MOISTURE REDUCTION AND NUTRIENT RETENTION ASSOCIATED WITH FIELD-DRYING FOREST HARVEST RESIDUES ON CLEARCUT SITES IN NORTHWESTERN ONTARIO, CANADA

by

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ABSTRACT

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Key Words: forest harvest residues, biomass, slash, field-drying, moisture content, decomposition, litterbag, foliage shedding, nutrient patterns.

The increased utilization of forest harvest residues as supplemental, inexpensive and renewable energy raises two key concerns: 1) continued removal may negatively affect long-term site productivity; and 2) because 50-60% of this material‟s green weight is water, transportation and burning costs of the green biomass very inefficient. Leaving the harvest residues to passively field-dry in the clearcut is a common forestry practice in the Nordic countries and is also used as a nutrient management strategy. While field-drying, nutrients are retained on site through the processes of physical foliage shedding, leaching and decomposition. The present study investigated the effects of field-drying on moisture reduction and the release of nutrients from black spruce [*Picea mariana* (Mill.) B.S.P.], jack pine [*Pinus banksiana* Lamb.] and trembling aspen [*Populus tremuloides* Michx.] harvest residues. Field-drying plots were established in recent clearcut sites near Thunder Bay, Ontario, Canada. Trees of each species were felled and the limbs gathered into small biomass piles inside netted enclosures. The piles were left to dry for one year and sampled at regular intervals (0, 4, 8, 12, 16, 48 and 52 weeks) for moisture content, nutrient concentration and percent foliage mass.

By week 4 (Jul) the average moisture content was reduced to a 17% (wet basis). However, the material regained moisture over the duration of the season; by week 16 (Oct) the moisture content increased to 28%, was 30% following the winter months (May), and then reached 16% by week 52 (Jun). Decomposition rates were 2, 3 and 5 $\%\cdot mth^{-1}$ for coarse branch, fine branch and foliage, respectively. Field-drying for a summer season (16 weeks) retained on site up to 34, 44, 48, 40, and 56% of the materials N, P, K, Ca, and B, respectively. If left to overwinter and field-dry 52 weeks, nutrient retention values increased up to 39, 57, 63, 36, and 59% for N, P, K, Ca, and B, respectively. Nutrient retention was very strongly influenced by the species of the material. The nutrient return from black spruce was almost entirely through the shedding of foliage and occurred very rapidly (45% shed by week 4). Trembling aspen and jack pine shed 30% of their foliage but required an overwintering period; however leaching and decomposition did return a substantial amount of nutrients to the site after 16 weeks of field-drying.

Field-drying forest harvest residues is an effective technique at reducing the material‟s moisture content in northwestern Ontario. Integrated field-drying into existing silvicultural systems can also increase the amount of nutrients retained on site during a biomass harvest. Optimum field-drying duration is highly dependent on the species composition of the stand; black spruce material can be removed after one summer season of field-drying, whereas the material from a mixed wood site (trembling aspen and jack pine) would benefit from an overwintering period.

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1. INTRODUCTION

The energy crisis that began in the 1970‟s, forced many oil-dependent countries to consider alternative energy sources. Much attention was given to investigating sources that were renewable and environmentally acceptable, while still remaining cost competitive. During this time period, many countries began looking at forests as a viable source of energy (Alemdag and Richardson 1993). Wood and forest harvest residues, also known as biomass, were seen as viable feedstock for large scale energy production and throughout the 1970‟s and 1980‟s attention began shifting to forest biomass for energy (Schobert 2002). Forest biomass was seen to hold great potential to be a successful supplemental fuel; one if combined with other renewable sources of energy, could fill the energy gap (McDaniels 1982).

With its plentiful forest resources, Canada began a research and development program in 1978 called ENFOR: Energy from the Forest. The program had five objectives: "(1) to assess, in the event of an emergency, the quantity of wood available for energy, including standing timber and residues, known as biomass; (2) to study fast-growing tree species for energy plantations; (3) to establish the most suitable harvesting methods to preserve the growing balance of trees and stands, and to practice these methods most economically; (4) to investigate the effects of biomass harvesting on forest soil, in particular, and on the environment in general; and (5) to improve or innovate methods of converting biomass into liquid or gaseous fuels" (Alemdag and Richardson 1993). The ENFOR program was successful in synthesizing a great deal of research from across Canada and organized many projects aimed at making biomass harvesting, conversion, and usage a reality.

When oil prices dropped back down in the mid 1980"s, so did much of the interest in forest biomass for energy. By the late 1980"s, much of forest bioenergy research in North American ceased and attention shifted over to other areas of forest research; all ENFOR projects were abandoned by 1990. With lower prices of oil, energy from the forest was no longer an economically viable prospect for most developed countries (Kimmins 1997). In Europe, however, research continued, government incentives were put in place, and biomass began being used as a supplementary energy source. The United Kingdom, the Netherlands and the Nordic countries became global leaders in energy from forest biomass. Forest biomass usage also became a reality in South American countries like Brazil, where large plantations of fast-growing *Eucalyptus* were developed as an alternative to coal in order to provide power to their steel industry (Kimmins 1997).

In the last five years, petroleum prices have increased dramatically and the world is now experiencing another oil crisis. Combined with an awareness of carbon emissions and global warming concerns, many governments are revisiting the search for inexpensive, carbon neutral, renewable energy sources and biomass is again part of the solution. For example, the United Stated Department of Energy has proposed the “25 by 25” goal, which requires 25-percent of its electricity and 25-percent of its motor fuel be produced from renewable sources by the year 2025 (EIA 2007). These requirements are to be implemented under the Renewable Portfolio Standard (RPS) and Renewable Fuel Standard (RFS), respectively (EIA 2007). In May of 2009, Ontario put into place the

Green Energy Act to encourage the development and usage of new renewable energy sources, while also aiming to reduce greenhouse gas emissions (OGEAA 2009). In conjunction with the Green Energy Act, the Ontario Ministry of Natural Resources is now implementing its Forest Biofibre Policy, which is moving the province toward greater utilization of harvesting residues for the production of bioenergy and other biomaterials (OMNR 2008).

In the spring of 2006, the Ministry of Energy and Infrastructure (MEI), through the Ontario Centres of Excellence (OCE), announced the investment of $4 million for the development of a Bioenergy Research Centre. The primary goal of the Centre was to work alongside the Atikokan Generating Station with the goal of searching out potential local bioenergy industries and determining whether bioenergy sources for electricity generation in northwestern Ontario was a viable and environmental sustainable option. The three main bio-energy sources that were explored are as follows: (1) agricultural by-products, (2) peat, and (3) wood/forest harvest residues. The current investigation however, focuses exclusively on the latter of these three bio-energy sources.

Increasing pressure to find inexpensive and renewable energy has turned attention to the use of forest harvest residues, or biomass, as a supplemental fuel source. This increased utilization raises two key concerns: 1) leaves, twigs, and branches, are very high in nutrient concentration and continued removal of such material may negatively affect long-term site productivity; and 2) on average 50-60% of this materials‟ green weight is water, which makes transportation and burning costs much higher. There is great incentive to implement operational forestry practices that reduce both the moisture and nutrient content of the green biomass. Leaving forest harvest residues in the clearcut to field-dry before removal from the site is a technique used for passively reducing moisture content, while leaving nutrients on the site. As the forest harvest residues are left to dry in the field, four main processes begin to alter the material"s physical and chemical properties: 1) water is both lost and gained from the residues through the processes of evapotranspiration and absorption, 2) mass is lost as microbial populations begin the process of decomposition, 3) mass is also lost mechanically as foliage and fine twigs are shed from the drying residues, and 4) nutrients are lost through the process of leaching. Factors such as climate, environment, type of residue, and drying times all will influence these processes and the rates at which they occur.

From an operational standpoint, the goal of a biomass harvest is to maximize the amount of water loss by evapotranspiration while minimizing the mass loss, so as to get the greatest yield from a site. From an ecological standpoint, the goal is to maintain soil fertility by maximizing the amount of nutrients left on site through the processes of decomposition, leaching, and mechanical mass loss. This research project is an attempt to merge these two, seemingly different goals, to find some middle ground that satisfies both operational and ecological requirements.

The purpose of this research project is two-fold:

1) To investigate the effects of field-drying on moisture reduction, decomposition, physical mass loss (shedding of foliage), and nutrient leaching from the fine harvest residues of northwestern Ontario"s three main merchantable tree species (black spruce, jack pine, and trembling aspen).

2) To develop a tree nutrient database for the tree species of Northwestern Ontario that would serve as a baseline for quantifying the degree of nutrient removal off site through biomass harvesting and supplement the already existing tree chemistry values from the literature (Appendix I).

2. LITERATURE REVIEW

Harvesting fresh crown material as a source of biomass poses problems because of its high moisture content. High moisture content increases transportation costs and decreases the efficiency of energy conversion (Johnson *et al.* 1985). On average, 50 to 60% percent of the crown‟s green weight is water, which must be vaporized before burning (Liang *et al.* 1996). Within this high moisture range, boiler efficiency can be improved by 1% for every percent drop in moisture content (Liang *et al.* 1996). As a result, there is great incentive to reduce the moisture content of the green biomass as much as possible before transporting. Considerable research has been conducted in Nordic countries to investigate the effectiveness of various biomass field-drying and storage techniques (Nurmi 1999, Nordfjell and Liss 2000, Pettersson and Nordfjell 2007). Often moisture reduction takes place in the field by piling or scattering residual biomass across the site for an established period of time. This allows the processes of evaporation and transpiration to dry the material before it is harvested from the site (Johnson *et al.* 1985). Nurmi (1999) found that piling Norway spruce [*Picea abies* (L.) H. Karst] residues to field-dry in the clearcut was better than drying the material in larger piles at the landing site and reduced the residue‟s moisture content from 56.0 to 28.5% (wet basis) in one year.

Field-drying is common practice in many Nordic countries because it also plays an important role in nutrient management, a key element to maintaining long-term site productivity. During the field-drying process, a percentage of needles are shed from the branches, reducing the amount of nutrient-rich biomass removed from the site. Nurmi

(1999) stressed the importance of leaving the needle mass on site to enhance nutrient cycling and stated that this was a far more important factor in the nutrient cycle than leaching. If the foliage, being high in nutrient concentrations, is left to decompose naturally, it should lessen the negative impact on long-term site productivity (Stupak *et al.* 2008). Percentages of needles shed by field-drying have been shown to vary by species. Raulund-Rasmussen *et al.* (2008) found that Norway spruce shed most of its needles after drying, whereas the needles of Scots pine (*Pinus sylvestris* L.) were more resistant. Nurmi (1999), looking at Norway spruce harvest residues, found that the average needle contribution to the total of harvesting residue was 27.7% (dry weight); however, within one year, only 6.9% of the residue mass was needles.

Field-drying has also been found to leave nutrients on the site through nutrient leaching and decomposition. In a one-year broadleaf-litter decomposition study carried out by Granhall and Slapokas (1984) in central Sweden on willow [*Salix* sp. L.], Speckled alder [*Alnus incana* (L.) Moench] and silver birch [*Betula pendula* Roth.], there was a rapid loss of dry matter within the first two weeks after placing the litter bags on the ground. Further investigation suggested that this was likely caused by rain and snow fall extracting the water soluble fraction of the litter. This trend, observed within the initial two weeks of decomposition, was described as a “physical „leaching phase‟, where early microbial growth took place mainly with the water extractable fraction as a carbon source”. Microbial degradation was found to be small during the initial leaching phase, but gradually increased throughout the year resulting in the release of recalcitrant fractions, such as lignin. Phosphorous (P) and potassium (K) were found to be the most rapidly lost mineral elements from the litter. Granhall and Slapokas

(1984) reported that the majority of the litter types they incubated for one year leached more than half of their P content. Litter was found to release up to 34% of the original nitrogen (N), but in some cases N actually accumulated in the litter due to fungal ingrowth and nitrogen immobilization. Even calcium (Ca), a recalcitrant element in plant tissue, was released from litter that had high initial Ca content. Possible explanations for this could be that Ca was in excess and thus could be water extractable, or that there was a physical break down of the cell walls by repeated freezing and thawing. Over the duration of the study, some of the leaf litter lost up to 45% of its original dry matter percentage.

A 16-week field-drying experiment carried out by Johnson *et al.* (1985) in Virginia on the twigs and leaves of red maple [*Acer rubrum* L.] and chestnut oak [*Quercus prinus* L.] showed similar results. They found that there were significant declines in the concentrations of P and K in both leaves and twigs over the drying period. When scaled up to the stand level, nutrients returned to the site through leaching and decomposition were found to be 37, 2, 34, 20, and 2 kg ha^{-1} for N, P, K, Ca, and magnesium (Mg), respectively. Johnson *et al*. (1985) identified that these levels are similar to the annual amounts naturally cycled in the litterfall of an Appalachian mixed oak stand. Therefore, one of their conclusions was that a summer harvest followed by a period of field-drying may retain the same amount of nutrients as a leaf-off, winter harvest. They also reported a drop in moisture content of the branches from 84 to 35% (wet basis), which is comparable to the moisture content achieved when industrial fuelwood is dried in heated rotating drums (Johnson *et al.* 1985).

Compared to the leaching and decay rates of broadleaf species, rates for coniferous species tend to occur much more slowly. Nurmi (1999) found needles of Norway spruce stored for one year in a clearcut, lost 20% of their original dry matter through decomposition, an average of 1.7% per month. Other studies have shown similar results averaging at approximately 2.0% per month for Norway spruce needles (Jirjis and Lehtikangas 1993, and Stupak *et al.* 2008). Stupak *et al.* (2008) reported the nutrient content decreases of between 35-60% for N, P, and K, whereas decreases in Ca and Mg were less than 32%.

In a review of literature pertaining to litter decomposition in northern forest soils, Berg (2000) reported that decomposition rates can range from 36.5% yr^{-1} for fresh litter but as little as 0.004% yr^{-1} for material in more advanced stages of decay. Many studies have confirmed that climate (temperature and precipitation) and substrate quality are the two main controlling factors of litter decomposition rate (Meetemeyer 1978; Johansson *et al.* 1995; Moore *et al.* 1999; Trofymow *et al.* 2002; Pare *et al.* 2006). Clear-cut harvesting drastically alters soil temperature and moisture (Ballard 2000), and as a result one would expect significant changes to the rates of litter decomposition and nutrient release following a clear-cut harvesting compared to the uncut forest. However, findings from litter decomposition experiments which compare uncut and clearcut treatments have yielded mixed results.

Significant differences in decomposition and nutrient release rates have been observed between clear-cut and forest for some litter material but not for others. For example birch leaves were the only material type to exhibit a greater decomposition rate on clearcut sites versus uncut sites, whereas the foliage, fine roots and branches of Scots pine and Norway spruce showed no difference in decomposition or release rates of N and P (Palviainen *et al.* 2004a). Another study by Palviainen (2004b) found that clearcutting slightly increased mineralization rate of K, Ca, iron and aluminum of all three tree species listed above. Another contrasting study by Prescott *et al.* (2000) found that broadleaf foliage showed no difference in decay rates between cut and uncut sites, but needle material was found to decompose slower on clearcut sites. In some cases, decomposition rates have been shown to differ within the first year, as predicted by Berg (2000) but not in later stages (Duhensne and Wetzel 2000). An additional factor influencing litter decomposition is site preparation. Disc trenching scarification has been shown to decrease the rate of litter decomposition, especially within the first year of incubation (Duhensne and Wetzel 2000).

Since the majority of forest harvest residue field-drying research has taken place in the Nordic boreal region and the southeastern deciduous forest region of the United States, and since the current research confirms that field drying rates, decomposition and nutrient release rates are strongly affected by a complexity of factors (site temperature, precipitation, tree species etc.), it is important to develop more regional experiments to help investigate the success of field-drying the residue materials of Canadian boreal tree species in northwestern Ontario.

The purpose of the current study was to investigate the effects of field-drying on the release (by the shedding of foliage, leaching and decomposition) of nutrients from the harvesting residues of northwestern Ontario‟s three main merchantable tree species: 1) black spruce [*Picea mariana* (Mill.) B.S.P.], 2) jack pine [*Pinus banksiana* Lamb.] and 3) trembling aspen [*Populus tremuloides* Michx.]. Piles made from the harvesting residues of each species were established in clearcut sites in the Lakehead Forest near Thunder Bay, Ontario. Samples were collected over a one-year period to monitor the changes in mass, moisture content and nutrient concentrations. Moist and dry ecosites were strategically chosen to determine if soil moisture conditions significantly affect the rate of nutrient leaching and decomposition of the drying materials. A litter bag decomposition experiment was also incorporated to monitor the mass loss trends for individual components (leaves, fine branches, and coarse branches) over the duration of the experiment.

Within the one-year drying period, and based on evidence from the literature, the following hypotheses were formulated and tested:

1. The majority of nutrients will be lost though the shedding of foliage as opposed to through leaching and decomposition.
2. Mass loss through decomposition is expected to be approximately 2% mth^{-1}, but should be higher for trembling aspen foliage compared to either jack pine or black spruce.
3. Nutrient leaching will play a smaller role, but will still contribute in the returning of nutrients to the site.
    a. More mobile or soluble nutrients, such as P and K, are expected to leach from material within the first four weeks.
    b. More recalcitrant nutrients, such as Ca, are expected to remain unchanged in the material until the material has overwintered.

c. Nitrogen will increase in concentration during the initial months as microbial populations break down the carbon rich compounds. Nitrogen levels will then begin to decrease as decomposition proceeds.
d. Moisture content is predicted to reach its lowest point (35-40%) by the end of the fall (week 16).
e. Moisture is predicted to increase into the following spring (May), due to melt water from snow and ice.
f. Moisture content should return to the same level as week 16 by the end of the experiment (June 2009)

3. METHODS

3.1 Site description

Six recent clearcut sites were chosen in the Lakehead Forest, near Thunder Bay Ontario (Figure 1). A preliminary screening of potential test sites was carried out using existing forest inventory ecosite information to identify stands that had similar soil nutrient regime, but varied moisture regime (Figure 2). The goal was to establish three test sites with moist mineral soil and three with dry mineral soil. Potential sites were visited and their soil moisture regimes verified by soil pit and soil type classification. A summary of the actual soil and site information can be seen in Table 1.

Dry sites D1 and D2 were located approximately 50 km north of Thunder Bay. Both of these sites had moderately dry sandy soil with rapid to very rapid drainage. Before being harvested, site D1 reportedly had a jack pine and black spruce mixedwood stand (ES-14), whereas site D2 had a trembling aspen, balsam fir, and black spruce mixedwood stand (ES-16) (Racey *et al.* 1996). The remainder of the sites (D3, W1, W2, W3) were located approximately 100-150 km southwest of Thunder Bay. Dry site D3 had a shallow coarse sandy loam soil with very rapid drainage and before harvest had a black spruce, jack pine, and feather moss stand (ES-20). All three of the moist sites had moist to moderately moist fine loamy to clayey soil with imperfect to poor drainage. Moist site W1 originally had a black spruce, jack pine, Labrador tea (*Ledum groenlandicum* Oeder), and feather moss stand (ES-22) whereas moist sites W2 and W3 reportedly had black spruce, jack pine stands with a feather moss understory. Sites D1, D3, W2, and W3 were the four sites used for the litter bag decomposition experiment, which is discussed in further detail in a later section.

At each site, plot locations were chosen based on several characteristics: 1) level micro-topography; 2) ease of accessibility (i.e., close proximity to the road to help maximize the efficiency of repeated visits and measurements); and 3) minimal ground obstructions (i.e., rocks, harvest residues, planted seedlings and other vegetation).

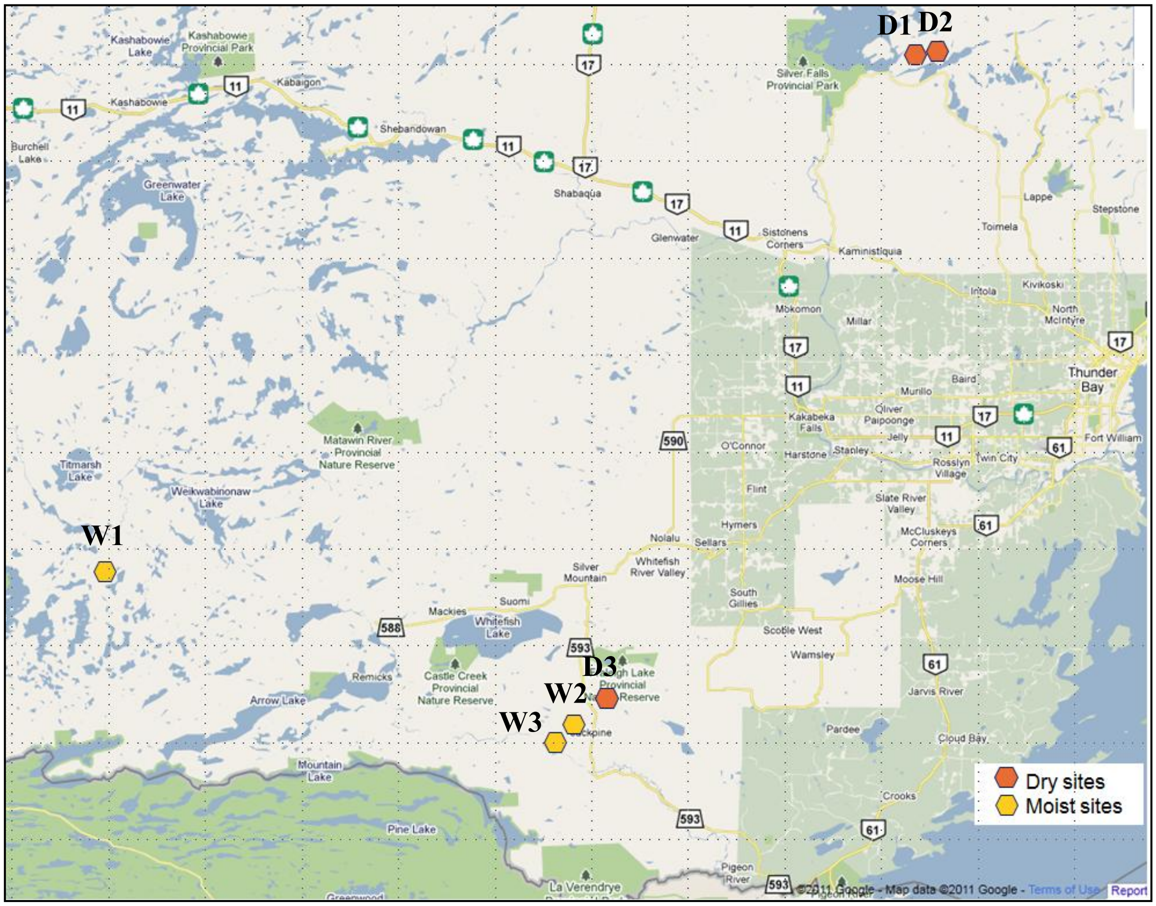

Figure 1. Map of the Thunder Bay region (Lakehead Forest) indicating the six test site locations. D and W indicate dry and moist sites, respectively. Corresponding ecosite information is also indicated.

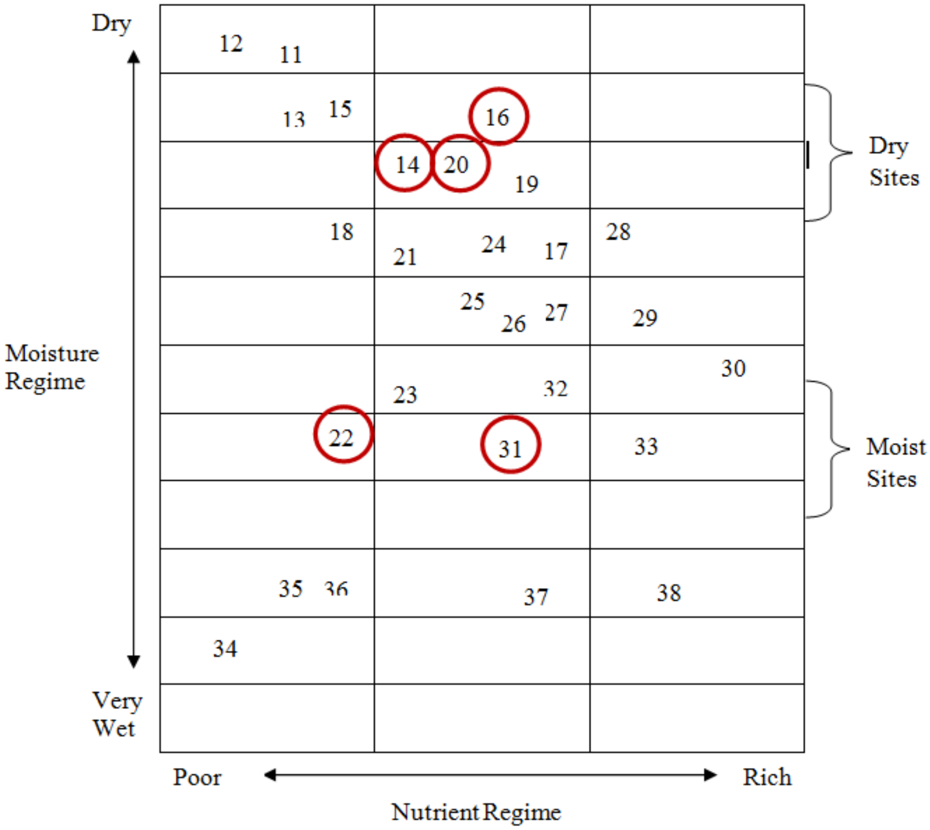

Figure 2. Ecosite moisture regime and nutrient regime relationship matrix. Circles indicate the ecosites of the actual test sites. Modified from Racey *et al.* 1996- Terrestrial and Wetland Ecosites of Northwestern Ontario.

Table 1. Soil and site descriptions for each of the six test sites.

Site	S-Type	Soil Description	Ecosite	Ecosite Description
D1	S1	dry - v. Fresh	ES-14	Pine-spruce mixed wood: sandy soil
D2	S1	dry - v. Fresh	ES-16	Hardwood-fir-spruce mixed wood: sandy soil
D3	SS3	dry - mod. Dry	ES-20	Spruce-pine/feathermoss: fresh, sandy-coarse loamy soil
W1	S10	moist/fine loamy-clayey	ES-22	Spruce-pine/ledum/feathermoss: Moist, sandy-coarse loamy soil
W2	S10	moist/fine loamy-clayey	ES-31	Spruce-pine/feathermoss: Moist, silty-clayey soil
W3	S10	moist/fine loamy-clayey	ES-31	Spruce-pine/feathermoss: Moist, silty-clayey soil

3.2 Climate data

Thunder Bay climate data for the time period of the field-drying experiment, June 2008 through June 2009, can be seen below in Figure 3. Total monthly precipitation tends to follows the same annual pattern as mean temperature but lags slightly behind. The average monthly temperature ranged from 17C in July to -17 C in January. On average, the precipitation in the summer months was 50 mm and 25 mm the winter months. During the period of study, Thunder Bay experienced two spikes of precipitation in the fall of 2008, where the monthly precipitation doubled and reached 98 and 82 mm for September and November, respectively. The average total annual precipitation for Thunder Bay is around 710 mm. The total precipitation for 2008 was 634.6 mm.

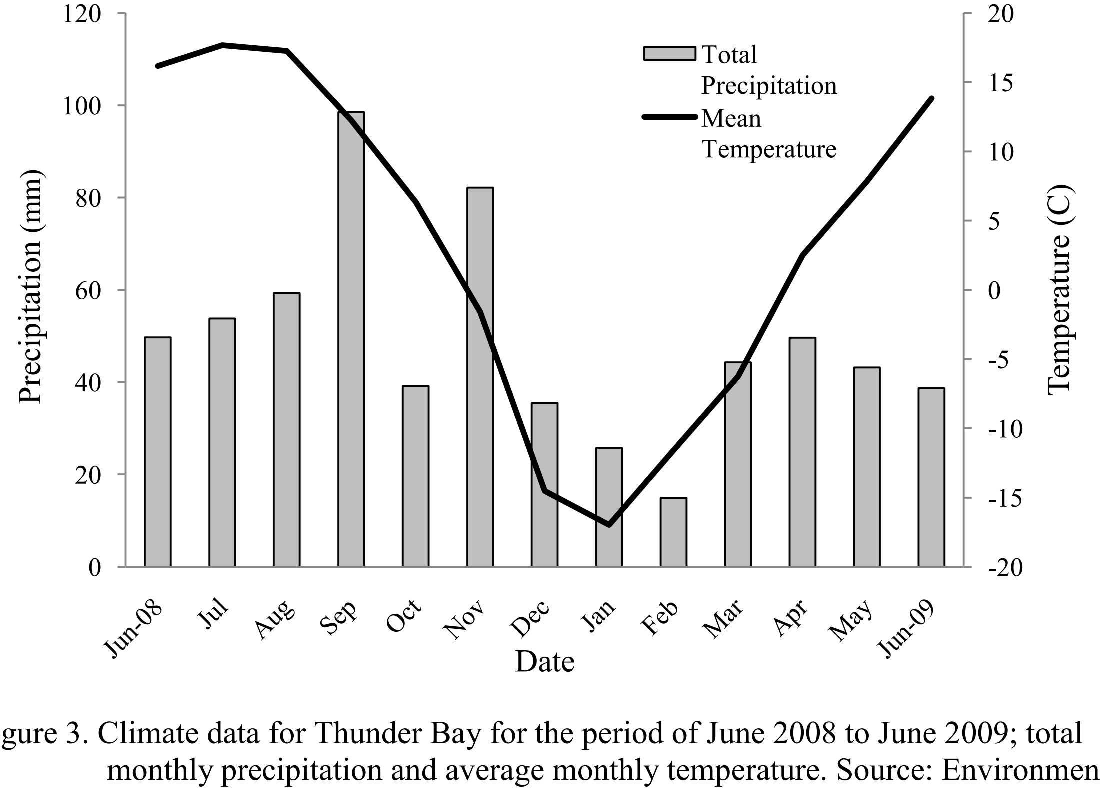

Figure 3. Climate data for Thunder Bay for the period of June 2008 to June 2009; total monthly precipitation and average monthly temperature. Source: Environment Canada Thunder Bay airport weather station.

3.3 Pile construction

In late June of 2008, representative trees of each species (black spruce (Sb), jack pine (Pj), and trembling aspen (Pot)) were selected from along the clearcut perimeter at each of the six sites. The trees were felled, delimbed, and the branches were used to make small biomass piles inside netted, framed enclosures (Figure 4). Two piles were created for each species for a total of six piles per site. The enclosures were constructed from 2.5 cm x 5.0 cm lumber and were 91 cm wide by 91 cm high by 152 cm long. The top and sides of the enclosures were covered with a 6.35 mm clear, polypropylene mesh netting and the bottom was covered with a 2mm fibreglass screen. The enclosure netting was designed to minimize any loss of material from the piles (*i.e.*, shed foliage) while still allowing the natural processes such as exposure to sun /ultra violet light, precipitation, wind and microorganisms, all of which are normally influencing the rates of decomposition, nutrient leaching and drying of harvest residues. General pile information was recorded as the piles were constructed (*i.e.,* number of branches per pile and total green weight of branches per pile). To estimate the total mass of each component in the piles, component mass ratios were calculated for each species using a total of six randomly selected branches. Each branch was divided up into three components (coarse branch [C], fine branch [F], and leaves/foliage [L]), weighed on a tripod scale, and the average dry mass ratios were calculated using the moisture contents calculated in the laboratory.

Figure 4. Typical arrangement of the netted biomass enclosures at a site.

3.4 Sampling procedure

Samples were collected immediately after felling in June 2008, and at four-week intervals for 16 weeks. The piles were left to overwinter from October to May and then sampled again in May (week 48) and June (week 52) 2009. At each time interval, subsamples were collected for the determination of moisture content, foliar mass loss, and nutrient concentration. Branch tips were cut at the 5 mm mark, and the green weight and lengths were recorded; these were considered fine branch material (F). A 10 cm section of branch was cut at the point where the branch connected to the main stem and the green weight and diameters recorded; these were considered coarse branch material (C). The leaves/foliage (L) were manually removed from the fine branch back in the laboratory.

3.5 Moisture content measurements

At each time interval, two coarse branch samples and two fine branch samples (including foliage) were collected from each pile; one from the upper region of the pile and one from the lower. Since moisture was assumed to vary by sampling height within the pile, an average pile moisture content was calculated using the upper and lower pile moisture content values. The green weight was recorded to the nearest tenth of a gram, on a digital field balance. The samples were taken back to the laboratory and dried at 70°C to remove most moisture, then dried for another two hours at 105°C to obtain the oven-dry weight or dry matter percent (Miller 1998a). Percent moisture content by dry weight was determined gravimetrically for each of the samples using equation [1].

$$\text{MC \% (wet basis)} = [\text{green weight (g)} - \text{oven-dry weight (g)}] / \text{green weight (g)} \times 100 \qquad [1]$$

3.6 Physical mass loss (shedding of foliage)

After the fine branch samples were oven-dried and used for moisture content determination, the foliage was removed, and the weights of the foliage and fine branch were recorded to the nearest tenth of a gram. This procedure was followed at each interval to monitor changes in fine branch to foliage ratio. The average percent leaf mass was determined for each pile at the beginning of the experiment using equation [2]. For the remainder of the experiment, percent leaf mass was calculated and the relative leaf mass left on the site, or shed leaf mass, was determined using equation [3].

$$\text{Leaf Mass (\%)} = [\text{oven-dry leaf mass} / \text{total branch mass (foliage and branch)}] \times 100 \qquad [2]$$

$$\text{Shed Leaf Mass (\%)} = [\text{average Leaf Mass \% at } T_0 - \text{Leaf Mass \% at } T_x) \qquad [3]$$

3.7 Litter bag decomposition experiment

A litter bag decomposition experiment was established to: 1) provide more detailed information about how rates of decay are affected by soil moisture regime, tree species and component type, and 2) accurately estimate the percent mass remaining at each of the sampling periods, not just the total mass lost from beginning to end.

In June of 2009, at the end of the field-drying experiment, one pile of each species (Sb, Pj and Pot), was left at sites D1, D3, W2 and W3. Three trees were felled (Sb, Pj and Pot), delimbed and the limbs brought back to the laboratory. The limbs were divided up by component, as described in the sampling procedure section, and 432 litter bags were filled with a known mass of leaf/foliage material (L), fine branch material (F), or coarse branch material (C). The litter bags were field-incubated in the middle of the biomass piles for a set duration of time (4, 8, 12, or 16 weeks) then brought back to the lab, and the contents sorted to remove any soil or ingrown, foreign vegetation. The samples were dried to a constant weight at 70°C, then dried for another two hours at 105°C to obtain the oven-dry weight (Miller 1998a). Mass loss was calculated using the equation seen below in equation [4].

Mass Loss (%) = 100 – ((change in mass / initial mass) x 100) [4]

or

100 – (starting oven-dry mass* – ending oven-dry mass) /starting oven-dry mass* x 100)

[*] Dry mass was estimated using MC data

3.8 Total mass loss of pile

Total pile mass (green weight) was determined to the nearest 10g on a tripod scale when the biomass piles were originally constructed, and at the end of the experiment. Green weights were converted to dry mass by combining the existing component moisture content data and the component percentage estimates. The one-year mass loss, due to leaching and decomposition, was determined by calculating the difference between the initial, total pile mass (M_0) and the mass at the end of the experiment (M_6). The percent mass remaining was calculated using equation [5].

Total Mass Loss (%) = 100 – ((change in mass / initial mass) x 100) [5]

or

$100 - ((M_0^* - M_6^* + \text{Subsample Mass, } M_S\ (T_0 \text{ to } T_6)) / M_0^* \times 100)$

* Dry mass was estimated using MC data

The end mass (M_6) was adjusted to include the moisture content and chemical analysis samples taken throughout the duration of the experiment. It was assumed that the mesh surrounding the piles prevented any physical loss of the material contained inside the enclosures. In some cases however, there were some observable losses of foliar mass from the enclosure, either from the enclosure tipping over, animal/human tampering, or needles falling through the side mesh. In these cases, as much of the material as possible was collected and weighed at the end of the experiment. If all of the lost material could not be reclaimed, estimations of the lost mass were made using subsamples of similar material.

3.9 Chemical analysis

At each time interval, for each component, three chemical analysis samples were also collected from the piles; from the upper, mid, and lower regions of the pile. The three samples collected from throughout the pile, were weighed and processed together and treated as a composite sample for the chemical analysis. The green weight of the composite sample was recorded to the nearest 0.1g, on a digital field balance. The samples were taken back to the laboratory and dried to a constant weight at 70°C. The leaves were removed from the dried, fine branches by hand and the two components were weighed, processed and analyzed separately for chemical composition. Each of the three components (C, F, L) were ground using a Wiley Mini-mill (Thomas Scientific) to pass through a number 20-mesh sieve (< 860 um). Coarse branches were pre-treated by drilling cross-sectional cores. The shavings from these cores, comprised of branch bark and wood, were collected and further ground using the Wiley Mini-mill to pass through a number 20-mesh sieve (< 860 um).

Nitrogen concentrations were determined from a 200 mg subsample using a LECO CNS-2000 (Dumas method) calibrated with a LECO orchard leaf calibration standard (#502-055). All other nutrient concentrations (P, K, Ca, and B) were determined by digesting a 500 mg subsample, using a concentrated hydrochloric/nitric acid digestion (Miller 1998b) and measured using an ICP-AES (Varian Vista Pro Radial). Additional nutrients (Mg, S, Mn, Fe, Zn) were also analyzed by acid digestion and measured by ICP-AES for the Northwestern Ontario Tree Nutrient Database (Appendix I).

3.10 Nutrient dynamics

To visualize the changes in actual nutrient content instead of merely observing the changes in nutrient concentration, the nutrient concentration data was combined with the amount of mass remaining of each component type, as determined from the results of the litter bag decomposition experiment. Since the contents were found to be quite variable between species, each of the nutrient content values were converted to the relative percent nutrient remaining using the equation outlined below in equation [6].

$$\text{Nutrient content remaining (\%)} = 100-[(\text{content at } T_0 - \text{content at } T_x)/\text{content at } T_0 \times 100] \qquad [6]$$

3.11 Cumulative nutrient retention

A spreadsheet model was developed to synthesize all of the processes taking place during the field-drying of the harvest residue material. The combined processes spreadsheet was used to estimate the total nutrients retained on site by the combined processes of: 1) physical mass loss (shedding of foliage due to drying), 2) nutrient leaching, and 3) decomposition. Two different scenarios were developed to help contrast the nutrient returns that could be expected if the material was removed from the site after one summer season of field-drying (16 weeks) versus if the material was dried for one full year (52 weeks). To facilitate a direct comparison between tree species, both of the field-drying scenarios started with 1 green metric tonne (gt) of harvest residue from each of the three tree species. Using the average initial moisture content of each component type and the average mass ratio of component types, the initial dry mass of each component type for each species was estimated. The dry masses remaining at week-16 (T_4) and week-52 (T_6) were calculated for each species by removing the amount of mass lost through the shedding of foliage and by determining how much mass of the remaining material was lost due to leaching and decomposition. Nutrient concentrations were then applied to the amount of dry mass remaining at each time for each component type and for each tree species. Nutrient concentrations were also applied to the original dry mass of the harvest residues to determine the total nutrient content of the residue‟s at the beginning of the experiment (T_0). The differences between the initial nutrient contents (T_0) and the nutrient contents at 16 weeks (T_4) and 52 weeks (T_6) were calculated and these values were then considered to be the amount that would be retained on site if the material was left to field-dry in the clearcut.

To scale up to a forest management level, the abovementioned cumulative nutrient retention data, were combined with the harvest and slash measurements reported by Morris (2003) (Table 2). The nutrient values (N, P, K and Ca) of the full-tree (stem only) residual/slash were adjusted using the cumulative nutrient retention data from the present study to investigate the effects of field-drying on the amount of years it would take to replace the nutrient levels back to their pre-harvest levels. This calculation was performed on three drying periods (0 weeks, 16 weeks and 52 weeks) and for two different forest types (an upland mixedwood stand and an upland black spruce stand). Manipulating the data in this manner would demonstrate if field-drying could significantly improve nutrient replacement times and if mixedwood harvest residue materials required longer or shorter field-drying times than black spruce forest residues.

Table 2. Mixedwood and black spruce forest nutrient replacement times. Source: Dave Morris 2003.

Forest Type	Ecosystem Compartment	Elemental Stores			
		N	P	K	Ca
		kg ha^{-1}			
	Tree length harvesting option (delimb at the stump)				
A. Mixedwood Forest	Soil Reserves	3899	36	172	1226
	Harvest	99	12	69	211
	Residual/Slash	372	49	194	381
	Annual Atmospheric Inputs	5	0.2	2	3
	Replacement times (Years)	**19**	**58**	**43**	**70**
B. Black Spruce Forest	Soil Reserves	2353	12	116	1331
	Harvest	74	6	40	181
	Residual/Slash	206	23	102	312
	Annual Atmospheric Inputs	5	0.2	2	3
	Replacement times (Years)	**14**	**31**	**25**	**60**

3.12 Field-drying experimental design

The experiment was set up as a repeated measures, nested, randomized complete block design. Two piles (2) were constructed for each species (3) at each of the sites (3), for each site moisture type (2); for a total of 36 piles. Measurements were taken (7) throughout the one-year duration of the experiment. The linear model is presented in equation [7].

$$Y_{ijklmn} = \mu + M_i + S_{(i)j} + Sp_k + MSp_{ik} + SSp_{(i)jk} + P_{(k)l} + MP_{i(k)l} + SP_{(i)j(k)l} + T_m + MT_{il} + ST_{(i)jl} + SpT_{kl} + \varepsilon_{(ijkl)} \qquad [7]$$

$i = 1, 2 \qquad j = 1, 2, 3\ k = 1, 2, 3 \qquad l = 1, 2, \quad m = 1, 2, 3, 4, 5, 6, 7 \qquad n = 1$

where:

Y = is the moisture content or shed foliar mass
μ = is overall Mean
M = is the fixed effect of site Moisture (Dry and Moist)
S = is the random effect of Site within Moisture type (3 replicate sites/ moisture type)
Sp = is the fixed effect of Species (Pj, Sb, Pot)
P = is the random effect of Pile within Moisture type, Site, and Species (2 piles/species/site)
T = is the fixed effect of Time (0, 4, 8, 12, 16, 48, and 52 weeks)

**The effects of the two 3-way interactions, $MSpT_{ikn}$ & $SSpT_{(i)jkn}$, were assumed to be insignificant and were therefore pooled in with the error term.

3.13 Litter bag decomposition experimental design

The litter bag experiment was set up as a nested, randomized complete block design. Three litter bags (3) for each of the 3 components (coarse branch, fine branch, and leaves/foliage), for each of the 3 species (black spruce, jack pine, and trembling aspen) was made for each time (4, 8, 12, and 16 weeks), and placed in the biomass piles at each of the 2 site moisture types (moist mineral and dry mineral) and for each of the replicate sites (2); for a total of 432 litter bags. The linear model for the litter bag decomposition experiment is similar to the model shown in equation [7], but some of the values differ however ($j = 2, l = 4$)

3.14 Statistical Analysis

Initial ANOVAs were performed using the general linear model (GLM), repeated measure function in PASW Statistic 18, Release Version 18.0.2 (SPSS Inc. 2010). Response variables used for the repeat measures analysis were moisture content and mechanical mass loss (foliage shed). For each time period, a GLM multivariate AVOVA followed by Duncan‟s post hoc test was used to determine if the tree species were responding differently to the treatment variables. A second GLM ANOVA was then performed with time as a treatment variable and Duncan‟s post hoc test was used to give an approximate indication of differences between the times. Additional response variables were moisture content, mechanical mass loss (foliage shed) and decomposition rate (mass loss). Since the litter decomposition experiment was not a repeat measures design, ANOVAs were performed, using the GLM multivariate function. Statistical analyses, as outlined above, were run separately for each of the component types (leaves, fine branches, and coarse branches).

4. RESULTS AND DISCUSSION

4.1 Moisture content

At the beginning of the experiment (June) the average moisture content of the freshly harvested fine and coarse branch residues was 50.1% and 41.8%, respectively (Figure 5 and 6). Moisture content values discussed in this section are reported on a wet basis; therefore, approximately half of the fresh, or green, harvest residue"s original mass was water. The initial moisture content of the branch material varied by tree species; jack pine (44.9%) and trembling aspen (43.5 %) had higher moisture contents than did black spruce (36.9 %) (Figure 5 and 6).

As the harvest residues dried, a consistent temporal pattern was observed across all sites, for all materials: 1) initially there was a rapid loss of moisture within the first four weeks after harvest (end of July) when there was very little precipitation (55mm); 2) moisture content gradually increased again into week 16 as autumn approached (end of October) after receiving 100mm of precipitation in September; 3) the post-winter material reached another peak in moisture in early spring as the snow finished melting; and 4) since there was very little spring precipitation (<43mm mth^{-1}) the material began to dry again and moisture content returned to the lowest point by week 52 (Figure 3,5 and 6).

The moisture content of both coarse and fine residues decreased to its lowest level after four weeks of field-drying; coarse branch moisture content decreased to 20.6% and fine branch moisture content to 14.8 % (Figure 5 and 6). By week 16, the moisture content had increased to 31.3% and 26.9% for coarse and fine branch material, respectively. Similar moisture content levels were observed in week 48 after overwintering; both coarse and fine branch moisture remained at around 30%. Moisture levels decreased again to 17.7% and 15.0% in week 52 for coarse and fine branch residues, respectively (Figure 5 and 6).

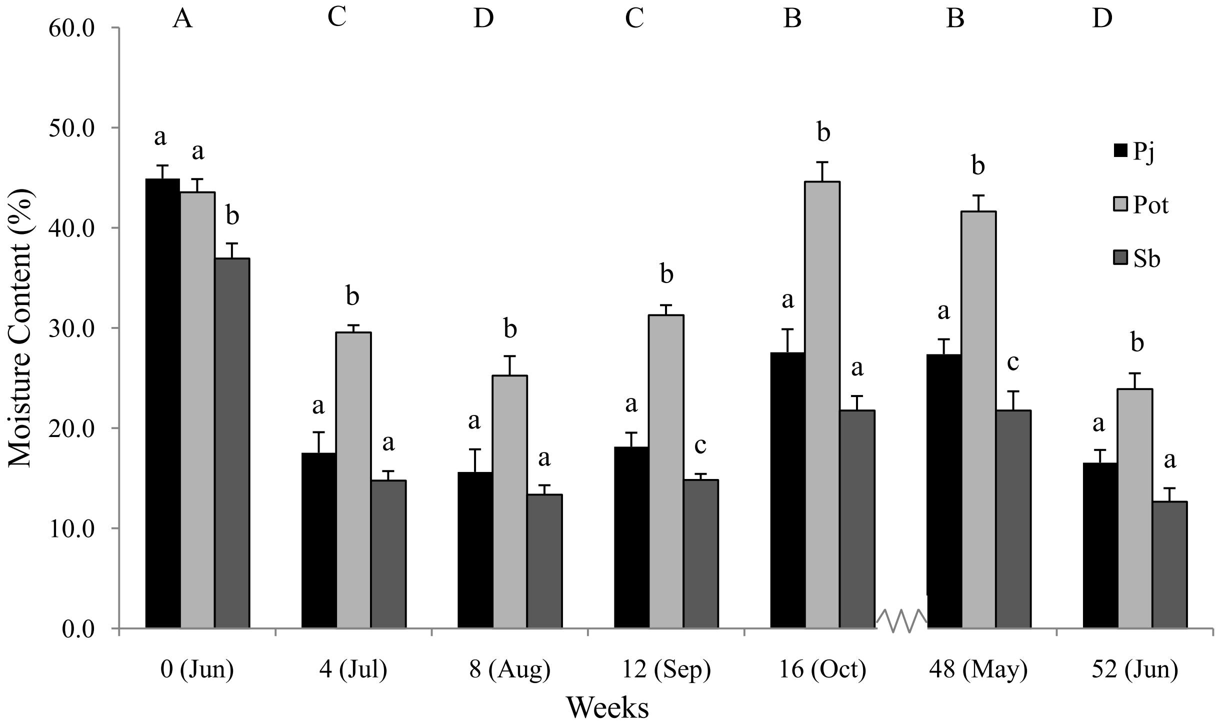

Figure 5. Coarse branch moisture content (wet basis) by tree species. Error bars denote standard error, upper case letters denote differences between weeks ($p<0.05$), and lower case letters denote differences between species ($p<0.05$).

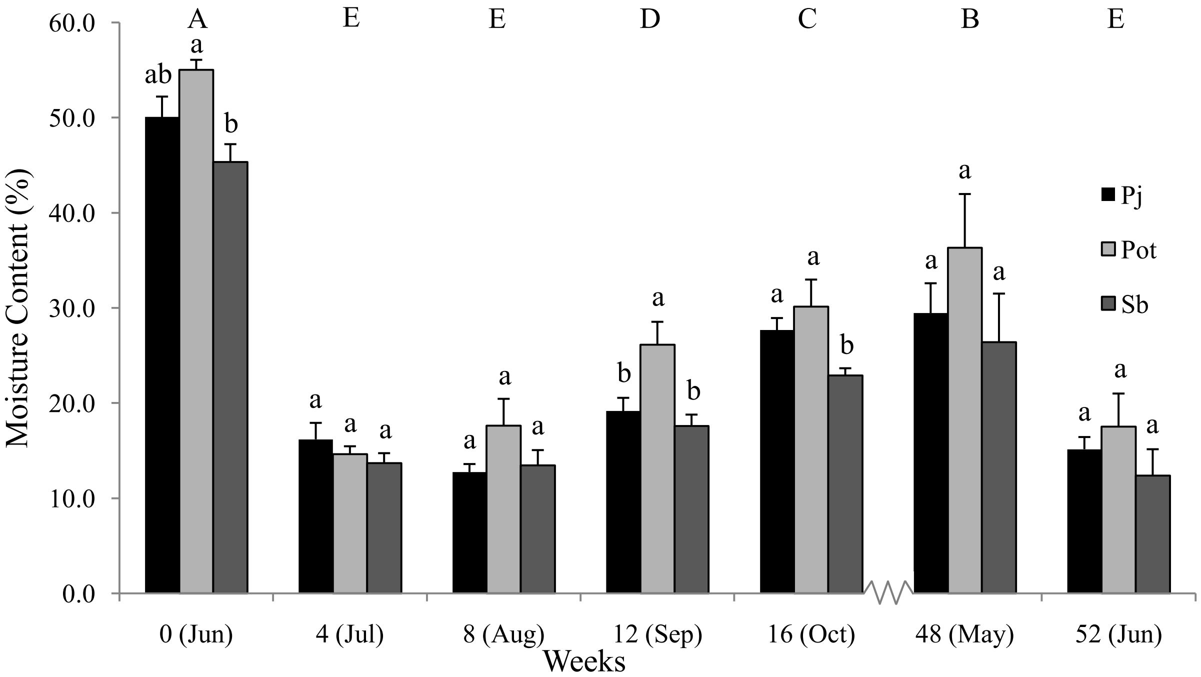

Figure 6. Fine branch moisture content (wet basis) by tree species. Error bars denote standard error, upper case letters denote differences between weeks ($p<0.05$), and lower case letters denote differences between species ($p<0.05$).

When analyzed using a repeated measures linear model, ANOVA results indicated that the rate of field-drying for coarse branch material was significantly different across species (Sp) at all seven weeks of measurement (weeks 0, 4, 8, 12, 16, 48 and 52) (Table 3). The main contributing factor to this difference was the moisture content of the trembling aspen coarse material, which was initially similar to jack pine at week 0 but then was notably higher than the other two species throughout the entire duration of the 52-week experiment (Figure 5). The drying resistance exhibited by the trembling aspen coarse branch material was likely due to its distinct bark characteristics; trembling aspen bark is notably thicker, spongier and more absorbent than the bark of the two coniferous species. Soil moisture type (M) however, had no consistent effect on coarse branch moisture content. The full ANOVA table for the repeated measures analysis of the coarse branch material can be seen in Appendix III.

With respect to fine branch harvest residues, repeated measures ANOVA again indicated that tree species (Sp) had an effect on the field-drying rate but only at specific times of measurement (Table 4): that is, Weeks 0 (June), 12 (September), 16 (October), and 48 (May). Figure 6 illustrates this trend whereby: 1) the three species begin with moisture contents ranging from 45-55%, 2) all species then dry rapidly to approximately 15% moisture content for weeks 4 (July) and 8 (August), 3) all species begin to regain moisture moving into week 12 (September) with trembling aspen accumulating moisture at a slightly faster rate than the two coniferous species, 5) by week 48 (May) the moisture content of all species is at its highest point since the beginning of the experiment, and 6) all three species again are similar to one another again and at their driest point by week 52 (June).

Unlike the coarse branch material, the ANOVA results for fine branch residues showed that both soil moisture type (M) and site (S) had an effect on the rate of field-drying at some point during the study (Table 4). These effects were largely driven by the higher moisture contents observed at sites D1 and D2 in weeks 48 (May) and 52 (June) (Figure 7). It should be noted that sites D1 and D2 are located in close proximity to each other 50 km north of Thunder Bay, whereas the other four sites were located 100 southwest of Thunder Bay; therefore it is possible that these sites experienced an increased spring moisture content as a result of different winter/spring climatic factors (*i.e.,* a greater snow load and/or a later spring thaw). It is probable that site precipitation has a greater effect on the field-drying rate than the sites soil moisture regime. The full

ANOVA table for the repeated measures analysis of the fine branch material can be seen in Appendix IV.

Similar to other studies [Nordfjell and Liss (2000), Nurmi (1999), Pettersson and Nordfjell (2007)], the present study confirmed that field-drying can successfully be used in northwestern Ontario as a passive technique to reduce the moisture content of fresh harvest residue materials. On average, transpiration and evaporation were found to reduce original water content to less than 15% if left to dry for 4 or 52 weeks. The present study did find that, in most cases, field-drying removed more moisture than expected and at a faster rate. For example, after 16 weeks of field-drying, moisture content in the fine branch material was reduced to 27% (wet basis), lower than moisture content numbers reported in Johnson *et al.* (1985) at 35%. After 52 weeks of field drying, the average moisture content was found to be around 16%, which is much lower than the value of 28.5% reported by Nurmi (1999).

The field-drying studies in the literature tended to use a coarse scale, usually by season or after one year, when monitoring fluctuations and trends in residual biomass moisture, making it difficult to detect subtle changes. With the frequent remeasurements in the current study, it was possible to detect moisture decreases to as low as 15-20% within the first four weeks (June-Juky), increased to 29% over the following months into autumn, remained at 30% after winter, and then returned to 15% again by June of the following year. The observations reported by Nurmi (1999) compliment the above findings; Nurmi (1999) made note that the moisture content of September harvested residues increased from 56% to 61.4% during the winter months due to snow load and ice, decreased to 46.7% by June, and reached 28.5% by the following September.

Moisture content fluctuations reported in the literature and in this study strongly support that field-drying is dependent on the season of harvest/drying, and on weather patterns (temperature and precipitation). Harvest residue biomass in this study dried more quickly than those reported in the literature because the present study investigated the field-drying effects: 1) following a spring harvest rather than an autumn or winter harvest; 2) in a region that experiences relatively hot and dry summer climate; and 3) in a region that experiences relatively low amounts of winter precipitation (*i.e.*, low snow load).

The timing of harvest or the season during which the field-drying takes place, likely plays a large role in the success of the field-drying practice. The present investigation only studied the effect of field-drying following a spring harvest: *i.e.,* the trees were harvested early in June and the residues were left to dry for the summer months and then left to over winter into the following spring. One would expect an autumn harvest to yield much different results. If the trees were harvested in September for example, instead of June, the residue material would likely be exposed to much cooler ambient air temperatures and higher relative humidity which would slow evapotranspiration following the harvest and thus decrease the rate of drying. Also, if the materials did not dry sufficiently before the winter months, there is a high probability that it would absorb more water from the snow load, thus making it more moist the following year. The moist and cool conditions of autumn harvested material would likely change (increase) the decomposition rates as well. A winter harvest could yield a different set of results again. A broader range of studies would be needed to conclude that the practice of field-drying could be successful in all seasons.

Table 3. Significant repeated measures ANOVA results for coarse branch moisture content from the field-drying experiment. (Soil moisture type-M, site-S, and tree species-Sp)

Source	Week	df	MS	F	Sig.
M	0	1	94.1	9.7	0.021*
	4	1	33.6	1.9	0.222
	8	1	46.5	8.9	0.025*
	12	1	4.9	0.1	0.755
	16	1	102.5	1.1	0.340
	48	1	45.8	1.0	0.364
	52	1	17.8	1.1	0.331
S(M)	0	2	0.9	0.1	0.916
	4	2	25.0	1.4	0.321
	8	2	91.9	17.6	0.003*
	12	2	7.8	0.2	0.848
	16	2	82.7	0.9	0.467
	48	2	41.2	0.9	0.467
	52	2	4.5	0.3	0.764
Sp	0	2	218.5	22.5	0.002*
	4	2	743.3	41.0	0.000**
	8	2	461.6	88.3	0.000**
	12	2	966.8	21.0	0.002*
	16	2	1416.8	14.8	0.005*
	48	2	1260.9	26.5	0.001*
	52	2	373.4	23.5	0.001*

Table 4. Significant repeated measures ANOVA results for fine branch moisture content from the field-drying experiment. (Soil moisture type-M, site-S, and tree species-Sp).

Source	Week	df	MS	F	Sig.
M	0	1	109.1	9.4	0.022*
	4	1	47.9	3.0	0.135
	8	1	38.5	2.4	0.172
	12	1	0.0	0.0	0.985
	16	1	304.1	36.1	0.001*
	48	1	1076.1	25.2	0.002*
	52	1	374.2	8.9	0.025*
S(M)	0	2	17.7	1.5	0.292
	4	2	19.1	1.2	0.367
	8	2	10.8	0.7	0.545
	12	2	136.2	6.9	0.028*
	16	2	16.5	2.0	0.222
	48	2	298.7	7.0	0.027*
	52	2	311.1	7.4	0.024*
Sp	0	2	279.6	24.1	0.001*
	4	2	18.9	1.2	0.370
	8	2	66.0	4.1	0.075
	12	2	290.2	14.6	0.005*
	16	2	150.0	17.8	0.003*
	48	2	231.6	5.4	0.045*
	52	2	58.0	1.4	0.323

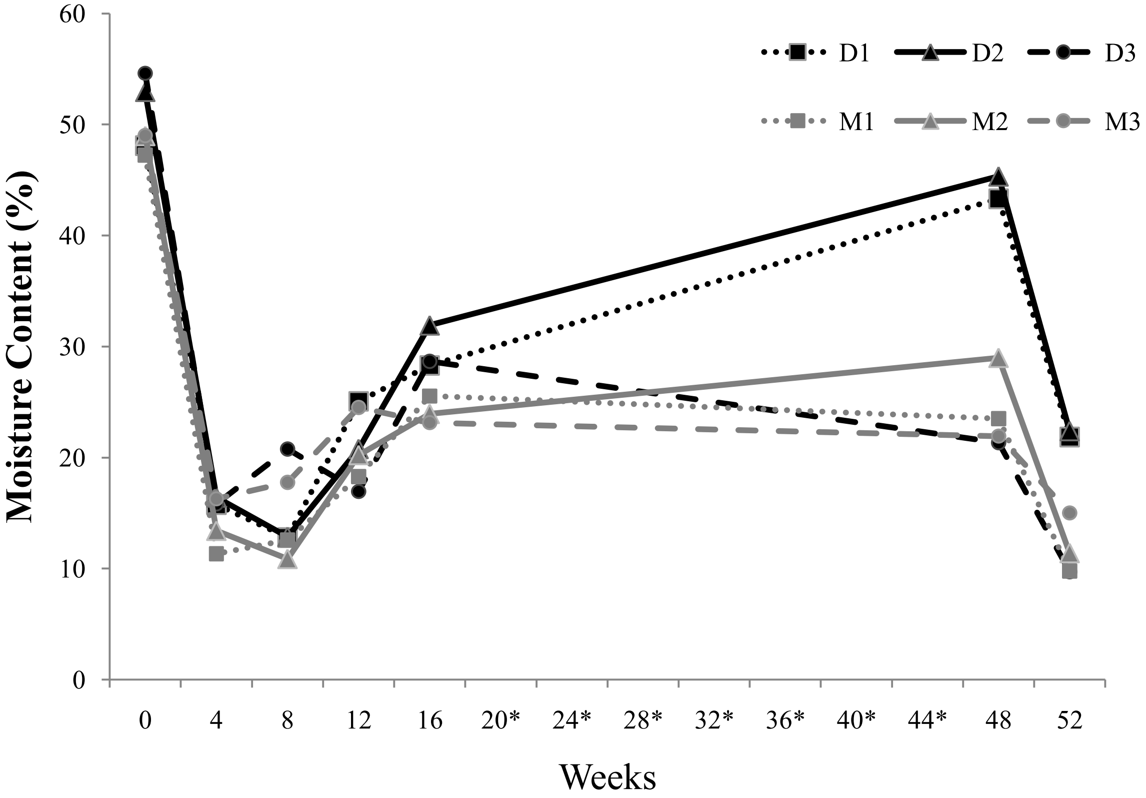

Figure 7. Fine branch moisture content dynamics by site. *No measurements were taken during the winter months from week 20 – 44.

4.2 Physical mass loss (shedding of foliage)

At the beginning of the field-drying experiment, the average relative percent leaf/foliage mass (dry weight) on the fine branch material was 61.0% for jack pine, 59.9% for trembling aspen, and 66% for black spruce. Neither tree species nor site type had a significant effect on the initial leaf mass percent. As the harvest residues dried, however, tree species had an immediate effect on the rate at which the foliage was shed (Table 5) (F=63.2, P<0.001). The physical mass loss of jack pine and trembling aspen were found to follow a similar trend; both species retained the majority of their leaves, losing less than 8.9% during the first 16 weeks of field-drying, followed by significant post-winter losses of up to 33.6% by weeks 48 and 52 (Figure 8). Although trembling aspen was consistently found to shed its foliage at a slightly greater rate than jack pine, this difference was insignificant in most cases. The exception to this statement was in week 48 where the average leaf percentage shed was much lower for jack pine (13.4%) than trembling aspen (31.0%) (Figure 8).

The greatest observable difference in the physical foliage mass loss trends was seen in black spruce; the needles from the field-drying black spruce were shed at a significantly greater rate than those of jack pine and trembling aspen in every measurement period. Black spruce lost 45.7% of its foliage within the first four weeks (Figure 8). By week-16, black spruce had shed 54.1% of its original foliar mass. After overwintering (weeks 48 and 52), mechanical mass loss of black spruce needles reached 63.3% (Figure 8). Site type did not affect the shedding of foliage from the field-drying harvest residues Table 5 (F=4.3, P=0.09).

As expected from the literature, a considerable amount of physical foliage mass loss was observed within the 52-week field-drying experiment. Raulund-Rasmussen *et al.* (2008) found that physical foliar mass loss was dependent on the type of tree species with Norway spruce shedding most of its needles after drying, whereas Scots pine retained its foliage. These findings are consistent with the current investigation; black spruce, like Norway spruce, held very little foliar mass by the end of the study, and jack pine, like Scots pine, tended to resist the shedding of foliage. To compare actual quantities of foliage mass remaining, Nurmi (1999) found that the harvest residue of Norway spruce shed approximately 75% of its foliage after one year of field-drying;

higher than the value of 63% observed in this investigation. Nurmi (1999) may have reported higher losses because the piles were moved by large machines and then weighed, whereas the current study carried out all measurements by hand.

Table 5. Significant repeated measures ANOVA results for foliar mass loss from the field-drying experiment (Site moisture type- M, site- S, tree species- Sp).

Source	Week	df	MS	F	Sig.
M	4	1	18.1	0.1	0.720
	8	1	153.6	4.3	0.085
	12	1	78.0	1.4	0.282
	16	1	61.2	0.5	0.515
	48	1	148.8	0.8	0.403
	52	1	25.2	0.2	0.689
S(M)	4	2	214.8	1.7	0.264
	8	2	59.5	1.7	0.268
	12	2	684.5	12.3	0.008*
	16	2	85.5	0.7	0.547
	48	2	222.8	1.2	0.361
	52	2	268.4	1.9	0.232
Sp	4	2	8108.9	63.2	0.000**
	8	2	9534.2	264.6	0.000**
	12	2	13139.1	235.6	0.000**
	16	2	10141.3	79.2	0.000**
	48	2	7637.7	41.6	0.000**
	52	2	4262.2	29.9	0.001*

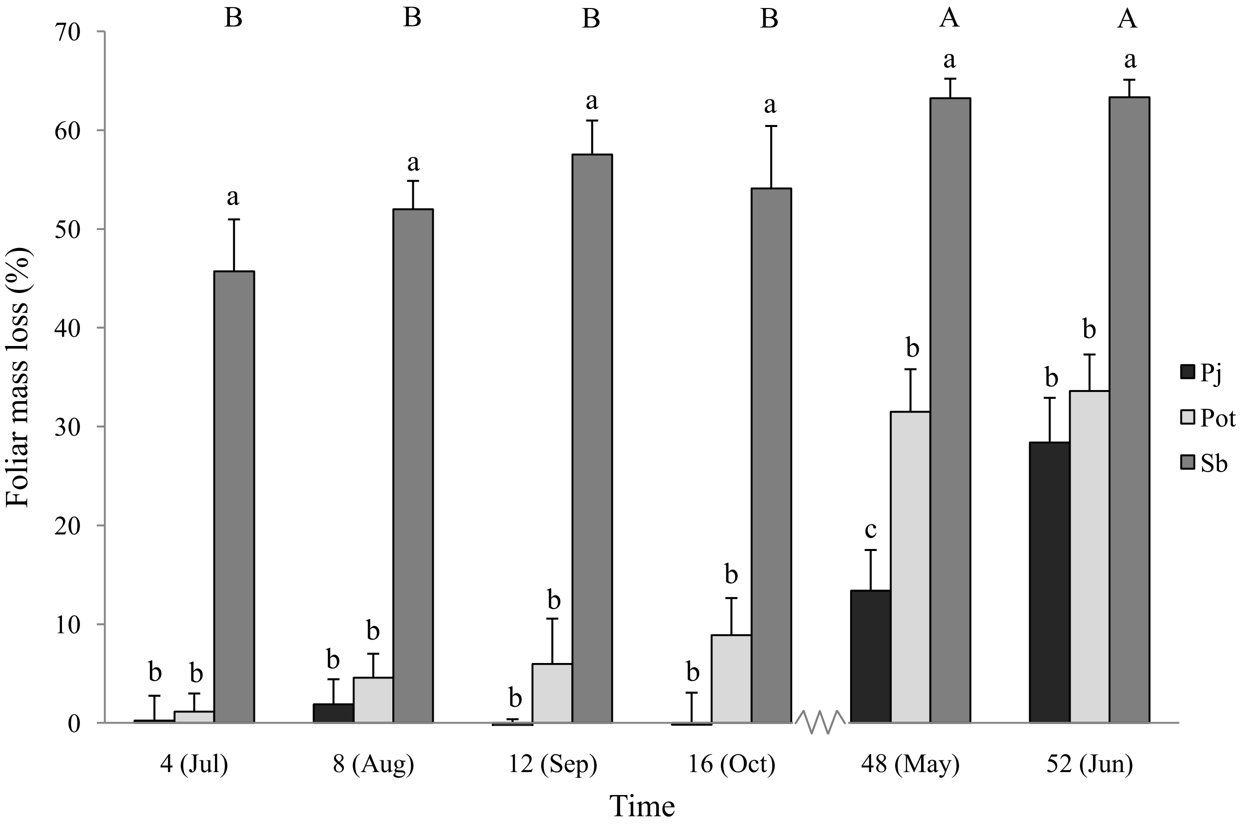

Figure 8. Percent foliar mass shed from the fine branch harvest residues and retained on the site. Error bars denote standard error, upper case letters denote differences between weeks ($p<0.05$), and lower case letters denote differences between species ($p<0.05$).

4.3 Litter bag decomposition experiment

4.3.1 **Foliage material**

Over the incubation period, the average mass loss of the foliar material was 4.8%·mth^{-1}, retaining approximately 81% of its original mass at the end of the 16-week experiment. The ANOVA results of the leaf material decomposition rates showed that there was an interaction effect between site type x time (F=7.66, P=0.02) and species x time (F=3.51, P=0.02) (Table 6). Within the first four weeks foliage mass loss occurred at a slightly faster rate on moister sites but then slowed for the remainder of the experiment; by week 16 the average mass remaining was 86.4% on moist sites compared to 75.2% on the dry sites (Figure 9). Trembling aspen foliage decomposed at a faster rate (F=14.56, P=0.02) than that of the two coniferous species (black spruce and jack pine). The mass of trembling aspen foliage remained relatively unchanged until week 8, when it was measured at 76.5% of its original mass. From week 8 to 16 the mass loss of the trembling aspen foliage slowed down to 3-4%·mth^{-1}, and it reached 69.4% of its initial mass by week 16 (Figure 10). Jack pine and black spruce foliage lost mass at a much slower, but consistent rate, retaining nearly 86% of their original mass by the end of the 16-week period. Jack pine decomposed more quickly than black spruce but only within the first 4 weeks; for the remainder of the experiment (weeks 8-16) their percent mass remaining was equivalent.

Table 6. ANOVA results for foliar mass loss from the 16-week litterbag decomposition experiment.

Source	Type III SS	df	MS	F	Sig.
M	243.72	1	243.72	8.73	0.098
S	55.84	2	27.92	0.43	0.687
Sp	2188.72	2	1094.36	14.56	0.015*
MSp	160.52	2	80.26	1.07	0.425
SpS	300.68	4	75.17	2.68	0.065
T	2330.08	3	776.69	43.51	0.000*
MT	410.07	3	136.69	7.66	0.018*
T S	107.11	6	17.85	0.64	0.701
SpT	591.77	6	98.63	3.51	0.018*
error	505.87	18	28.10	-	-

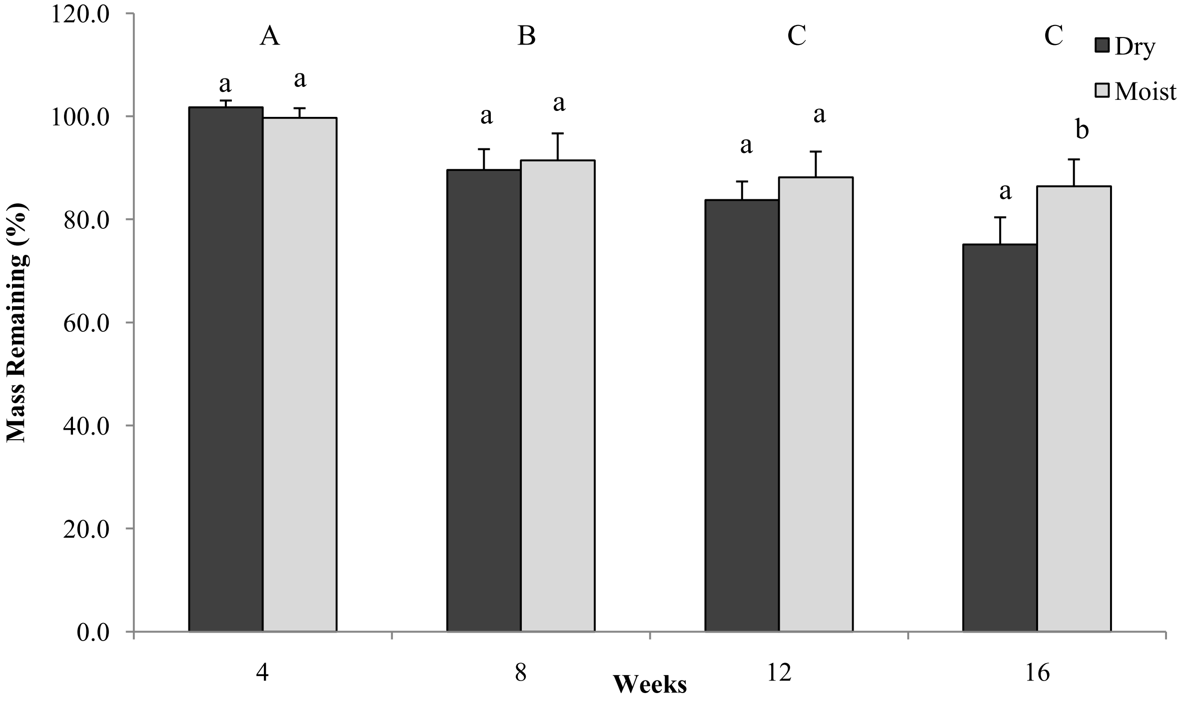

Figure 9. Percent foliar mass remaining in the litter bag by site type. Error bars denote standard error, upper case letters denote differences between weeks (p<0.05), and lower case letters denote differences between site types (p<0.05).

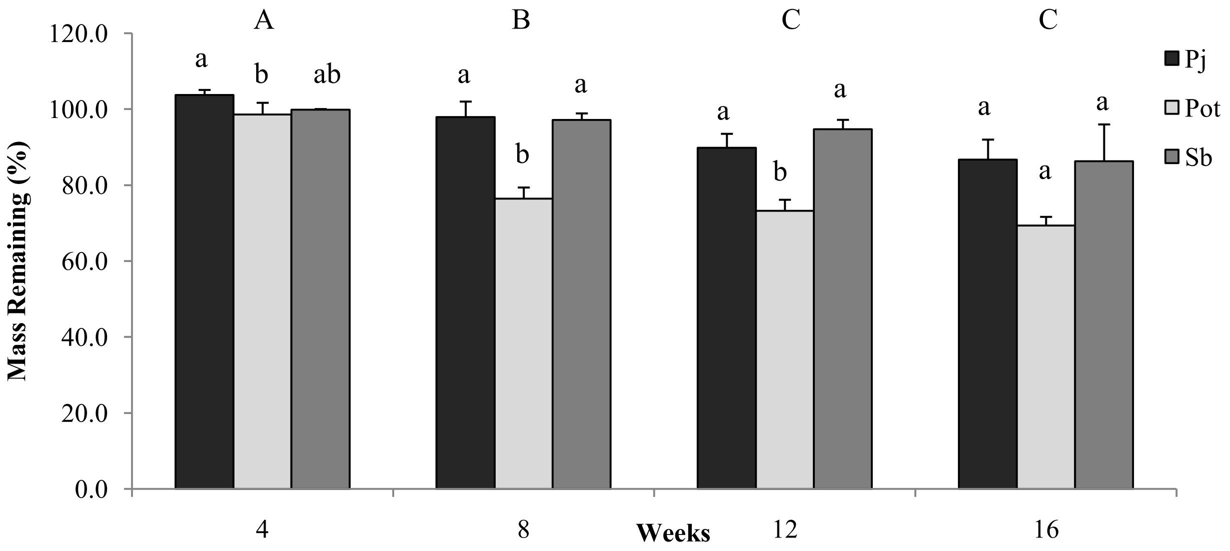

Figure 10. Percent foliar mass remaining in the litter bag by species. Error bars denote standard error, upper case letters denote differences between weeks ($p<0.05$), and lower case letters denote differences between species ($p<0.05$).

4.3.2 **Fine branch material**

The fine branch residues showed similar trends to the foliage material but with slightly slower decomposition rates. The average mass loss of the fine branch material was $3\% \cdot mth^{-1}$, retaining nearly 88% of its original mass at the end of the 16-week experiment. Similar to the ANOVA results of the foliage, the fine branch decomposition rates were affected by both site type x time and species x time interactions (Table 7). Mass loss of the fine branch material was slightly less on sites with a moist soil regime; the average mass remaining after 16 weeks was 90.4% for moist site types, compared to 84.6% on the dry site types (Figure 11). The fine branch material of jack pine took the longest of the three species to begin decomposition but over the 16 weeks exhibited the most drastic, linear decline in mass and by week 16 had 83% mass remaining. The fine branch material from the trembling aspen and black spruce was found to begin mass loss sooner than jack pine (week 4), but over the 16 week experiment decomposed more slowly and by week 12 still had approximately 90% of their original mass remaining (Figure 12). After week 12, the black spruce fine harvest residues did not experience any additional mass loss, whereas trembling aspen continued to decompose and by week 16 was left with approximately 86% of its original mass (Figure 12).

Table 7. ANOVA results for fine branch mass loss from the litterbag decomposition experiment.

Source	Type III SS	df	MS	F	Sig.
M	284.66	1	284.66	26.05	0.036*
S(M)	21.86	2	10.93	1.56	0.385
Sp	230.56	2	115.28	12.65	0.019*
M * Sp	32.63	2	16.32	1.79	0.278
Sp * S(M)	36.45	4	9.11	1.84	0.166
T	1622.45	3	540.82	189.49	0.000*
M * T	73.36	3	24.46	8.57	0.014*
T * S(M)	17.13	6	2.85	0.58	0.745
Sp * T	618.24	6	103.04	20.78	0.000*
error	89.27	18	4.96	-	-

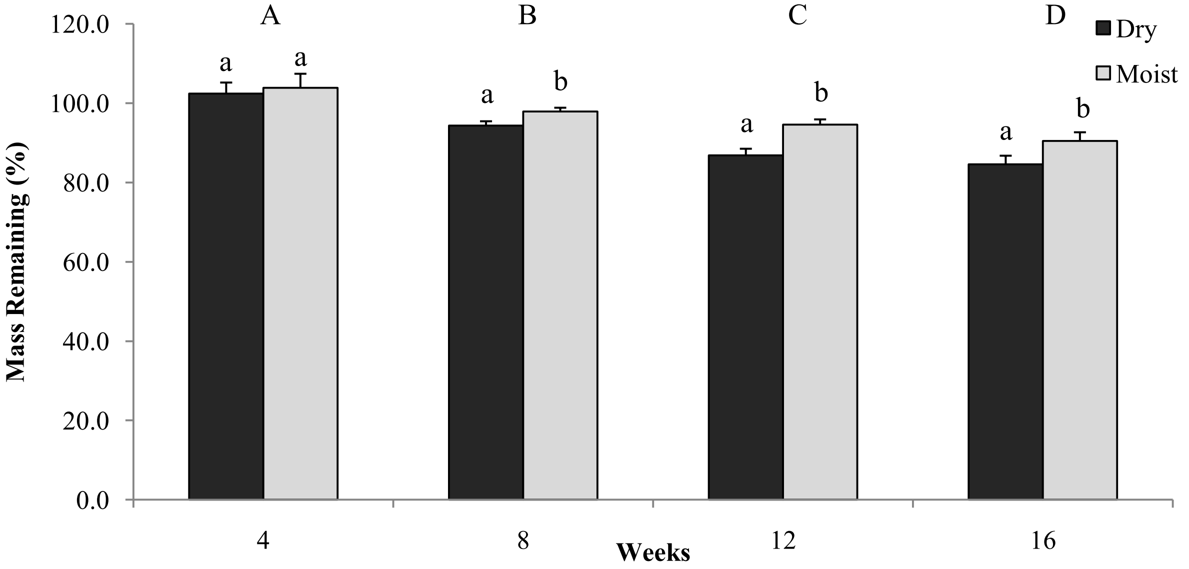

Figure 11. Percent fine branch mass remaining in the litter bag by site type. Error bars denote standard error, upper case letters denote differences between weeks (p<0.05), and lower case letters denote differences between site types (p<0.05).

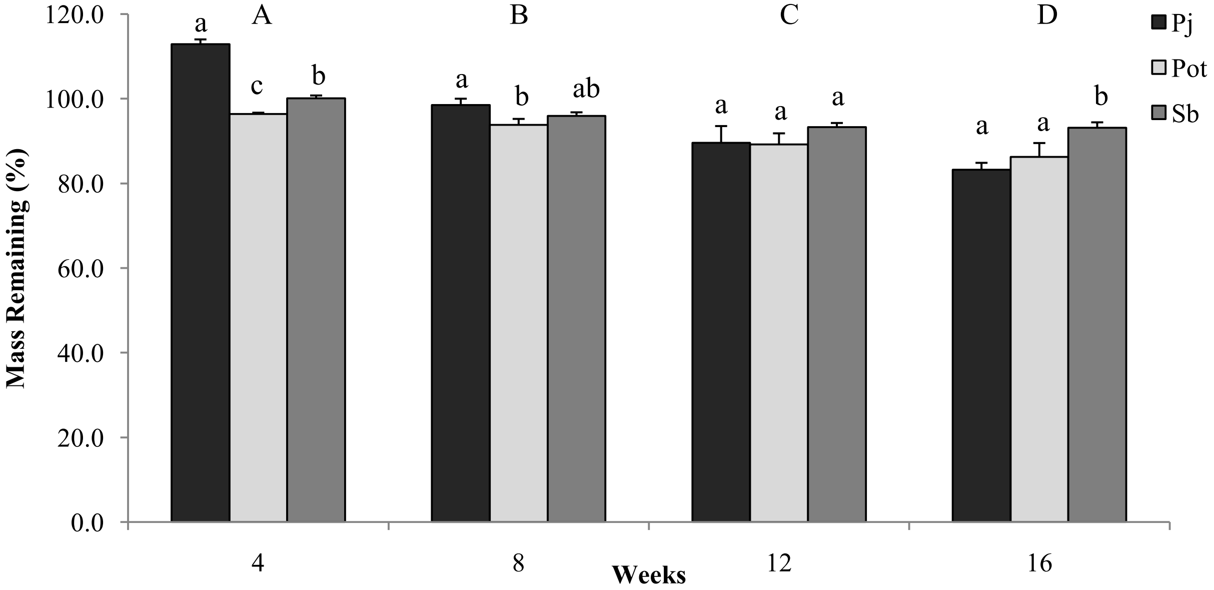

Figure 12. Percent fine branch mass remaining in the litter bag by species. Error bars denote standard error, upper case letters denote differences between weeks (p<0.05), and lower case letters denote differences between site types (p<0.05).

4.3.3 **Coarse branch material**

As expected, decomposition rates were much slower for the coarse branch residues when compared to the other two material types (i.e., 2%·mth^{-1}, leaving over 90% of its original mass at the end of the 16-week incubation period). The ANOVA showed that both species (F=7.72, P=0.04) and time (F=12.01, P=0.006) affected the rate of decomposition. Unlike the foliage and fine branch material, no interaction effects were observed. Black spruce was found to lose very little mass (3%) throughout the duration of the experiment when compared to average overall mass loss (11%) of the other two species (Figure 13).

Table 8. ANOVA results for coarse branch mass loss from the litterbag decomposition experiment.

Source	Type III SS	df	MS	F	Sig.
M	21.01	1	21.01	0.56	0.532
S	75.02	2	37.51	1.82	0.318
Sp	310.66	2	155.33	7.72	0.042*
MSp	22.96	2	11.48	0.57	0.605
SpS	80.45	4	20.11	1.27	0.318
T	588.90	3	196.30	12.01	0.006*
MT	8.87	3	2.96	0.18	0.906
T S	98.07	6	16.34	1.03	0.436
SpT	201.23	6	33.54	2.12	0.101
error	284.87	18	15.83	-	-

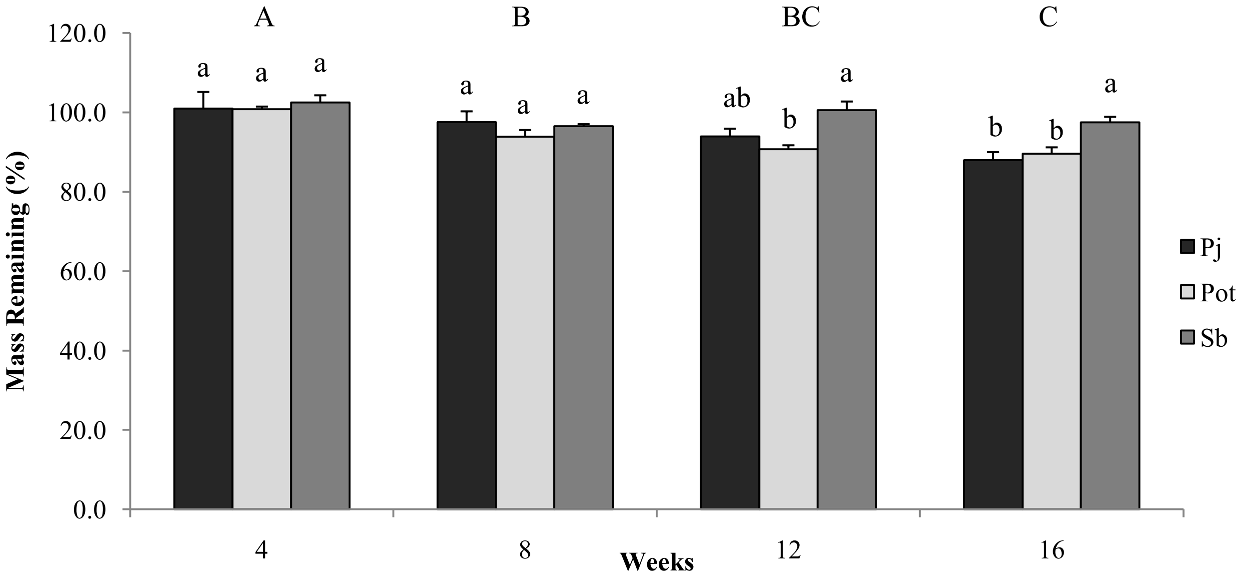

Figure 13. Percent coarse branch mass remaining in the litter bag by species. Error bars denote standard error, upper case letters denote differences between weeks ($p<0.05$), and lower case letters denote differences between site types ($p<0.05$).

4.3.4 **Decomposition trends**

The mass loss results from each of the harvest residue materials were plotted and the data fitted with power trendlines enabling the extrapolation of the 16-week decomposition rates to 52 weeks. Foliage and fine branch material graphs were separated by species and site moisture type, since the ANOVA results indicated that rates of decomposition rates were affected by these factors. Coarse branch material graphs were only separated by species, since the ANOVA results indicated that decomposition was unaffected by site moisture type. In most cases, the trendlines fit the data very closely; the average R^2 was 0.85, with most of the R^2 values being above 0.95. Predicted mass retention values for week-52 averaged 78% ranging from 47% (trembling aspen leaves) to 96% (black spruce coarse branches). The decomposition trendlines for jack pine, trembling aspen, and black spruce harvest residues can be seen in Figure 14-Figure 16.

The final pile mass measurements were plotted on the decomposition curves to determine how well the extrapolated litter bag values fit the actual field measurements. In almost all cases the extrapolated curves were very similar to the actual measured mass loss values. In some cases, however, the difference between these values was greater. For example, the extrapolated mass remaining value for trembling aspen foliage on dry sites was much greater than the actual value determined from the final pile measurements. One possible explanation for this difference is that the litter bags themselves may have some effect on the rates of decomposition. Because the material in the litter bags was packed tightly inside a fine mesh bag compared to the material spread loosely throughout the larger pile, it is possible that the material in the bags could have experienced slightly different microclimate conditions than the material in the piles. Different microclimate conditions could have ultimately affected the rate of decomposition. Another possible explanation is that the total mass measurements of the bulk piles were much more coarse when compared to the measurements made on the litter bags. Since the litter bag study was much more precisely measured, in most cases, it could be argued that the extrapolated values from the litter bag study were more trust worthy than the average final pile measurements.

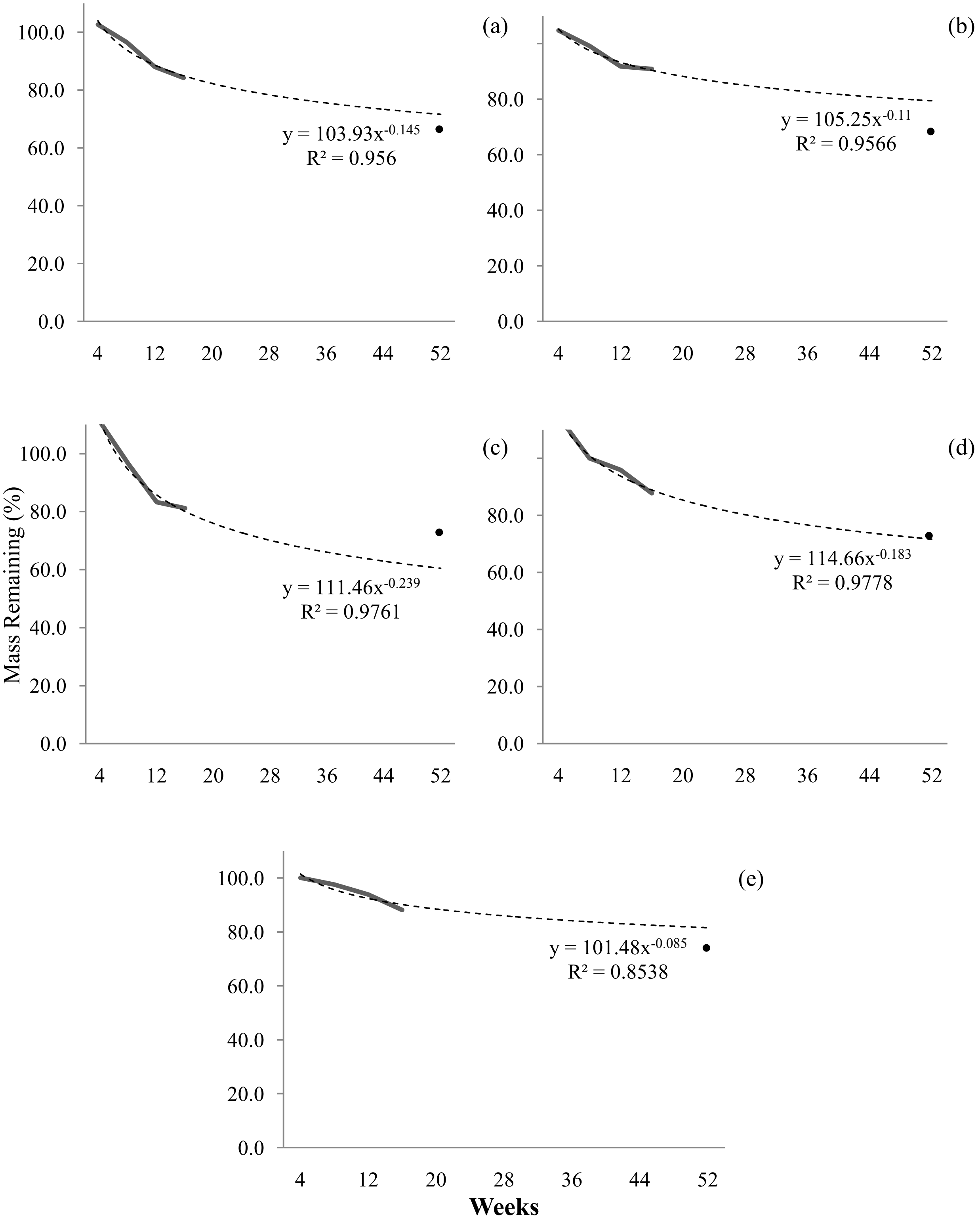

Figure 14. Decomposition rates of jack pine residues: foliage on dry sites (a) and moist sites (b), fine branch on dry sites (c) and moist sites (d), and coarse branch material (e). Point at 52 weeks is the actual final pile measurement.

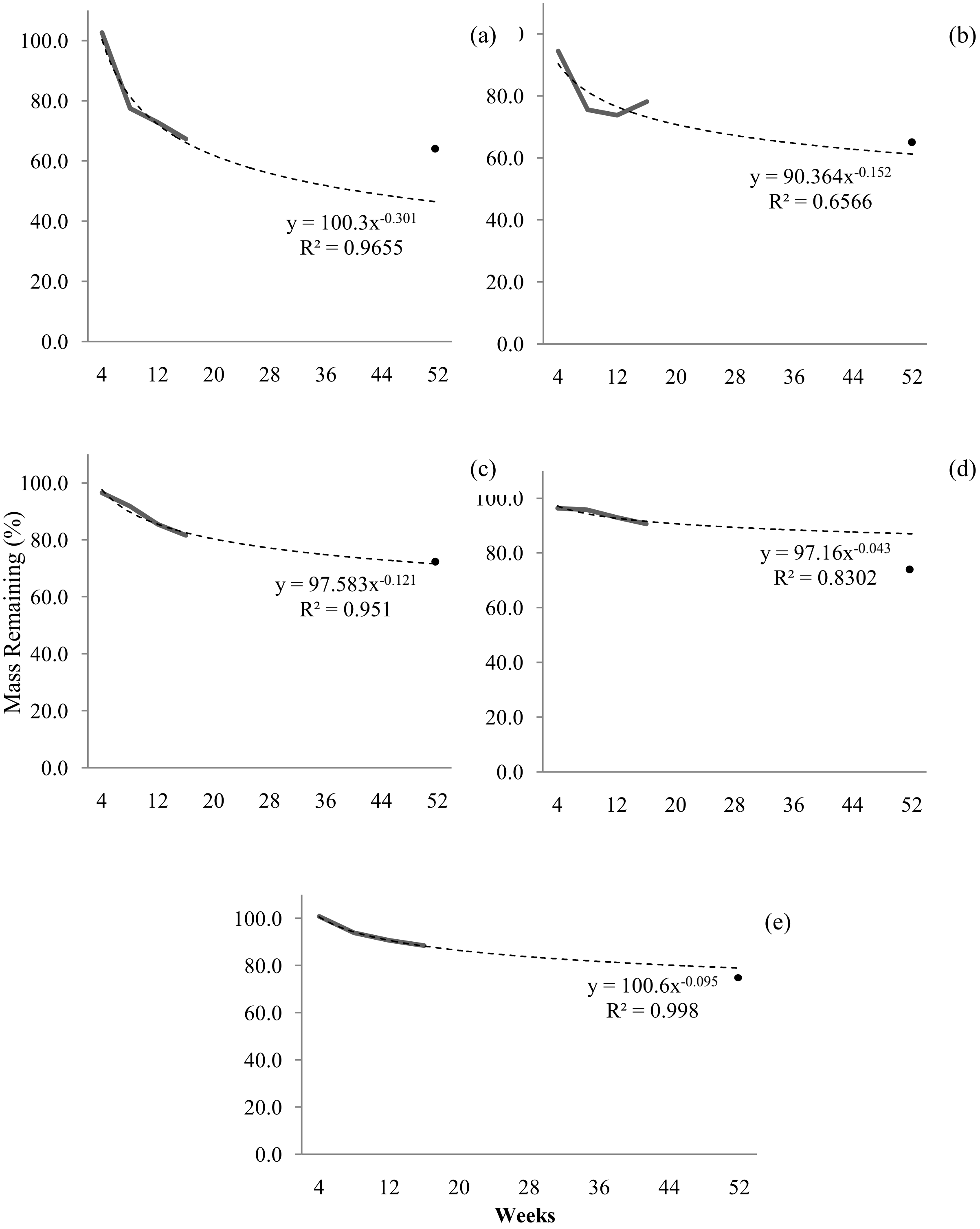

Figure 15. Decomposition rates of trembling aspen residues: foliage on dry sites (a) and moist sites (b), fine branch on dry sites (c), and moist sites (d), and coarse branch material (e). Point at 52 weeks is the actual final pile measurement.

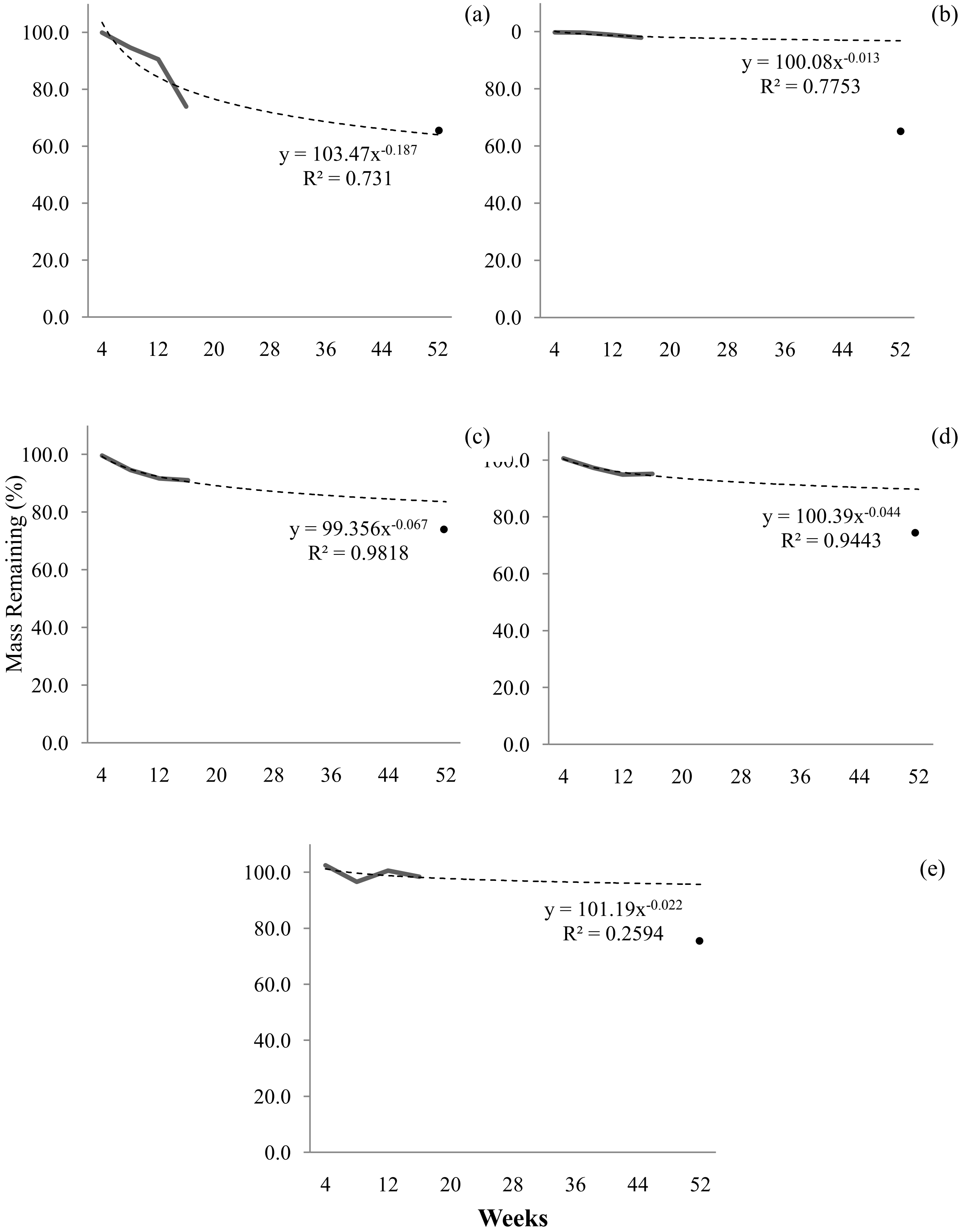

Figure 16. Decomposition rates of black spruce residues: foliage on dry sites (a) and moist sites (b), fine branch on dry sites (c) and moist sites (d), and coarse branch material (e). Point at 52 weeks is the actual final pile measurement.

Harvest residue decomposition rates in this study were found to be similar, or slightly above average. For example, Granhall and Slapokas (1984) found that broadleaf foliage lost up to 45% of its original dry matter percentage over a one-year study period. Berg (2000) stated that the decomposition rate for fresh litter is approximately 36% per year or 3% mth^{-1}. In more temperate forests, broadleaf foliage in drying slash was found to lose as much as 70% of original dry mass in four months (Johnson *et al.* 1985).

The decomposition rates observed in the foliage material of the two coniferous species (jack pine and black spruce) were also consistent with those found in the literature. Decomposition rates for Norway spruce needles ranged from 1.4% to 2.0% mth^{-1}, or 17% to 24% yr^{-1} (Jirjis and Lehtikangas 1993, Nurmi 1999, Stupak *et al.* 2008, Lehto *et al.* 2010). The average in my study was 22% per year or 1.8% mth^{-1}. It should be noted however, that the decomposition of the needle material, like most other materials, was non-linear and did not occur at a consistent rate. For example 14% of the original needle mass was lost within the first four months and in the following months decomposition decreased. This same trend of early decomposition could safely be assumed for the results found in the literature, which only reported measurements after one year of field-drying thus potentially missing this early decomposition phenomenon.

Average mass loss of woody harvest residue material, was 12% and 7.8%, for fine and coarse branches, respectively. When extrapolated to one year, the average annual mass loss of the fine and coarse branch material was 22% and 14.2%, or 1.8% and 1.2% mth^{-1}, respectively. Stupak *et al.* (2008) reported that the crown material (including coarse branches) of Norway spruce lost around 2.1% of its original mass mth^{-1} or 17% of its mass within an 8 month period. In the early stages of decomposition, in more temperate forest regions, wood loses mass at a rate of 5% to 20% yr^{-1} (0.4 – 1.6% mth^{-1}) depending on diameter size, climate, tree species etc (Ganjegunte 2004 and O‟Connell 1997).

The results from this study confirm the findings from existing literature; woody harvest residue material loses, on average, between 1-2% ·mth^{-1} within the first year of field-drying. Therefore, from an operational standpoint, an addition loss of up to 24% needs to be factored in if the material is left to field-dry for one year, in addition to the losses in mass from the machinery‟s biomass harvesting inefficiencies. The operational planner also needs to be aware of the differences between tree species, primarily that black spruce branch material is most resistant to losses in mass due to decomposition.

Decomposition was found to occur faster on the dry sites than on the sites with a higher soil moisture regime, which seems counterintuitive. However, a study by Barker (2008), found that reduced moisture increased soil respiration rates and as a result accelerated decomposition rates. Attempting to relate decomposition rates to soil moisture in this study is further complicated by the inconsistencies observed at sites D1 and D2; the residue materials at these two dry site types were actually found to have much higher moisture values following the winter months than at any of the three moist sites. Without microclimate data from within the biomass piles, there is no means of confirming that soil moisture even affects the pile humidity/moisture. Although site moisture was statistically found to affect the decomposition rates of the residue material, ecologically and operationally these differences are minor compared to the differences observed between component type (foliage, fine branches and coarse branches) and tree species.

4.4 Nutrient Patterns

4.4.1 **Nitrogen**

Using the calculated decomposition rates and combining these values with the nutrient concentrations of the different harvest residue material, the actual changes in nutrient content could be estimated. In most cases, N content of the field-drying harvest residues showed minimal change over the duration of the 52-week field-drying experiment. The N content in the jack pine foliage material fluctuated slightly and decreased to its lowest point (93% of its original amount) between weeks 12 and 48 (Figure 17a). By week 52, N content of the jack pine foliage returned to nearly 100% of its original amount, indicating that the concentration of N was increasing at the same rate as the material was decomposing and losing mass. The N content of the trembling aspen foliage however, decreased linearly over the 52-week period, retaining less than 70% of its original amount by the end of the field-drying experiment (Figure 17a).

The black spruce foliage data were removed from the nutrient study because it was determined that the sampling procedure was becoming skewed as the study progressed. The older, less nutrient dense foliage was being shed more quickly, leaving the newer foliage, with a higher nutrient concentration, to be collected for analysis. Analyzing a greater percentage of new foliage, gave the impression that the black spruce foliage material was accumulating nutrients as it dried.

The N content of the jack pine fine branch material exhibited a slightly different pattern when compared to the changes seen in the jack pine foliage; where N content of the jack pine fine branch residues decreased at a near linear rate, reaching 83% and 74% of its starting content by weeks 16 and 52, respectively (Figure 17b). Little change was seen in the N content of the fine branch material of the other two species (trembling aspen and black spruce), as it fluctuated up and down by +/- 10% (Figure 17b). Similar trends were observed in the N content of the coarse branch material of the two coniferous species (jack pine and black spruce); where minimal changes (+/-10 %) were observed (Figure 17c). N content of the trembling aspen coarse material, however, exhibited a rapid decrease to 79% by week 12 but stabilized thereafter (Figure 17c).

Considering species differences is important when attempting to minimize nitrogen removal during a slash harvesting operation. Forest managers need to recognize that field-drying to retain nitrogen is effective for some harvest residue material but not others. For example, field-drying jack pine foliage for 16 weeks before removing it from the site retained only 7% of its original nitrogen, whereas trembling aspen foliage retained 15% of its original nitrogen on site. If left to dry for 52 weeks, nitrogen retention changes to 1% for jack pine foliage and 32% for trembling aspen foliage material. Granhall and Slapokas (1984) reported results comparable to trembling aspen from the current study such that, after one year, their leaf material had lost up to 34% of its original nitrogen. Similarly, with the branch material, nitrogen returns were only observed in the jack pine fine branches and trembling aspen coarse branch residues. Little change in nitrogen content was seen with the other branch harvest residues. This is consistent with Johnson *et al.* (1985) in oak and maple twigs; a peak in nitrogen content after 2-4 weeks of field-drying was followed by a decrease to original levels by the end of the 16th week. Therefore field-drying will only improve nitrogen retention (though leaching and decomposition) if the slash material is predominantly trembling aspen (foliage and coarse branches) or jack pine (fine branches). Field-drying may not be an effective technique of returning nitrogen (through leaching and decomposition) of black spruce residue material. Although black spruce likely returns a large amount of nitrogen to the site through physical foliage loss; this will be explored further in the cumulative returns section of this study.

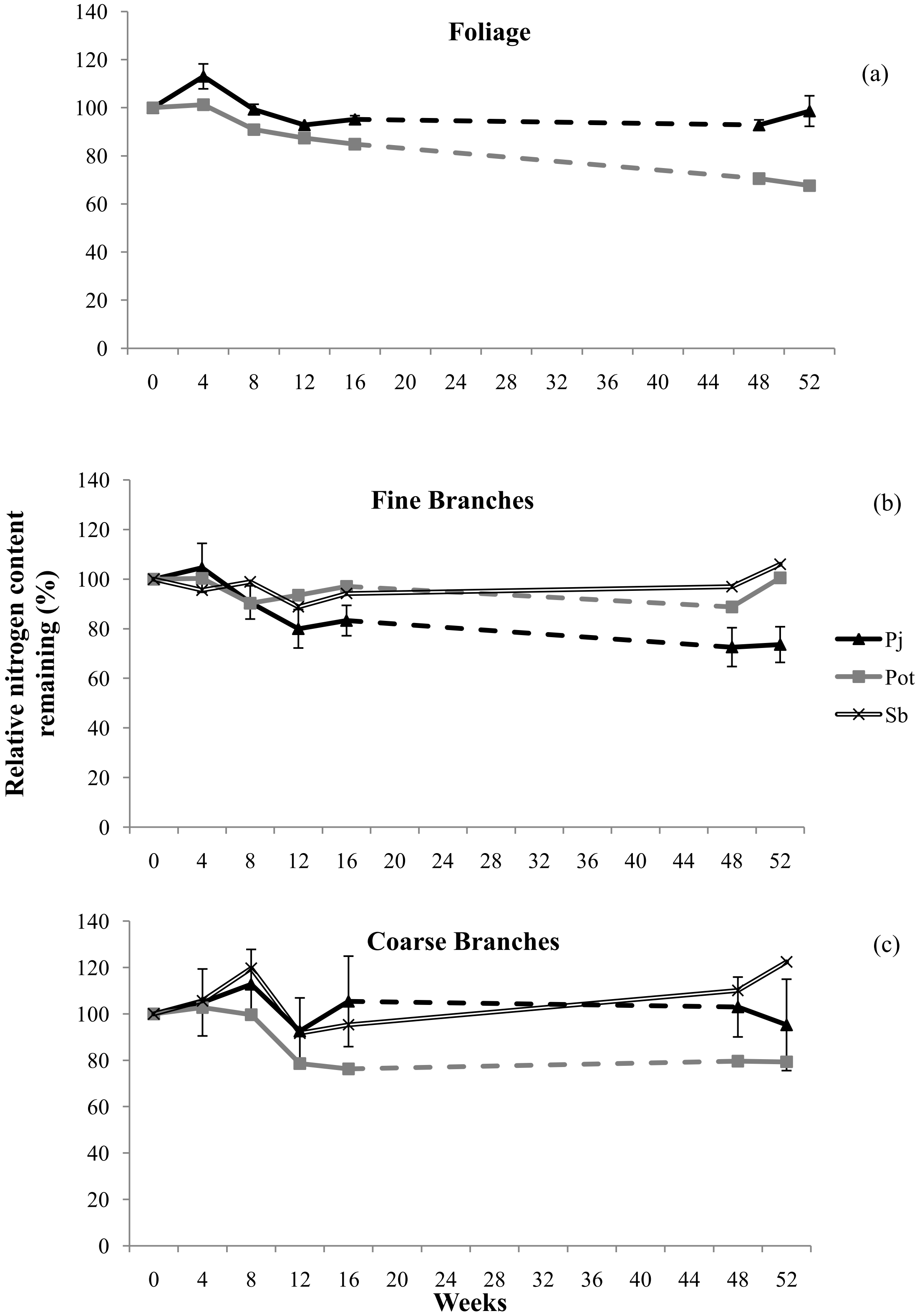

Figure 17. Relative nitrogen content remaining in foliage (a), fine branches (b) and coarse branches (c). Dotted line indicates winter period where no measurements were taken. Typical variance is indicated by standard error bars on jack pine data only.

4.4.2 **Phosphorous**

By the end of the 52-week field-drying experiment, foliar P levels had decreased to 81% and 39% of the original content, for jack pine and trembling aspen, respectively (Figure 18a). P was released from the aspen foliage at a faster rate than from the jack pine foliage, indicating that whether the material is broadleaf or needle influences the release rate. Twenty percent of the trembling aspen foliar P was released within the first 4 weeks of field-drying and by week 16 (Oct), nearly 50% of the P had been released from the material through the combined mechanisms of leaching and decomposition (Figure 18a).

Release of P from the fine branches followed similar temporal patterns and release rates for all three tree species. By October (16th week) the P content in the fine branch material ranged between 73-82% of its original amount (Figure 18b). By the 48th week, after overwintering, the fine branch P levels was reduced further to 51-63% of its original amount (Figure 18b), at which point no further changes were observed out to 52 weeks.

The P content of the coarse branch material remained relatively unchanged until week 8 (Aug), then at week 12 (Sept) declined down to 78% and 83%, for jack pine and black spruce, respectively (Figure 18c). A decrease in the P levels of the aspen coarse branch material was also observed but was delayed until week 16 at which point it was down to 64% of its original content (Figure 18c). Following the winter months, the trembling aspen coarse material had released approximately 50% of its P by leaching and decomposition. The black spruce coarse branch material on the other hand, experienced an accumulation of phosphorous and by the end of the experiment was back up to its original level (Figure 18c).

Other studies indicate that phosphorous is readily leached from drying plant material (Granhall and Slapokas 1984, Johnson *et al.* 1985, Stupak et al 2008. Lehto *et al.* 2010). Left on site for 16 to 32 weeks, broadleaf and coniferous harvest residue materials have been found to lose between 15 and 65% of the original phosphorus and potassium through the processes of leaching and decomposition. The current investigation shows a loss of 17 to 61%. One exception, however, is that black spruce coarse branches experienced no decrease in phosphorous. As expected, broadleaf foliage released phosphorous at a faster rate than did coniferous foliage (Johnson *et al.* 1985, and Stupak *et al.* 2008) and foliage and fine branches lost phosphorous at a faster rate than did coarse branches. Since phosphorous is a rather mobile nutrient in plant material, it is quickly and easily leached when exposed to the elements during field-drying. If P levels were of concern on a site, field-drying could be an effective method for retaining P on the site, especially if hardwood foliage and fine material was targeted.

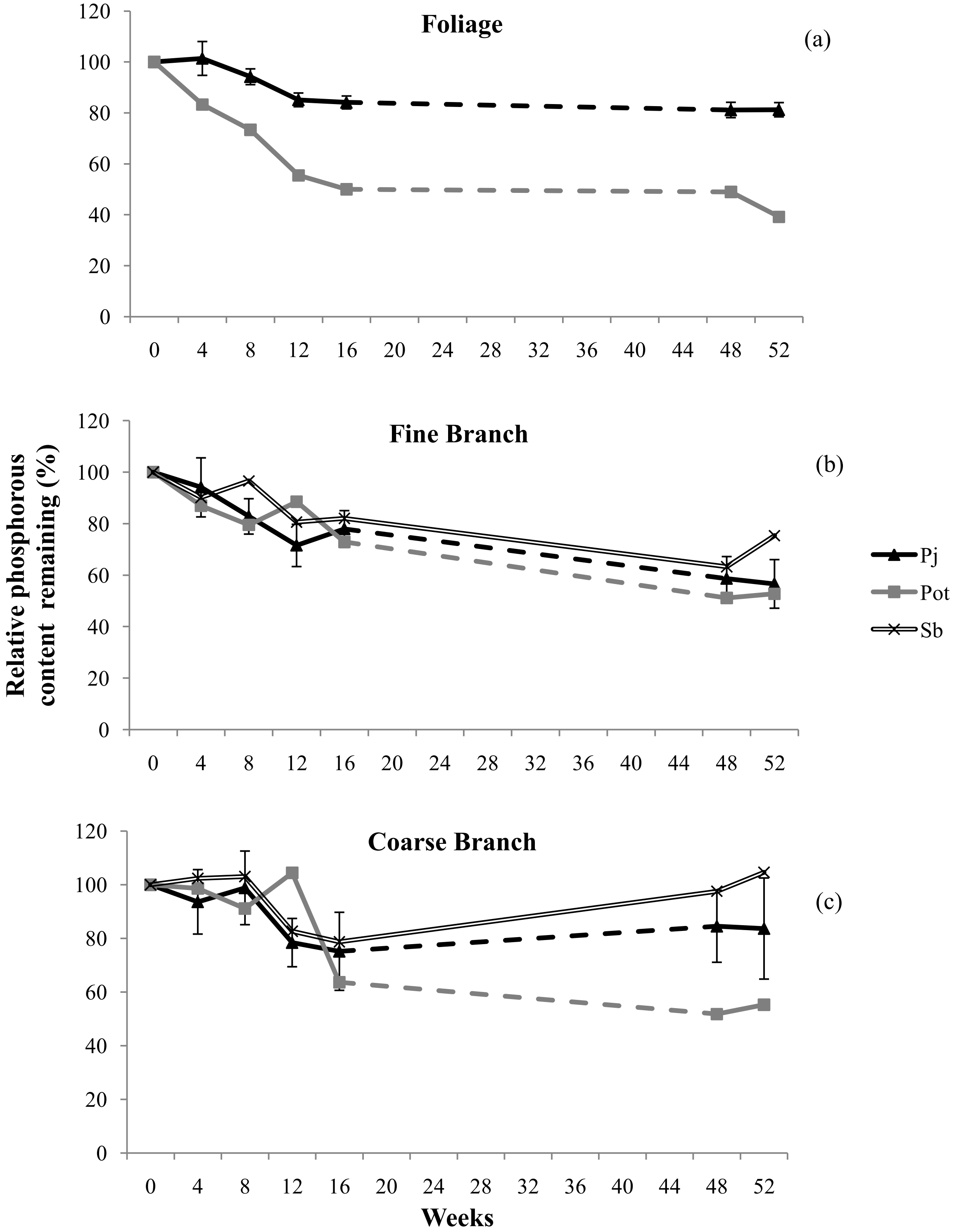

Figure 18. Relative phosphorous content remaining in foliage (a), fine branches (b) and coarse branches (c). Dotted line indicates winter period where no measurements were taken. Typical variance is indicated by standard error bars on jack pine data only.

4.4.3 **Potassium**

Potassium was released rapidly from the foliage material. At week 16 (Oct), foliar K was down to 75% of its original content for jack pine and 30% for aspen (Figure 19a). Additional K loss occurred until the end of the 52 week field-drying experiment, and was reduced to 54% and 14% of its original content, for jack pine and aspen, respectively (Figure 19a).

The rate of K release observed in the fine branch materials was slower but followed a near linear trend. By week 16, the average K content remaining in the fine harvest residues was 69% of its original amount and was consistent for all species (Figure 19b). After field-drying for 52 weeks, and experiencing a period of overwintering, K levels decreased to 33%, 50%, and 48% of the original content for jack pine, trembling aspen, and black spruce, respectively (Figure 19b).

Changes in K content in the coarse branch material varied by species as well. Jack pine coarse branch harvest residues slowly released K after 4 weeks of field drying, whereas trembling aspen residues took between 12-16 weeks of field-drying before it began to release K via decomposition and leaching. By week 16, the K levels of the coarse branch residues had decreased to 81% and 69% of its original content, for jack pine and trembling aspen, respectively (Figure 19c). By the following June (week 52), the K levels had continued to decrease; levelling out at 77% and 58% of its original content, for jack pine and trembling aspen, respectively. The K content of the black spruce coarse branch material, however, fluctuated only slightly, and remained relatively unchanged throughout the entire duration of the experiment (Figure 19c).

Potassium is known to be the most readily leached nutrient from drying plant material; left on site for 16 to 32 weeks, broadleaf and coniferous harvest residue materials have been shown to lose between 50 and 85% of the original K through the processes of leaching and decomposition (Granhall and Slapokas 1984, Johnson *et al.* 1985, Stupak et al 2008. Lehto *et al.* 2010). The current study found the residue materials lost between 23 and 86% of the original K. One exception, however, is that black spruce coarse branches experienced no decrease in K. Similar to P, broadleaf foliage lost K faster than coniferous foliage and fine branches were found to lose K at a faster rate than coarse branches. Similar to P, the K results from this study support that the benefits of field-drying varies by tree species. Therefore forest managers need to be considerate of the slash material‟s species composition when managing a site‟s K levels. The most extreme example of this species difference is again seen in the black spruce coarse branch material which tends to release no K during the field-drying process. The high physical loss of foliage exhibited by black spruce, however, also needs to be considered, but as mention previously this will be explored further in the cumulative returns section of this study.

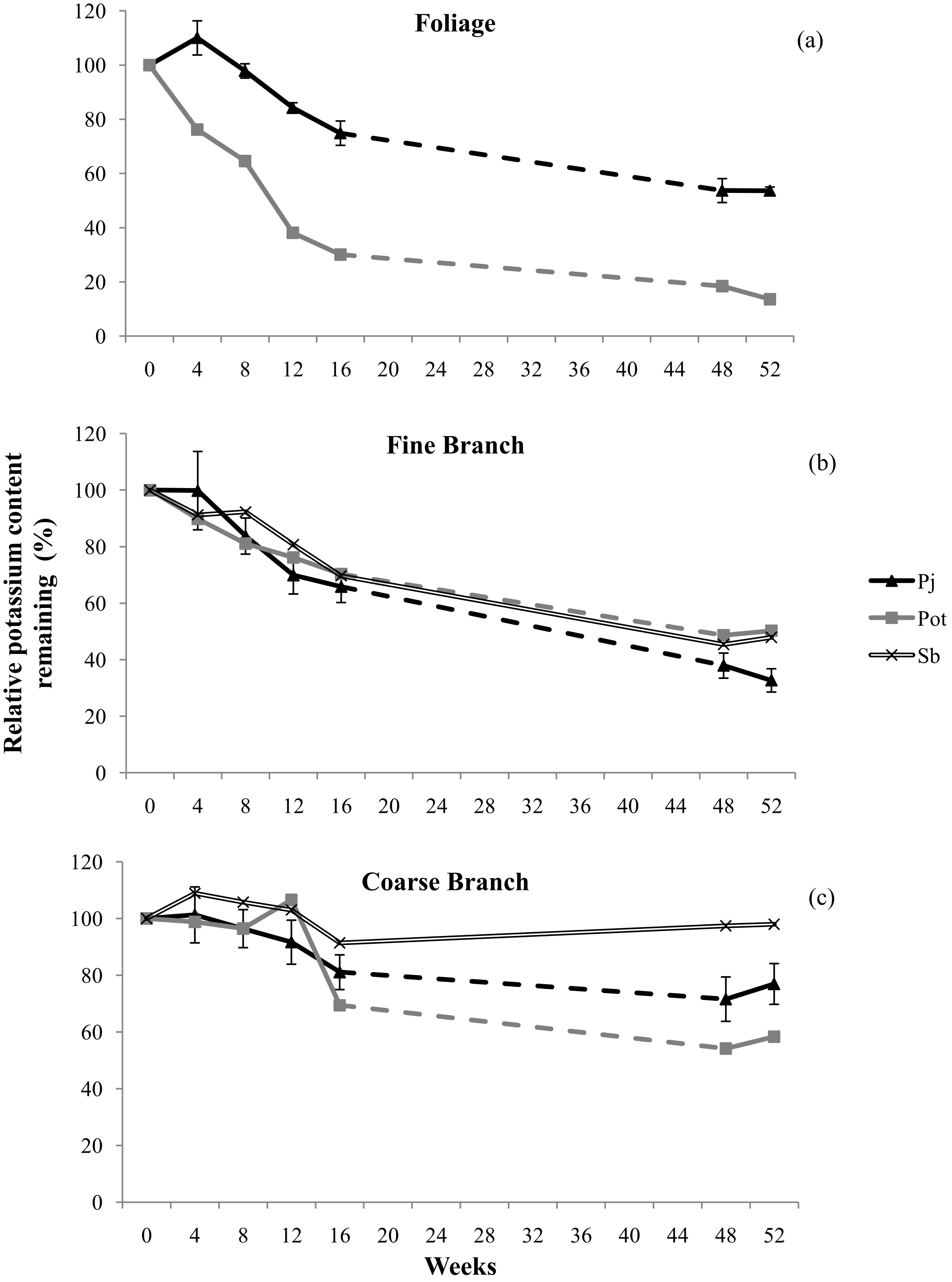

Figure 19. Relative potassium content remaining in foliage (a), fine branches (b) and coarse branches (c). Dotted line indicates winter period where no measurements were taken. Typical variance is indicated by standard error bars on jack pine data only.

4.4.4 **Calcium**

Calcium declines in soils are commonly reported, but calcium was the only nutrient that consistently showed little to no release from any of the residue types over the 52-week field-drying experiment (Figure 20). It is assumed that Ca was retained in the material since the concentration of Ca increased as the material lost mass by decomposition and the leaching of other nutrients. Any subtle trends seen in the Ca contents are questionable since the variability was observed to be quite high, especially in the fine branch and coarse branch material. There is one exception to this trend however, the Ca content of the trembling aspen coarse branch material showed an evident decrease of 35% to 40% by the end of the 52-week period.

Johnson *et al*. (1985), Lehto *et al.* (2010) and Stupak *et al.* (2008) found that through decomposition and leaching, calcium was either retained entirely or decreased up to 50%, depending on the material type. The present study found that, in almost all cases, calcium was not released from any of the field-drying material. Rather, it was retained in the biomass fluctuating only slightly over the 52-week experiment. The calcium content of the trembling aspen coarse branch material was the one exception to this trend as it decreased by 40%. Calcium is an element that is supposed to be resistant to degradation or loss from plant material. It is unclear as to why trembling aspen coarse branch material was the only residue type to loss Ca by field-drying. The initial concentration of Ca for trembling aspen (0.7%) was much higher than the concentration measured in black spruce (0.4%) or jack pine (0.2%). Perhaps the higher concentration of Ca in the trembling aspen coarse branch material indicates that it is in a more mobile phase instead of being bound up in the cell wall structure. Calcium depletion may not be a concern if the slash is predominantly trembling aspen.

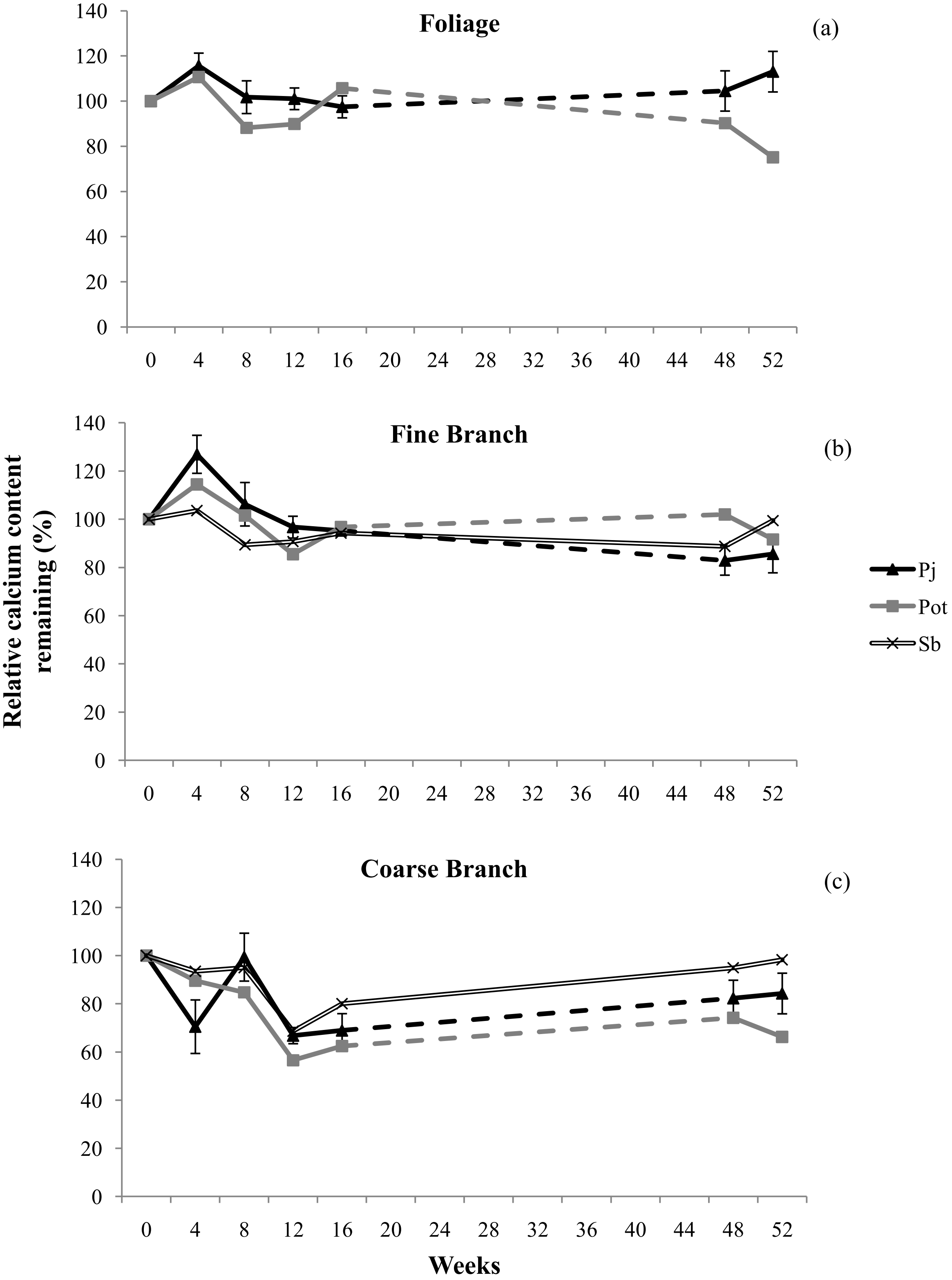

Figure 20. Relative calcium content remaining in foliage (a), fine branches (b) and coarse branches (c). Dotted line indicates winter period where no measurements were taken. Typical variance is indicated by standard error bars on jack pine data only.

4.4.5 **Boron**

The release rates of B from the foliage of both jack pine and trembling aspen was found to be comparable during the first 16 weeks of field-drying, with the average foliar B content remaining being 81% of its original amount (Figure 21a). Following the winter months however, trembling aspen began releasing B at a faster rate and after 52 weeks of field drying had 44% of its original B content remaining, compared to 71% in the jack pine foliage (Figure 21a).

The rate of decrease in the fine branch B was found to be similar for all tree species for the entire duration of the experiment. At week 16 (Oct), the amount of B remaining in the fine branch residues was 68%, 84%, and 71% of its original content for jack pine, trembling aspen, and black spruce, respectively (Figure 21b). After 52 weeks (Jun) of field-drying, relative B contents in the fine branch material had been reduced to 47%, 58% and 57% of its original content for jack pine, trembling aspen, and black spruce, respectively (Figure 21a).

Boron trends in the coarse branch material were found to vary by tree species, however, the amount of boron remaining in the material at the end of the experiment was similar (60-70%) (Figure 21c). The B in the jack pine coarse residues followed a fairly slow and consistent release over the 52-week field-drying period, reaching 85% and 73% of its original content by weeks 16 and 52, respectively (Figure 21c). Trembling aspen coarse branch material B was found to remain unchanged during the initial 16 weeks of field drying, and then dropped to approximately half of its original amount following the winter months (Figure 21c). Boron in the black spruce coarse branches remained was retained until week 8, dropped to 60% of its original amount by week 12, and then remained relatively constant for the remainder of the experiment (Figure 21c).

The only study which investigated changes in boron content of residue material left in the field was Letho *et al*. (2010) who reported losses of up to 50% in Norway spruce needles left in the field for one year. The present investigation found that between 30% and 60% of boron was lost from the field-drying material through the processes of leaching and decomposition. Many of the acidic and/or sandy soils in the boreal forest, have been found to be deficient in B (Stone 1990). Field-drying, therefore, may be a successful technique for managing micronutrients such as boron to ensure they remain on site.

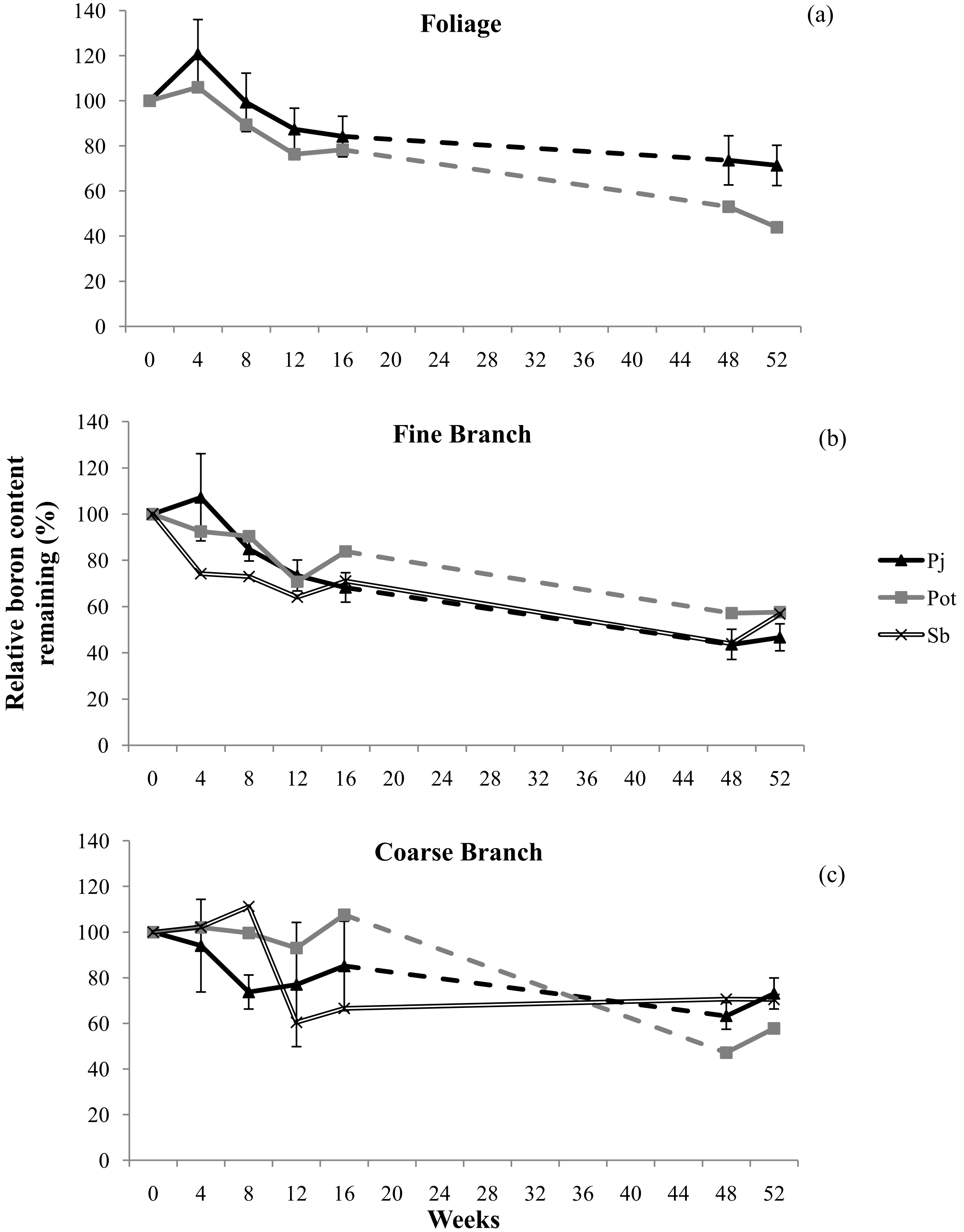

Figure 21. Relative boron content remaining in foliage (a), fine branches (b) and coarse branches (c). Dotted line indicates winter period where no measurements were taken. Typical variance is indicated by standard error bars on jack pine data only.

4.5 Cumulative nutrient retention

When all of the processes were combined (foliar mass loss, decomposition, and leaching), the results suggest that, in most cases, nutrient retention was greatest when the material was left to field-dry for 52 weeks before removal (Figure 22 and Table 9). Black spruce was the one exception to this statement, since for some nutrients it was observed that field-drying for an additional 36 weeks had little effect on nutrient retention or was found to have the opposite effect and site nutrient retention actually decreased when the black spruce harvest residue was left on site to field-dry longer (16 weeks vs. 52 weeks).

Approximately 34% of the N in the black spruce harvest residue (87.9 $kg \cdot gt^{-1}$) was retained on site when left to dry for 16 weeks, however, this amount decreased to 14% (36.4 $kg \cdot gt^{-1}$) if the material was left in the field to dry for 52 weeks (Figure 22a). An additional 36 weeks of field drying increased the amount of N retained on site for the other two species from 7-26% (18.5-65.2 $kg \cdot gt^{-1}$) for jack pine and 22-39% (65.3-115.8 $kg \cdot gt^{-1}$) for trembling aspen.

The average relative P retention of all tree species was found to be 19% of its original amount if left to field-dry for 16 weeks (Figure 22b). If the material was left to dry for an additional 36 weeks, the average relative P retention increased to 31% of its original amount (Figure 22b). Phosphorous retention after 16 weeks of field-drying was found to be 6.0 $kg \cdot gt^{-1}$ for jack pine and black spruce, and 16.9 $kg \cdot gt^{-1}$ for trembling aspen (Table 9). After 52-weeks of field-drying, the amount of P retained on site increased up to 10.5 $kg \cdot gt^{-1}$ for jack pine and black spruce, and 21.7 $kg \cdot gt^{-1}$ (Table 9).

After 16 weeks of field-drying, between 27-48% of the material‟s K was left on site through leaching, decomposition, and the shedding of foliage (Figure 22c). After 52 weeks of field-drying, 52-62% of the material‟s potassium was left on site (Figure 22c). Potassium retention after 16 weeks of field-drying was found to be 23.3, 43.4, and 97.9 kg·gt^{-1} for jack pine, black spruce, and trembling aspen (Table 9). After 52-weeks of field-drying, the amount of potassium retained on site increased as high as 128.0 kg·gt^{-1} in the case of trembling aspen residues (Table 9).

Field-drying for at least 16 weeks was found to leave between 20 and 40% of the material‟s Ca on site (Figure 22d). No further retention of calcium was observed if the material was left to field-drying for longer (52 weeks). Actual quantities of Ca retained through field-drying were calculated to be approximately 25, 115, and 112 kg·gt^{-1} for jack pine, trembling aspen, and black spruce, respectively (Table 9).

For black spruce harvest residues, boron exhibited almost no change between field-drying for 16 weeks versus field-drying for 52 weeks; leaving black spruce biomass to dry in the field only retained an additional 3% more boron (0.02 kg·gt^{-1}) on the site (Figure 22e). In contrast, jack pine and trembling aspen retained 23% and 31% more boron on the site when left to overwinter and dry for an additional 36 weeks (Figure 22e).

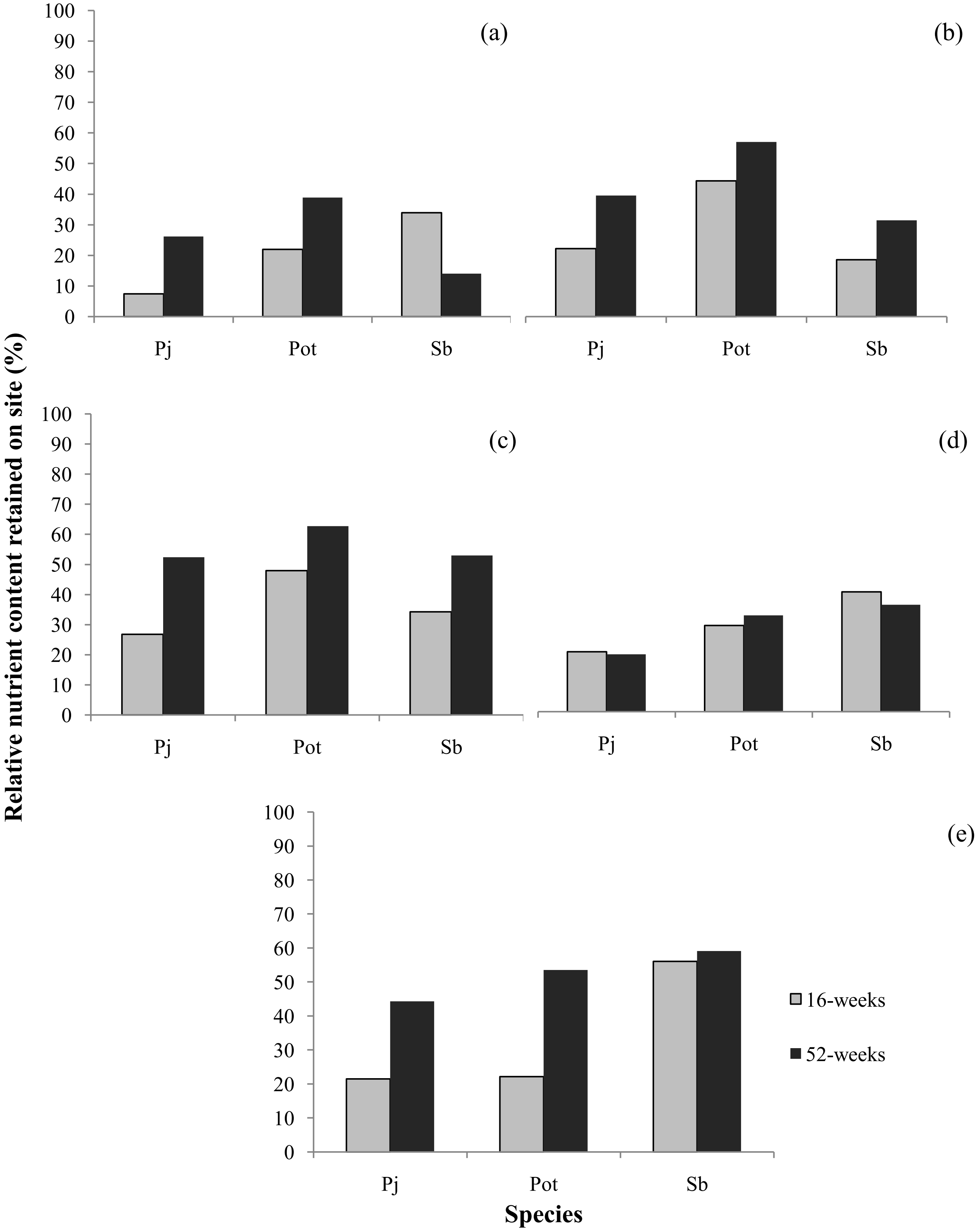

Figure 22. The relative amount of nutrients retained on site by all processes (foliar mass loss, decomposition, leaching) after16-weeks and 52 weeks of field-drying. Nitrogen (a), phosphorous (b), potassium (c), calcium (d) and boron (e).

Table 9. Amount of nutrients retained on site by all processes (physical foliar mass loss, decomposition, leaching) in kilograms·tonne^{-1} of green harvest residue; comparison of two different field-drying durations (16 weeks vs. 52 weeks field-drying).

		Jack Pine		Trembling Aspen		Black Spruce	
Nutrient		16-Weeks	52-Weeks	16-Weeks	52-Weeks	16-Weeks	52-Weeks
Nitrogen	(kg gt^{-1})	18.5	65.2	65.3	115.8	87.9	36.4
Phosphorous	(kg gt^{-1})	6.0	10.7	16.9	21.7	6.1	10.4
Potassium	(kg gt^{-1})	23.3	45.6	97.9	128.0	43.4	67.2
Calcium	(kg gt^{-1})	25.5	24.5	108.1	121.0	117.9	105.3
Boron	(kg gt^{-1})	0.10	0.21	0.17	0.40	0.40	0.42

4.6 Management implications

The abovementioned cumulative retention results strongly support that each of the three tree species respond differently to the field-drying treatment. Factors such as the initial nutrient levels, the distribution of biomass by component (mass of leaves to fine branches to coarse branches), and the rate of foliage shedding, differed considerably by tree species and these differences largely drove the effect that field-drying had on site nutrient retention. Species differences were seen most notably between black spruce and the other two tree species (trembling aspen and jack pine). Unexpectedly trembling aspen and jack pine were found to respond similarly, especially in physical foliage mass loss.

This species effect is further magnified when the results are scaled up to a stand management level using the slash measurements and nutrient replacement times recorded by Morris (2003). The nutrient replacement times for four different biomass harvest scenarios and two different forest types are contrasted in

Table **10**. According to the findings of Morris (2003), mixedwood stands are more sensitive to intensive biomass harvesting than black spruce. With the exception of N, all of the nutrient replacement times for the mixedwood forest extend are between 100-170 years, well beyond an average mixedwood rotation age (Table 10). Compared to the nutrient replacement times for intensively harvested black spruce stands (30-89 years), all were found to fall within a natural ecological rotation. Therefore, field-drying the harvesting residue to retain nutrients on mixedwood sites is far more imperative than on black spruce sites.

When comparing the benefits of the two field-drying durations, mixedwood sites were also determined to benefit from overwintering and field-drying longer (52 weeks vs. 16 weeks). The additional benefit of leaving the material to field-dry until the following spring (52 weeks) is largely due to the overwintering period whereby the material is exposed to a continuous freezing and thawing action and a heavy snowload which loosens the foliage enough to be shed from the branches. However, from a forest management perspective, the logistically feasibility would still need to be taken into consideration as well. Compared to a single summer of drying (16 weeks), drying the mixedwood residue material for a full year shortens the nutrient replacement time by 4, 37 and 24 years for N, P and K, respectively. The replacement time for Ca was found to be unaffected by a longer field-drying time. Even though field-drying for 52 weeks significantly shortened the nutrient replacement times on mixedwood sites, P and Ca still require 99 and 110 years, respectively, to return to their pre-harvest levels. Again, this is beyond the normal rotation age for a typical mixedwood stand in northwestern Ontario. Therefore, depending on the nutrient pools in the soil, even after field-drying for one year, sites could potentially experience deficienies in P and Ca after several rotations.

Field-drying residues on black spruce site for 52 weeks only shortened the nutrient replacement times for P and K by a small amount; 15 and 12 years, respectively. When left to field-dry for 16 weeks the nutrient replacement times were 25, 78, 41 and 81 years, for N, P, K and Ca, respectively. All of these replacement times are well within the normal rotation time for a black spruce stand. Therefore, there is almost no benefit in leaving black spruce to field-dry for longer than 16 weeks. A possible explanation for this phenomenon is that bulk of the nutrient retention on a black spruce site is through foliar mass loss, which occurs early on in the drying process. Almost no additional foliage is retained on the site if left to overwinter. In addition, black spruce harvest residues were found to be the most resistant to decomposition and nutrient leaching.

Field-drying is already being used as a biomass management tool in many Nordic countries, however, most of the harvesting operations in these instances utilize harvester equipment and cut-to-length operations, which make it easy to leave the material spread across the site to dry, shed foliage, and release nutrients fairly evenly throughout the clearcut. In northwestern Ontario, most harvest operations utilize feller-buncher equipment and delimb the trees at roadside. In order to field-dry harvest residue material in small piles or in a thin layer across the site, there would need to be a switch from full-tree operations to a cut-to-length. Field-drying could be integrated into a standard cut-to-length harvesting operation with little modification. Since the moisture content of the harvest residue decreases so quickly and since a beneficial return of nutrients occurs in a relatively short time frame, by the time the harvest cutblock is complete, the machinery could return to the area first harvested and begin removing the dried biomass material.

Harvesting operations usually take several months to a year to complete, depending on the size of clearcut and the intensity of the operation, therefore the same equipment could be used for harvesting both the trees and the biomass without the need to float truck equipment back to the site to remove the biomass material. Therefore, in most instances, the system could be set up as such: 1) the harvest of the clearcut would commence in the spring, 2) over a period of several months to a year, the remainder of the harvest area would be cut, 3) once the harvest is complete the equipment would return to the first area cut, 4) the dried biomass material would be removed at this time, and 5) the removal of the biomass material would be done just before site preparation and/or the planting/regeneration of the site.

Table 10. Nutrient replacement times for a mixedwood and black spruce forest stand under different biomass harvesting intensities and field-drying scenarios.

Forest Type	**Biomass Harvest Scenario**	**Replacement Times**			
		N	**P**	**K**	**Ca**
		years			
A. Mixedwood Forest	Conventional tree-length (No biomass removal)	19	58	43	70
	Intensive biomass harvest (Immediate removal)	58	170	100	128
	Field-dried biomass harvest (dried 16 weeks)	47	136	72	109
	Field-dried biomass harvest (dried 52 weeks)	43	99	48	110
	Decreased replacement time (16 weeks -52 weeks)	**4**	**37**	**24**	**-1**
B. Black Spruce Forest	Conventional tree-length (No biomass removal)	14	31	25	60
	Intensive biomass harvest (Immediate removal)	30	71	45	89
	Field-dried biomass harvest (dried 16 weeks)	25	78	41	81
	Field-dried biomass harvest (dried 52 weeks)	33	63	30	85
	Decreased replacement time (16 weeks -52 weeks)	**-8**	**15**	**12**	**-4**

5. CONCLUSION

The results from this study demonstrated that field-drying forest harvest residues can be a successful, multi-functional forest management tool. Leaving the material to passively dry in the clearcut can reduce the moisture of the green material by more than 50% in as little as 4 weeks if cut in early summer, thus doubling the efficiency of transportation as well as greatly increasing the energy conversion efficiency during burning. Through the combined processes of physical foliage mass loss, leaching and decomposition, field-drying can also successfully retain more nutrients on site instead of having them be exported off-site through the removal of this biomass material.

It was originally predicted that moisture content would reach its lowest point by the end of week 16 (Oct), that melt water from snow and ice would increase the moisture content of the material for the week 48 (May) measurement, and that moisture content would return to the same level as week 16 by the end of the 52-week experiment (Jun). This study found that moisture was lost at a much faster rate than expected and reached its lowest point by week 4. The current investigation also found that moisture content was reduced to a much lower levels than originally predicted; 17% instead of 35% (west basis), respectively. Frequent monthly measurements unexpectedly found that moisture content began to increase again into early autumn. As predicted, moisture content increased for the early spring measurement (week 48) following the winter months and then reached its lowest level again by June of the following year (week 52).

Predictions were that the majority of nutrients would be returned to the site though the shedding of foliage as opposed to the processes of leaching and decomposition. This study found that the retention of nutrients was very strongly dependent on the species of the material. For black spruce, nutrient return was almost entirely through the process of physical foliage shedding. Trembling aspen and jack pine, however, experienced almost no physical foliage loss until week 48 and 52, but returned a significant amount of nutrients to the site after 16 weeks of field-drying. In this instance, leaching and decomposition played a larger role that expected.

The actual decomposition rates observed in this study were greater than the expected 2% mth^{-1}. Decomposition rates of the harvest residue materials were 2, 3 and 5% mth^{-1} for coarse branch, fine branch, and foliage, respectively. As predicted, the rate of decomposition for the broadleaf trembling aspen foliage was found to be greater ($7.5\%\cdot\text{mth}^{-1}$) than the needle foliage of jack pine or black spruce ($3.5\%\cdot\text{mth}^{-1}$).

More mobile or soluble nutrients, such as P and K, were expected to leach quickly from material within the first four weeks, while more recalcitrant nutrients, such as Ca, were expected to remain unchanged in the material until the material overwintered. The study found that both P and K were readily leached from the harvest residue material, however, they were either released from the material at a linear rate over the duration of the experiment, or were found to have a slight lag time and were not released until week 8 -12. The study found that calcium remained bound in the material even following the overwintering period. The one exception to this statement was that calcium was immediately released from the trembling aspen coarse branch material within the first 16 weeks of field-drying.

Nitrogen was predicted to increase during the initial months as microbial populations broke down the carbon rich compounds and would later decrease as decomposition proceeded. The current investigation did not find this pattern to be true. Instead, for most of the material, the nitrogen content remained relatively unchanged over the entire 52-week period. This does, however, indicate that the nitrogen concentration of that material was in fact increasing slightly, but at a rate similar or equivalent to the rate of mass being lost to decomposition.

Weather patterns likely played an important role in the field-drying process; however, the present investigation only had access to general climate trends for the region (Thunder Bay mean temperature and total monthly precipitation). To accurately study the response of the material to temperature and precipitation fluctuations, further research including the incorporation of microclimate stations in the drying slash piles at each of the experimental sites would be required. Other factors that were not investigated in this study but should be taken into consideration are questions such as: 1) how the removal of harvest residues affects habitat for micro and mesofauna (insects, small mammals etc.), 2) what effect would the removal of this biomass material ultimately have on site biodiversity, and 3) what effect would continual biomass harvesting have on site long-term site productivity. The removal of fine harvest residues could also have a negative effect on soil erosion due to the loss of soil cover and greater chance of soil compaction from the increased mechanical activity needed to harvest the biomass material. However, if the material is going to be removed regardless, it would be more ecologically sound and a better economic management practice to leave the material to dry for some duration of time before removing from the site.

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APPENDIX I

NORTHWESTERN ONTARIO TREE NUTRIENT DATABASE

Tree Species	Component	N	P	K	Mg	Ca	S	Mn	Fe	Zn
		%						mg kg^{-1}		
Black Ash	Lower Bole	0.095	0.002	0.178	0.018	0.100	0.010	1.0	20.7	0.4
	Upper Bole	0.111	0.003	0.394	0.027	0.121	0.013	1.0	26.7	0.0
	Lower Bark	0.418	0.025	0.464	0.088	2.744	0.054	67.6	45.1	17.2
	Upper Bark	0.413	0.027	0.391	0.087	2.493	0.055	54.8	70.0	15.5
	Branches	0.421	0.025	0.308	0.055	0.958	0.047	22.1	85.2	14.4
	Foliage	3.44	0.251	1.935	0.389	1.577	0.276	41.5	88.7	27.0
Balsam Fir	Lower Bole	0.065	0.005	0.140	0.021	0.098	0.006	51.5	41.0	7.0
	Upper Bole	0.066	0.004	0.140	0.027	0.150	0.007	77.4	44.1	9.4
	Lower Bark	0.363	0.043	0.285	0.068	0.698	0.038	285.3	82.2	48.2
	Upper Bark	0.421	0.048	0.372	0.072	0.522	0.042	348.5	254.9	39.2
	Branches	0.258	0.022	0.179	0.048	0.441	0.027	177.2	168.7	32.7
	Foliage	1.22	0.089	0.529	0.107	0.856	0.095	540.7	106.9	47.4
White Birch	Lower Bole	0.145	0.005	0.035	0.021	0.061	0.006	45.8	29.5	10.4
	Upper Bole	0.177	0.007	0.045	0.026	0.073	0.006	59.3	36.2	11.7
	Lower Bark	0.378	0.026	0.127	0.050	0.578	0.026	634.2	32.0	131.8
	Upper Bark	0.406	0.031	0.137	0.065	0.713	0.031	573.3	35.1	176.7
	Branches	0.476	0.022	0.112	0.051	0.359	0.019	191.9	78.7	50.6
	Foliage	2.70	0.244	1.030	0.289	0.538	0.171	488.0	147.6	100.8
Jack Pine	Lower Bole	0.045	0.003	0.033	0.016	0.064	0.005	23.0	40.6	13.0
	Upper Bole	0.061	0.005	0.045	0.022	0.070	0.006	26.8	50.8	6.7
	Lower Bark	0.243	0.016	0.070	0.039	0.441	0.025	54.0	59.0	21.9
	Upper Bark	0.330	0.037	0.163	0.080	0.349	0.032	75.9	67.3	49.1
	Branches	0.158	0.012	0.065	0.034	0.174	0.015	41.2	73.9	17.9
	Foliage	1.36	0.088	0.314	0.097	0.293	0.087	195.5	74.2	30.9
Trembling Aspen	Lower Bole	0.051	0.005	0.069	0.024	0.091	0.007	7.4	22.7	9.7
	Upper Bole	0.065	0.007	0.075	0.029	0.098	0.008	9.9	18.4	14.4
	Lower Bark	0.329	0.032	0.290	0.098	1.055	0.040	42.4	61.3	109.0
	Upper Bark	0.545	0.052	0.248	0.128	0.847	0.050	62.7	40.4	154.9
	Branches	0.339	0.035	0.292	0.093	0.555	0.034	49.3	75.0	80.4
	Foliage	3.19	0.247	1.280	0.251	0.531	0.211	81.9	94.6	85.4
Black Spruce	Lower Bole	0.068	0.002	0.031	0.011	0.097	0.005	100.8	25.0	9.9
	Upper Bole	0.078	0.002	0.037	0.013	0.102	0.005	114.3	37.9	12.8
	Lower Bark	0.194	0.031	0.177	0.052	0.994	0.027	470.8	35.0	72.3
	Upper Bark	0.236	0.036	0.196	0.069	0.752	0.028	504.8	35.6	67.4
	Branches	0.445	0.028	0.119	0.040	0.378	0.030	266.0	133.6	37.1
	Foliage	0.527	0.059	0.229	0.084	0.625	0.069	855.7	52.2	46.3
Tamarack	Lower Bole	0.031	0.002	0.056	0.022	0.075	0.005	46.9	27.9	3.2
	Upper Bole	0.038	0.003	0.065	0.024	0.089	0.005	53.9	17.2	4.4
	Lower Bark	0.307	0.035	0.190	0.071	0.885	0.038	516.4	56.6	51.6
	Upper Bark	0.329	0.038	0.236	0.079	0.603	0.044	707.9	90.3	66.9
	Branches	0.153	0.013	0.110	0.041	0.262	0.017	185.8	117.7	22.0
	Foliage	2.04	0.144	0.870	0.106	0.277	0.142	198.9	149.6	24.8

APPENDIX II

EMS TABLE

Source	EMS	df	Test	Test Stat.
M_i	$\sigma^2 + 21\sigma^2_S + 63\phi(M)$	1	MS(S)	7.71
$S_{(i)j}$	$\sigma^2 + 21\sigma^2_S$	4	MS(Error)*	2.53
Sp_k	$\sigma^2 + 7\sigma^2_{SSp} + 42\phi(Sp)$	2	MS(SSp)	4.46
MSp_{ik}	$\sigma^2 + 7\sigma^2_{SSp} + 21\phi(MSp)$	2	MS(SSp)	4.46
$SSp_{(i)jk}$	$\sigma^2 + 7\sigma^2_{SSp}$	8	MS(Error)*	2.10
T_l	$\sigma^2 + 3\sigma^2_{ST} + 18\phi(T)$	6	MS(ST)	2.51
MT_{il}	$\sigma^2 + 3\sigma^2_{ST} + 9\phi(MT)$	6	MS(ST)	2.51
$ST_{(i)jl}$	$\sigma^2 + 3\sigma^2_{ST}$	24	MS(Error)*	1.70
SpT_{kl}	$\sigma^2 + 6\phi(SpT)$	12	MS(Error)*	1.92
$\mathcal{E}_{(ijkl)m}$	σ^2	60*	*	-

*pooled $MSpT_{ikl}$ and $SSpT_{(i)jkl}$

APPENDIX III

COARSE BRANCH MOISTURE CONTENT REPEAT MEASURES ANOVA TABLE

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
M	T0	94.1	1	94.1	9.7	**0.021**
	T1	33.6	1	33.6	1.9	0.222
	T2	46.5	1	46.5	8.9	**0.025**
	T3	4.9	1	4.9	0.1	0.755
	T4	102.5	1	102.5	1.1	0.340
	T5	45.8	1	45.8	1.0	0.364
	T6	17.8	1	17.8	1.1	0.331
S(M)	T0	1.7	2	0.9	0.1	0.916
	T1	50.1	2	25.0	1.4	0.321
	T2	183.9	2	91.9	17.6	**0.003**
	T3	15.6	2	7.8	0.2	0.848
	T4	165.4	2	82.7	0.9	0.467
	T5	82.5	2	41.2	0.9	0.467
	T6	8.9	2	4.5	0.3	0.764
Sp	T0	437.0	2	218.5	22.5	**0.002**
	T1	1486.6	2	743.3	41.0	**0.000**
	T2	923.1	2	461.6	88.3	**0.000**
	T3	1933.5	2	966.8	21.0	**0.002**
	T4	2833.7	2	1416.8	14.8	**0.005**
	T5	2521.7	2	1260.9	26.5	**0.001**
	T6	746.7	2	373.4	23.5	**0.001**
M * Sp	T0	15.0	2	7.5	0.8	0.503
	T1	1.1	2	0.5	0.0	0.971
	T2	21.6	2	10.8	2.1	0.208
	T3	81.1	2	40.6	0.9	0.462
	T4	10.4	2	5.2	0.1	0.947
	T5	207.2	2	103.6	2.2	0.194
	T6	18.3	2	9.1	0.6	0.590
S * Sp(M)	T0	86.5	4	21.6	2.2	0.182
	T1	117.2	4	29.3	1.6	0.285
	T2	124.8	4	31.2	6.0	**0.028**
	T3	91.2	4	22.8	0.5	0.741
	T4	67.2	4	16.8	0.2	0.943
	T5	72.7	4	18.2	0.4	0.815
	T6	202.8	4	50.7	3.2	0.099
P(Sp)	T0	31.3	3	10.4	1.1	0.428
	T1	50.4	3	16.8	0.9	0.483
	T2	27.5	3	9.2	1.8	0.255
	T3	46.4	3	15.5	0.3	0.800
	T4	389.4	3	129.8	1.4	0.342

	T5	119.3	3	39.8	0.8	0.521
	T6	126.0	3	42.0	2.6	0.143
M * P(Sp)	T0	1.8	3	0.6	0.1	0.978
	T1	27.0	3	9.0	0.5	0.698
	T2	28.3	3	9.4	1.8	0.246
	T3	35.3	3	11.8	0.3	0.855
	T4	520.8	3	173.6	1.8	0.244
	T5	99.9	3	33.3	0.7	0.585
	T6	17.2	3	5.7	0.4	0.783
S * P(Sp)	T0	36.1	6	6.0	0.6	0.712
	T1	48.1	6	8.0	0.4	0.828
	T2	63.0	6	10.5	2.0	0.208
	T3	184.1	6	30.7	0.7	0.682
	T4	961.6	6	160.3	1.7	0.273
	T5	229.3	6	38.2	0.8	0.601
	T6	167.8	6	28.0	1.8	0.254
Error	T0	58.2	6	9.7		
	T1	108.7	6	18.1		
	T2	31.4	6	5.2		
	T3	276.2	6	46.0		
	T4	573.2	6	95.5		
	T5	285.3	6	47.5		
	T6	95.2	6	15.9		

APPENDIX IV

FINE BRANCH MOISTURE CONTENT REPEAT MEASURES ANOVA TABLE

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
M	T0	109.1	1	109.1	9.4	**0.022**
	T1	47.9	1	47.9	3.0	0.135
	T2	38.5	1	38.5	2.4	0.172
	T3	0.0	1	0.0	0.0	0.985
	T4	304.1	1	304.1	36.1	**0.001**
	T5	1076.1	1	1076.1	25.196	**0.002**
	T6	374.2	1	374.2	8.9	**0.025**
S(M)	T0	35.3	2	17.7	1.5	0.292
	T1	38.2	2	19.1	1.2	0.367
	T2	21.5	2	10.8	0.7	0.545
	T3	272.3	2	136.2	6.9	**0.028**
	T4	32.9	2	16.5	2.0	0.222
	T5	597.3	2	298.7	7.0	**0.027**
	T6	622.2	2	311.1	7.4	**0.024**
Sp	T0	559.2	2	279.6	24.1	**0.001**
	T1	37.9	2	18.9	1.2	0.370
	T2	132.0	2	66.0	4.1	0.075
	T3	580.4	2	290.2	14.6	**0.005**
	T4	300.0	2	150.0	17.8	**0.003**
	T5	463.2	2	231.6	5.4	**0.045**
	T6	115.9	2	58.0	1.4	0.323
M * Sp	T0	8.2	2	4.1	0.4	0.715
	T1	25.9	2	12.9	0.8	0.490
	T2	71.1	2	35.5	2.2	0.190
	T3	76.6	2	38.3	1.9	0.225
	T4	71.3	2	35.7	4.2	0.071
	T5	231.9	2	115.9	2.7	0.145
	T6	47.6	2	23.8	0.6	0.596
S * Sp(M)	T0	101.9	4	25.5	2.2	0.186
	T1	59.5	4	14.9	0.9	0.507
	T2	67.8	4	16.9	1.1	0.452
	T3	79.7	4	19.9	1.0	0.473
	T4	175.5	4	43.9	5.2	**0.037**

	T5	48.6	4	12.1	0.3	0.878
	T6	209.3	4	52.3	1.2	0.387
P(Sp)	T0	61.2	3	20.4	1.8	0.254
	T1	24.5	3	8.2	0.5	0.691
	T2	57.7	3	19.2	1.2	0.387
	T3	116.5	3	38.8	2.0	0.222
	T4	70.8	3	23.6	2.8	0.131
	T5	54.6	3	18.2	0.4	0.741
	T6	39.6	3	13.2	0.3	0.816
M * P(Sp)	T0	6.3	3	2.1	0.2	0.906
	T1	3.7	3	1.2	0.1	0.970
	T2	16.6	3	5.5	0.3	0.795
	T3	256.7	3	85.6	4.3	0.061
	T4	23.8	3	7.9	0.9	0.477
	T5	124.9	3	41.6	1.0	0.464
	T6	177.0	3	59.0	1.4	0.332
S * P(Sp)	T0	73.8	6	12.3	1.1	0.473
	T1	49.2	6	8.2	0.5	0.783
	T2	123.7	6	20.6	1.3	0.384
	T3	100.8	6	16.8	0.8	0.577
	T4	133.5	6	22.3	2.6	0.131
	T5	455.9	6	76.0	1.8	0.251
	T6	140.7	6	23.4	0.6	0.754
Error	T0	69.6	6	11.6		
	T1	96.3	6	16.1		
	T2	96.2	6	16.0		
	T3	119.0	6	19.8		
	T4	50.5	6	8.4		
	T5	256	6	42.7		
	T6	253.2	6	42.2		

APPENDIX V

FOLIAR MASS LOSS ANOVA TABLE

Source	Dependent Variable	Type III SS	df	MS	F	Sig.
Corrected Model	T1	20415.7	29	703.991	5.488	0.020
	T2	21569.2	29	743.767	20.642	0.001
	T3	33016.6	29	1138.504	20.416	0.001
	T4	28073.5	29	968.054	7.561	0.009
	T5	19406.6	29	669.196	3.647	0.055
	T6	12604.7	29	434.647	3.047	0.083
Intercept	T1	8858.6	1	8858.625	69.063	0.000
	T2	13672.5	1	13672.482	379.465	0.000
	T3	14085.0	1	14084.995	252.578	0.000
	T4	15768.9	1	15768.929	123.156	0.000
	T5	46737.7	1	46737.721	254.747	0.000
	T6	62788.3	1	62788.324	440.142	0.000
M	T1	18.1	1	18.143	0.141	0.720
	T2	153.6	1	153.586	4.263	0.085
	T3	78.0	1	78.008	1.399	0.282
	T4	61.2	1	61.227	0.478	0.515
	T5	148.8	1	148.778	0.811	0.403
	T6	25.2	1	25.151	0.176	0.689
S(M)	T1	429.6	2	214.813	1.675	0.264
	T2	119.0	2	59.492	1.651	0.268
	T3	1369.0	2	684.497	12.275	0.008
	T4	171.0	2	85.5	0.668	0.547
	T5	445.6	2	222.789	1.214	0.361
	T6	536.8	2	268.386	1.881	0.232
Sp	T1	16217.9	2	8108.926	63.218	0.000
	T2	19068.4	2	9534.224	264.612	0.000
	T3	26278.3	2	13139.133	235.617	0.000
	T4	20282.7	2	10141.33	79.204	0.000
	T5	15275.3	2	7637.654	41.63	0.000
	T6	8524.3	2	4262.15	29.877	0.001
M * Sp	T1	11.6	2	5.808	0.045	0.956
	T2	733.4	2	366.681	10.177	0.012
	T3	2452.2	2	1226.08	21.987	0.002
	T4	1306.3	2	653.141	5.101	0.051
	T5	574.0	2	286.978	1.564	0.284
	T6	390.4	2	195.202	1.368	0.324

S * Sp(M)	T1	553.9	4	138.477	1.08	0.443
	T2	26.8	4	6.701	0.186	0.937
	T3	1716.9	4	429.215	7.697	0.015
	T4	951.0	4	237.75	1.857	0.237
	T5	690.4	4	172.588	0.941	0.501
	T6	323.3	4	80.835	0.567	0.697
P(Sp)	T1	892.6	3	297.543	2.32	0.175
	T2	238.2	3	79.395	2.204	0.188
	T3	130.9	3	43.619	0.782	0.546
	T4	1111.6	3	370.54	2.894	0.124
	T5	127.0	3	42.328	0.231	0.872
	T6	123.9	3	41.301	0.29	0.832
M * P(Sp)	T1	73.2	3	24.401	0.19	0.899
	T2	129.4	3	43.145	1.197	0.388
	T3	278.4	3	92.809	1.664	0.272
	T4	258.9	3	86.307	0.674	0.599
	T5	400.8	3	133.596	0.728	0.572
	T6	965.3	3	321.757	2.255	0.182
S * P(Sp)	T1	465.3	6	77.548	0.605	0.722
	T2	193.8	6	32.305	0.897	0.551
	T3	261.8	6	43.635	0.782	0.613
	T4	2420.7	6	403.444	3.151	0.094
	T5	283.1	6	47.185	0.257	0.939
	T6	470.2	6	78.369	0.549	0.758
Error	T1	769.6	6	128.269		
	T2	216.2	6	36.031		
	T3	334.6	6	55.765		
	T4	768.2	6	128.04		
	T5	1100.8	6	183.467		
	T6	855.9	6	142.655		
Total	T1	30044.0	36			
	T2	35457.9	36			
	T3	47436.2	36			
	T4	44610.7	36			
	T5	67245.2	36			
	T6	76249.0	36			
Corrected Total	T1	21185.3	35			
	T2	21785.4	35			
	T3	33351.2	35			
	T4	28841.8	35			
	T5	20507.5	35			
	T6	13460.7	35			