material began to decrease after year three and, in the case of needle P, converged with the levels found in the twig material.

Table 3. Initial nutrient concentrations (mg kg^{-1}) for the needle and twig litter samples for each of the study sites.

Area	N	P	K	Ca	Mg	C:N
Needles						
UM	4159	454	1163	9957	875	125.0
WM	4711	361	1274	11973	807	110.4
LP	3788	246	1021	8838	827	137.3
Twigs						
UM	5761	461	926	4017	480	92.0
WM	6018	414	932	4530	465	88.1
LP	6066	392	832	4449	466	87.4

Note: Initial (Time 0) nutrient concentrations were based on a bulk sample by litter type and site type prior to filling the litter decomposition bags.

Table 4. ANOVA results summarizing the effect of time on the relative nutrient content in the needle and twig litter.

Nutrient	Needles		Twigs	
	$F_{5,391}$	$p > F$	$F_{5,288}$	$p > F$
N	55.6	< 0.001	28.3	< 0.001
P	66.3	< 0.001	41.1	< 0.001
K	358.1	< 0.001	88.1	< 0.001
Ca	18.9	< 0.001	15.4	< 0.001
Mg	42.8	< 0.001	12.0	< 0.001

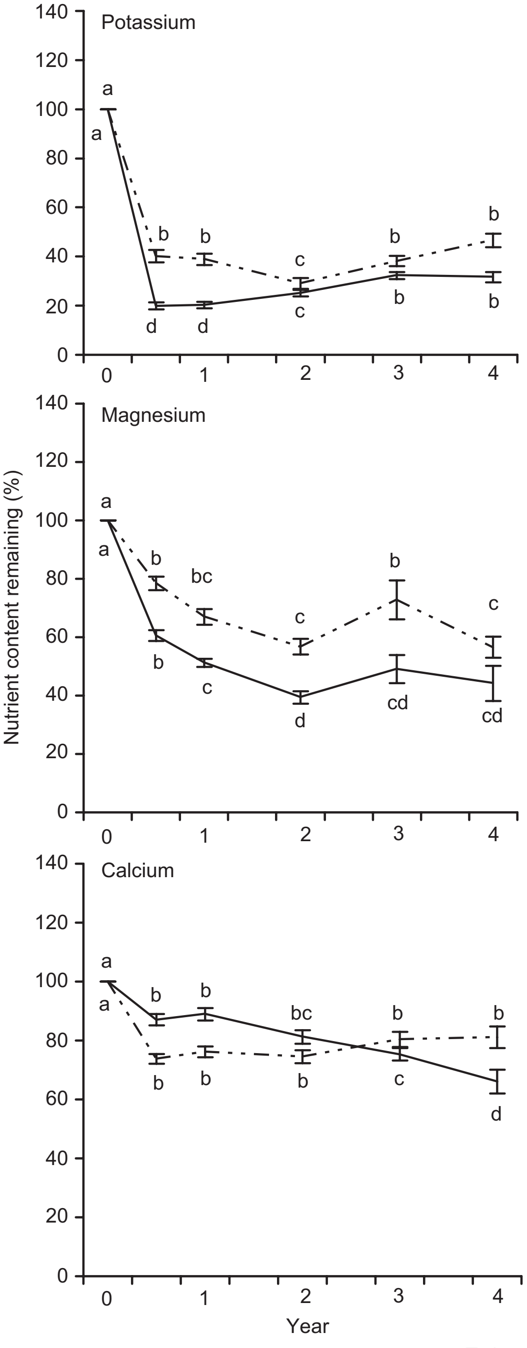

Fig. 5. Mean ± SE base cation (K, Mg, Ca) content (%) remaining for needle and twig material. Different letters indicate statistically significant differences (post-hoc test) at $p < 0.05$ by year.

Potassium content dropped significantly within the first six months, the loss being between 60%–80% of the original value, and then increased slightly over the remainder of the experiment (Fig. 5). Magnesium content dropped 20%–40% within the first six months, then followed a gradual and consistent loss to year two (Fig. 5). Between years two and four, Mg content levelled out to a point of equilibrium at around 60% of the original value. Calcium trends were dependent on the type of litter material. Calcium was released steadily from the needle material at a rate of approximately 15% per year for the full four years, whereas Ca in the twig material dropped by 25% in the first six months then remained unchanged for the next three years (Fig. 5).

Discussion

Mass loss

Research results evaluating the effect of clearcutting and soil moisture on decomposition rates are highly variable, showing increased, decreased, and no effect on decomposition (Blair and Crossley 1988, Cortina and Vallejo 1994, Prescott 1997, Prescott *et al*. 2000c, Palviainen *et al*. 2004a, 2004b, Moore *et al*. 2005), and would suggest that the complete answer is not a simple one. The present study affirms this complexity as our results advocate that decomposition rates are dependent on a combination of four factors: (1) litter material (needle foliage *vs*. twig), (2) harvest intensity (exposure of mineral soil), (3) soil moisture, and (4) incubation period.

General mass loss trends in our study were similar to those found in the literature; final needle mass loss values (47%) were comparable, but on the lower end of those reported in similar studies (40%–65%) (Lundmark-Thelin and Johansson 1997, Moore *et al*. 1999, Prescott *et al* 2000c, Palviainen *et al*. 2004a). Our findings were likely low with respect to the above decomposition values since these averages were taken from a broad range of climates, and many studies have shown cooler climates can slow early decomposition rates of some litter material (Meentemeyer 1978, Vogt *et al*. 1986, Johansson *et al*. 1995, Moore *et al*. 1999, Trofymow *et al*. 2002, Berg and Laskowski 2006). Studies have shown that foliage type also can affect the rate of decomposition, most notably the difference in mass loss rates expressed between broadleaf and needle foliage (Moore *et al*. 1999, Prescott *et al*. 2000c, Palviainen *et al*. 2004a). Differences have also been shown to exist between various needle types and have been attributed to different lignin: N ratios of different needle species (Moore *et al*. 1999). Contradictory to this statement and the findings of Palviainen (2004a), our results showed that there were no differences between decomposition rates of our two needle types, jack pine and black spruce. The percentages of twig mass loss results from year three (27%) was also very similar to the percentages reported by Palviainen *et al*. (2004a) (15%–25% at year three) for Norway spruce and Scots pine, and support the premise that because twig material has a lower C:N ratio, fewer soluble nutrients, and higher lignin content, decomposition has been found to occur more slowly (Berg and Laskowski 2006).

Although many studies have shown that decomposition tends to occur more slowly at clearcut sites (Blair and Crossley 1988, Cortina and Vallejo 1994, Prescott 1997), this clearcut effect appears to vary depending on the type of foliar litter examined. When comparing clearcut treatments with an uncut control plot, Prescott *et al*. (2000c) found that trembling aspen foliage decomposition rates were unaffected, but lodgepole pine needles slowed following clearcut harvest. In contrast, Palviainen *et al*. (2004a) found that silver birch leaves decomposed faster in clearcut plots than in forest plots, but Norway spruce needle decomposition rates were slowed by clearcutting, and Scots pine needle decomposition rates were unaffected. This high degree of variability in results would suggest that no clear connection can be made between foliage type and the effect of clearcutting on decomposition, although the findings from our study support that twig material decomposes at a slower rate than needle material.

Most existing studies have simply contrasted forested *versus* clearcut litter decomposition rates and have not compared varying harvest treatments. Since our study also compared a range of harvest intensity, we can attempt to dissect the processes further and speculate as to why some studies have shown clearcut effects while others have not. Contrasting the more conventional harvest treatments, FT and SO, to the uncut RS, we found that decomposition was slightly slower on the conventionally harvest sites (FT and SO), but these differences were not statistically significant. Similar results (i.e., harvest method did not influence litter mass loss) were reported by Smolander *et al*. (2008) for thinned Norway spruce stands. However, we did determine that the main factor affecting the mass loss was the removal of forest floor. Hendrickson *et al*. (1985) found similar results and noted that as compared with those at conventionally harvested sites, decay rates were significantly slower at sites that were whole-tree harvested (i.e., removal of stumps and greater mineral soil exposure). Removal of forest floor material may be an uncommon forest practice; however exposure of mineral soil commonly occurs through various types of silvicultural site preparation. Studies comparing the effect of site preparation on litter decomposition have found that exposure of mineral soil significantly slows decomposition (Duchesne and Wetzel 2000). It has been suggested that this effect is a result of site microclimate alteration, mainly increased temperatures and dryness, thus desiccating the litter and hindering the growth of microbial populations and ultimately decomposition (Hendrickson *et al*. 1985, Mallik and Hu 1997, Chapin *et al*. 2002, Berg and Laskowski 2006). Other studies however, have suggested that site preparation has the opposite effect and speeds up decomposition because it creates a more suitable microclimate (Johansson 1994, Lundmark-Thelin and Johansson 1997).

As mentioned above, there is a common understanding that soil moisture has a strong, positive relationship with decomposition. Not only do our harvest treatment findings support this statement (moist, uncut RS decomposed faster than the drier, harvested sites), but our site moisture regime treatments also support this as well. For example, we found that initial mass loss rates were fastest at the WM sites. However, it should be mentioned that this effect was short lived, since our decomposition rates converged again at years three and four and there was no longer any effect of site moisture regime. At this stage, it is likely that litter quality becomes a more determinant factor controlling decomposition rates (Meentemeyer 1978, Berg 2000). In addition, we found that there was no difference between our site type extremes (LP *versus* UM sites), which is inconsistent with the premise that increased moisture results in increased decomposition. It is possible however, that the decomposition rate on our LP sites was slowed either due to saturation conditions (Chapin *et al.* 2002), or from extreme moisture fluctuations, both of which have been shown to hinder decomposition (Clein and Schimel 1994).

The results from our study also demonstrate that differences were highly dependent on the incubation period. Harvest treatment was found to have no effect on decomposition until year three. This is contradictory to the results presented by Duchesne and Wetzel (2000), who showed that harvesting and site preparation significantly affected decomposition rates at year one but these effects were diminished and were insignificant at year three. General mass loss trends over time were quite predictable; mass loss of twig material was rapid initially but then slowed by year two and remained unchanged for the remainder of the experiment, whereas the needle mass loss continued over the full four years. The lack of mass loss of the twig material beyond year two is likely because the soluble compounds have all been leached by this point in time and what remains in the woody material at year two is the slow decomposing lignin and other recalcitrant compounds (Berg and Laskowski 2006).

Nutrient dynamics

Though many studies have investigated the effect of clearcutting on litter decomposition rates, fewer studies exist regarding the effect on litter nutrient dynamics and the few studies that are available, present mixed results. Some studies have shown that clearcutting does have a significant effect on litter nutrient dynamics (Berg and Ekbohm 1983, Hendrickson *et al.* 1985, Palviainen *et al.* 2004b), while others support that clearcutting has no effect (Palviainen *et al.* 2004a). We found that both harvest treatment and site moisture had no effect on the release or accumulation of any nutrient (N, P, K, Mg, or Ca) from either of the litter types (needle or twig).

Unaffected by harvest treatment or soil moisture, we found that N and P levels dropped immediately (20%–60%), then slowly accumulated over the rest of the study (up to 125% of the original needle N). In the case of the needle material, there was a slight release between years three and four. Unlike our finding however, many studies (Berg and Ekbohm 1983, Barber and Van Lear 1984, Kim *et al.* 1996, Palviainen *et al.* 2004a) failed to find any initial loss of N, rather they all found either an immediate accumulation of N in the material within the first few years or it remained unchanged for the first few years followed by an accumulation. The release of N from our foliage litter occurred slightly later (i.e., between years three and four) than when Palviainen *et al.* (2004a) observed this occurrence (i.e., between years one and two). Another notable result from our study was the P accumulation in decomposing needle and twig material; other studies report a steady release over time, particularly in foliage (Palviainen *et al.* 2004a). The only other references to P accumulation that could be found were in woody slash materials (Barber and Van Lear 1984, Palviainen *et al.* 2004a). Barber and Van Lear (1984) recorded constant P levels initially but then found an accumulation of P after a few years, and Palviainen *et al.* (2004a) only observed P accumulation in pine branches (≤ 10 mm). It is suggested that an initial flush of P can be easily missed, since it may occur within a matter of days after cutting. For example, in a greenhouse leaching experiment, S. A. Wiebe and D. M. Morris (unpubl. data) found that P leached immediately from fresh coarse woody debris at a rapid rate and suggested that this trend is likely caused by a rapid decomposition of the phloem.

Potassium trends observed in our study (60%–80%) are consistent with those found in the literature, which document an immediate rapid loss (60%–90%) within the first year, followed by minimal fluctuation for the next three years (Palviainen *et al.* 2004b) or even a slight increase (Barber and Van Lear 1984, Berg and Laskowski 2006). It is commonly understood that this rapid loss occurs because K is present almost entirely in ionic form, thus making it highly soluble and mobile in nature (Berg and Laskowski 2006). Magnesium is also known to be a relatively mobile element (Berg and Laskowski 2006) and our Mg trends support this statement. Magnesium content remaining was found to decrease at a fairly rapid rate within the initial two years of decomposition, at which point it began to accumulate slightly; a general trend also documented by Barber and Lear (1984), and Berg and Laskowski (2006). Calcium is known to be a much more stable element and leaches at a more consistent rate from litter material (Barber and Van Lear 1984, Palviainen *et al*. 2004b, Berg and Laskowski 2006). Foliar Ca remaining was found to decrease at a slow and steady rate (15% per year), whereas the fine-twig Ca dropped drastically (25%) within the first six months, but then remained stable for the duration of the study. With the exception of the initial twig-Ca drop, these trends are similar to those found by Palviainen *et al*. (2004b). The initial pulse of Ca being lost from the fine twig material could be a result of Ca rich bark being sloughed off, not identified as bark (but unidentifiable chaff material) and thus not analyzed with the twig material. If this was the case, twig Ca would have remained unchanged for the full length of the study, as expected.

Management implications

Contrary to our assumptions, conventional harvest treatments (SO and FT) were shown to have no effect on litter decomposition or nutrient release rates but were comparable to the rates observed in the uncut reference stand. In addition, we found no differences between the decomposition processes following the two conventional harvest treatments (SO and FT), even though they are commonly contrasted against one another to display their differences. One main difference however, is that they generate different slash loadings of residual biomass; SO harvesting produces a higher slash load (40 t ha^{-1}) than that of FT (25 t ha^{-1}) (Duckert and Morris 2001). Therefore, even though the decomposition processes are the same (i.e., mass loss and nutrient release), there would be greater assart flush following the SO harvest since there is a greater retention of live crown materials (foliage, twigs, and branches). The increased flush of nutrients would be available for plant uptake or could also be leached off site through surface runoff.

Conclusions

Our results did not support hypothesis I (there will be a decline in decomposition rates along the gradient of increased biomass removal) as decomposition rates in the conventional harvest treatments (SO and FT) were comparable to those in the uncut reference stands. The removal of the forest floor (FTB), however did reduce decomposition rates by year 3 of the study.

Our results supported hypothesis II (lower decomposition rates will occur on both the moderately dry and wet sites following harvesting) in that the initial mass loss was greatest at the WM (moist) site, with reduced decomposition at both the UM (moderately dry) and LP (wet) sites.

As per hypothesis III (differences in decomposition rates will diminish over time), the soil moisture effect noted above (hypothesis II) was short lived as the decomposition rates across the sites converged by year 3. The harvest treatment effect (hypothesis I), however, did not manifest itself until years 3 and 4 of the study.

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