Nutrient Cycling in Hybrid Poplar Stands in Saskatchewan: Implications for Long-Term Productivity

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Abstract

Intensive management of short rotation hybrid poplar (HP) plantations on agriculture land has demonstrated good early yields and promise as an alternative crop for farmers selling fibre to the forest industry. However, multiple rotations of HP may impact the future productivity of plantations through nutrient removals. The objectives, therefore, of this study were to determine the nutrient stores and fluxes for two HP plantations with differing site quality, fertilizer applications and past land management practices and to construct a 20-year nutrient budget to examine impacts of harvesting short rotation HP on long-term productivity.

Heights and biomass were measured by harvesting above- and below-ground and separating biomass into tree components; measurement of atmospheric deposition, mineral weathering, litterfall, litter decomposition, and leaching for HP plantations on an Alfalfa (HPA) and Pasture (HPP) sites in 2004-05. The budget was developed by averaging fluxes over 2 years and scaling up to a 20-year rotation.

Unfertilized treatments in the HPA plantation showed greater tree growth than all other treatments. Fertilized and unfertilized treatments had greater biomass production and nutrient pools than treatments at the HPP plantation. The fertilizer treatments did not affect on biomass production and nutrient accumulation.

Nutrient additions to the HPA were greater than the HPP plantations for leaf litterfall and leaching. Nutrient resorption from senescing leaves was greater at the HPP plantation suggesting that nutrient pools were smaller and that trees responded by keeping nutrients in the biomass. Fertilization at both plantations increased nutrient flow for inputs and outputs in 2004-05. Water leachate and leaf litterfall showed increased nutrient contents in fertilized treatments at both plantations.

A high fertility plantation that used fertilizer and practiced whole-tree harvesting exported more nutrients (and fibre) than a plantation with marginal site quality practicing stem-only harvesting. Time to replenish nutrients from atmospheric deposition and mineral weathering would range from 6 to 50 years for Ca and N, respectively, suggesting that subsequent plantations would require fertilizers to replenish soil nutrient reserves.

While HP plantations in Saskatchewan can produce high yields, they require large nutrient inputs and are inefficient (sequester a large amount) in nutrient use. High site quality is important to obtain high yields but conservational techniques, such as stem-only harvesting, are important in maintaining site quality over the long-term.

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1.0 INTRODUCTION

Cultivation of *Populus* species including hybrid poplars (HP), has received a lot of attention for achieving high fiber yield with short rotations (Ceulemans et al., 1992; Eckenwalder, 1996). Hybrid poplar are expected to have shorter rotations (≤ 20 yrs) (Zsuffa et al., 1996) compared to native species (> 60 yrs) and with a multitude of end use products, could be harvested for lumber, pulp, oriented strand board, or other value-added products. Walker poplar, an open pollinated *P. deltoides* selection developed by Agriculture and Agri-Food Canada –Prairie Farm Rehabilitation Administration Shelterbelt Centre in SK (Zsuffa et al., 1996), is consistently productive in the prairies especially for shelterbelts. In Saskatchewan, the areas best suited for growing HP are in the boreal forest fringe areas in the black to gray wooded soil areas (van Oosten, 2006). Some of the black soils can be very productive while soils in the gray wooded can have some nutrient deficiencies.

One of the concerns regarding HP plantations is nutrient availability (N, P, K, Mg, Ca) with respect to sustained high volume tree growth. The main question regarding HP plantations is whether intensively managed plantations on marginal forest-fringe farmland can be sustainable over multiple rotations without nutrient amendments (organic or inorganic). Nutrient cycling and budgeting studies have been completed for natural stands of aspen (Pastor and Bockheim, 1984); however, there is no information about nutrient cycling for hybrid poplar plantations in the prairies. The key to determining nutrient sustainability of HP is determining the nutrient budget of the plantations for short time periods and scaling up to estimate nutrient cycling for longer rotations.

The hypothesis for this study is that harvesting of 20 year old hybrid poplar plantations does not remove more nutrients from the site than can be replaced by natural processes. The objectives of the study were to measure nutrient pools and fluxes in four-year-old HP plantations and use the values to build a nutrient budget that estimated sustainability.

This thesis is divided into five chapters. The second chapter is a literature review of nutrient cycling examining the various inputs and outputs for forest stands. Chapter 3 investigates the nutrient pools for two different hybrid poplar sites, while chapter 4 determines the nutrient fluxes for the two sites with three different plantations, Hybrid Poplar Pasture (HPP), Hybrid Poplar Alfalfa (HPA) and Old Hybrid Poplar Alfalfa (OHPA). The fluxes that were measured included atmospheric deposition, mineral weathering, leaf recycling and leaching and how they were impacted by fertilization. Chapter 5 uses the information from chapters 3 and 4 to project a nutrient budget for a 20 year old HP plantation on two different quality sites and determines the impact of harvesting these sites on the nutrient budget and thus long-term productivity of these sites. Chapter 6 concludes with a discussion of nutrient cycling and the implications for intensively managing these short rotation plantations on agricultural land in Saskatchewan.

2.0 LITERATURE REVIEW

2.1 Nutrient Budgeting

There has been increasing interest in converting agricultural land, particularly along the forest fringe in Saskatchewan into hybrid poplar plantations. Before undertaking large scale plantations, however, the effects of nutrient cycling on long-term productivity for different soil classes needs to be understood. The fertility of an ecosystem, from which its performance depends, has often been considered an inexhaustible or totally renewable resource, which isn't necessarily true (Ranger and Turpault, 1999). Therefore, the best way to address questions about plantation rotation lengths and long-term nutrient sustainability is to undertake nutrient cycling and budgeting studies. Nutrient budgets have been developed for mixed-wood forests (Pastor and Bockheim, 1984; Alban, 1982), evergreen plantations (Lian and Zhang, 1998; Helmisaari, 1995; Jorgensen et al., 1975), aspen forests following harvesting (Silkworth and Grigal, 1982), and hybrid poplar plantations in Europe and Asia (Berthelot et al., 2000; Lodhiyal et al., 1994). Nutrient cycling and budgeting studies, however, have not been developed for hybrid poplar on the Canadian prairies. *Populus* is an excellent genus to study for nutrient cycling and budgeting because it is fast growing and the use of clonal material ensures that experiments are repeatable with small error (Taylor, 2002).

Nutrient budgets summarize nutrient inputs and outputs from a clearly defined agroecosystem over a defined time period (Oenema et al., 2003). A budget measures changes at the ecosystem level, including the vegetation (above and belowground), forest floor, and mineral soil (Ranger and Turpault, 1999). The forest nutrient cycle has three segments: inputs, transfers of nutrient movement within the ecosystem and outputs and consists of a series of interdependent processes, thought of as series of pools or components, such as soil or plant biomass, connected by transfer paths (Jorgensen et al., 1975). The purpose of a budget is to identify all fluxes entering and leaving a section of the budget. Some of these fluxes are impossible to measure directly, such as uptake of nutrients by vegetation (Ranger and Turpault, 1999), so calculations using other identifiable fluxes are used to estimate these fluxes.

There are three types of soil nutrient budgets (Oenema, and Heinen, 1999):

1.Farm gate budget – records the nutrients in products that enter and leave the farm via the farm gate,

2.Soil surface budget – records all nutrients that enter the soil via the surface and that leave the soil via crop uptake, and

3.Soil system budget – records all nutrient inputs and outputs including gains and losses within and from the soil.

The budgets can be done on three different soil site classes:

1.Rich Soils – sustainable management possible even with nutrient consuming species,

2.Moderate soils – sustainable management possible if adjusted to take care of nutrient depletion without short-rotation forestry or whole tree harvesting, and

3.Poor soils – sustainable management cannot be achieved due to length of regeneration time.

Typically most budgets are done with a mixture of farm gate and soil surface components and are done on all three theoretical site classes so that a wider range of values can be processed.

A nutrient surplus or deficit is calculated as the physical difference between nutrient inputs and outputs per hectare of land (Oenema and Heinen, 1999). Elements that accumulate in the soil have a positive budget and elements that are depleted in the soil have a negative budget. The interpretation of a budget solely based on whether it is positive, negative or neutral is not necessarily accurate (Jannsen, 1999). Positive budgets are good as long as they do not exhibit extreme accumulation, as it can lead to toxicity, increased leaching (Silkworth and Grigal, 1982) or nutrient imbalances that may leave secondary elements lacking. Neutral budgets may seem fine, but if there are excessive quantities of available N in the soil for example, the N may be susceptible to denitrification or leaching. Negative balances are generally fine as long as the nutrient stocks are quantified (Ranger and Turpault, 1999) and the losses are not large compared to the total nutrient stocks at the site.

In the following sections, all of the input and output and transfer components of the current nutrient cycling study will be addressed. These include mineral weathering, atmospheric deposition, leaching, litter fall, litter decomposition and harvesting.

2.1.1 Mineral weathering

Weathering is the combination of physical, chemical and organic processes that decompose, disintegrate, and alter rocks and minerals at or near the Earth's surface (Birkland, 1984; Gregorich et al., 2002). Weathering is considered a crucial soil process that counteracts acidity in soil and water (Olsson and Melkerud, 1991) and acts as a long-term supply of base cations. Weathering is a fundamental process important to environmental issues such as forestry production, agricultural systems, and nutrient budgets (Melkerud et al., 2003). The long-term ability of a soil to meet plant requirements for macro and micronutrients, with the possible exclusion of N and P, is controlled by their rate of release by weathering (Kolka et al, 1996; Zabowski, 1990). Nitrogen inputs are seldom noteworthy and phosphorus weathering is hard to quantify (Zabowski, 1990).

Mineral weathering is a function of physical, chemical and biological processes. Physical weathering is caused by temperature changes (freeze-thaw), fire, physical pressures (frozen water expanding within cracks in rock) and erosion (water, wind), while chemical weathering is caused by a combination of hydrolysis, chelation and oxidation. Biological processes include ectomycorrhizal fungi that mobilize nutrients directly from minerals through excretion of strong organic acids (Landeweert et al., 2001; van Breeman et al., 2000; Blum et al., 2002) and plants that exude weathering agents like CO_2 and organic acids (Kelly et al., 1998) as well as physically breaking up rock with their roots. Minerals formed at high temperatures and pressures and minerals that contain elements such as Mg, Ca, and Fe are more susceptible to weathering (April and Newton, 1992). There are three stages of mineral weathering based on the age of the soil: Stage 1 in which weathering rates are assumed to be low because of small soil surface area, high H^+ concentration and little organic inputs; Stage 2 where weathering rates are higher due to increased soil surface area, organic inputs and lower acidity; and Stage 3 where weathering inputs are lower due to the soil having more resistant elemental materials present (Zabowski, 1990). Soils in northern Saskatchewan would be classified as young, in the late 1st to 2nd stage.

Weathering rates in boreal and northern temperate ecosystems are slow and difficult to quantify in short time periods and therefore historical weathering rates that take into account current and past weathering are recommended (Melkerud et al., 2003; Olsson and Melkerud, 2000). Historical weathering rates cannot be expressed as present weathering rates, however, because weathering rates have varied substantially since the end of glaciation and weathering is affected differently now, because of acid deposition, plants and weather, than it would have been in the past (Olsson and Melkerud, 1991; Melkerud et al., 2003). One of the most effective methods of determining historical soil mineral weathering is the elemental depletion method (Bain et al., 1993; Kolka et al. 1996; Hodson, 2002; Olsson and Melkerud, 1991, 2000; Melkerud et al., 2003). Historical weathering, using the mineral depletion method, can be estimated from the bulk chemistry of the soil; with mineral pools compared to the composition of a reference C horizon taking a stable mineral as an internal standard (Wesselink et al., 1994; Hodson and Langan, 1999). Zircon ($ZrSiO_4$) is one of the most persistent, least weatherable heavy minerals present in the soil (Hodson, 2002) and therefore can be used as an internal standard by which the depletion of other elements can be judged. After deglaciation, the amount of Zr was considered uniform throughout the soil profile and as time passed, Zr has become relatively enriched in upper horizons compared to other base cations as they are removed by plant uptake or leaching. Determining the base cation to Zr ratios for weathered and unweathered horizons allows for the calculation of lost base cations (Starr et al., 1998).

The major elements that are determined using the elemental depletion method are Mg, K, Ca, Na, and P. Magnesium, K, Ca, Na and P (PO_4) enter the soil solution via mineral weathering as a major proportion of their total in the soil, especially for soils that were developed from glacial deposits (Cole, 1995). Calcium is weathered from both carbonates and silicates (anorthite), while Mg is weathered from carbonates, illite, biotite and silicates. Potassium is derived from the weathering of microcline feldspar, orthoclase, illite and micas and Na is usually weathered from albite (April and Newton, 1992; Wesselink et al., 1994; Xiao et al., 1991).

Weathering is considered a major component of nutrient budgeting in forested ecosystems because nutrient inputs usually come from only two natural sources: weathering and atmospheric deposition (Ranger and Turpault, 1999). For nutrient budgets to be considered accurate the mineral weathering component must be determined. Table 2.1 shows values of mineral weathering from different places in North America determined for other nutrient cycling studies.

Table 2.1. Base cation mineral weathering (kg ha^{-1} yr^{-1}) determined from several other nutrient cycling studies

Site	Forest Type	P.M.†	Ca	Mg	K	Na	Citation
			-------- kg ha^{-1} yr^{-1} --------				
State of New Hampshire	N. Hardwood	Granitic	21	3.5	7.1	5.8	Likens,1977
State of Wisconsin	N. Hardwood	Glacial	62	6.1	26	----	Pastor and Bockheim, 1984
State of Minnesota	Aspen	Glacial till	20	10	8.7	----	Silkworth and Grigal 1982

† P.M. is parent material

2.1.2 Atmospheric deposition

Several forms of atmospheric deposition (dry deposition and wet deposition) contribute nutrients to the forest ecosystem. Both forms can add nutrients directly or can add nutrients to the soil after passing through forest canopies. Two processes are involved with this form of precipitation transformation: throughfall (TF) and stemflow (SF). Throughfall is the rainfall that directly reaches the forest floor after coming in contact with the vegetative canopy, whereas stemflow is that portion of the gross rainfall, which is caught on the canopy and reaches the litter or mineral soil by running down the tree stems (Helvey and Patric, 1965; Eaton et al., 1973). Chemistry of the throughfall and stemflow includes not only the nutrients leached from the vegetation, but also nutrients washed from the surface of the vegetation and those contained in the incident precipitation (Eaton et al., 1973). Forested areas in the Ontario shield had up to 90% of the precipitation that reached the ground passing through the canopy and undergoing chemical change (Neary and Gizyn, 1994). All of these processes are important to the soil system for nutrient additions, especially for cations when rock weathering is slow and in areas that are nutrient poor (Neary and Gizyn, 1994; Parker, 1983).

2.1.2.1 Throughfall and stemflow

Throughfall is important for the construction of input/output budgets, nutrient turnover times and estimations of annual plant nutrient uptake. Throughfall is more important as the growing season progresses (leaf development to leaf abscission) because nutrient concentrations generally increase. Throughfall quality and quantity of nutrients varies greatly and one year does not necessarily represent long-term trends. Throughfall comes from three sources: wet deposition, dry deposition and canopy exchange. Wet deposition is comprised of the nutrients that inherently constitute rainwater. Dry deposition (DD) originates from leaves sorbing gases from the atmosphere, dry particulate matter that is intercepted and sedimentation (dust from roads, agriculture etc.). Most pollution borne compounds are considered DD. Canopy exchange (CE) is the leaching of nutrients out of the leaf tissues or absorption of the nutrients from rainwater by the leaves. Elements are leached from leaves in the following order: K > Ca > Mg > Mn > carbohydrates. Canopy exchange of nutrients depends on whether they are considered conservative or non-conservative. Non-conservative elements tend to have a lot of CE reactions with the foliage whereas conservative elements tend to pass through the canopy with little canopy interaction and generally have the same concentration as the initial wet deposition. Elements in TF include: K (CE) > Ca (mostly CE) > Mg (mostly DD) > Na (CE and DD in coastal areas) > P (CE - but very little leached) > N (NO_3 and NH_4 usually decrease meaning that they are removed through CE).

Nitrogen is not easily leached and is usually the element that is most highly scavenged from rainwater by the canopy. Canopy exchange accounts for the majority of K in TF (Parker, 1983; Lovett et al., 1996).

Stemflow is a spatially localized point input of precipitation and is of hydrological and ecological significance in forested and agricultural ecosystems (Levia and Frost, 2003). Stemflow is highly concentrated compared to TF, although stemflow enters the ecosystem in much smaller amounts, it often results in elevated nutrient concentrations at the base of trees (Eaton et al., 1973). The input of stemflow around the base of the tree provides nutrients for deficient trees in early spring (Levia and Herwitz, 2000). Stemflow has been documented to account for roughly 5-10% of the total incident precipitation (Herwitz and Levia, 1997; Crockford and Richardson, 2000) and has been marginalized for its contribution to nutrient cycling when compared to throughfall, but may still be important with its small amounts because it is deposited in a small area around the tree (Eaton et al., 1973). The amount of stemflow that can occur after a rainfall depends on the type of tree, bark texture and the intensity of the storm (Levia and Frost, 2003; Crockford and Richardson, 2000). Smooth-barked trees have lower total surface area and water storage capacity than other trees and therefore produce much more stemflow (Levia and Frost, 2003). Large amounts of stemflow in monoculture tree plantations are viewed negatively as the stemflow may wash fertilizer away from the base of the tree. Stemflow is an important flux in smooth branched trees, with Na, Ca, Mn and Mg being the elements with the highest concentrations.

2.1.2.2 Atmospheric deposition nutrient concentrations

The nutrient concentration of the TF solution is dependant on many different factors: the volume of rainfall (more rainfall equals more throughfall), location (proximity to oceans will affect Na concentration and proximity to industrial pollution will affect SO_x and NO_x concentrations), tree stand composition (hardwoods in general yield higher amounts of nutrients than softwoods, and softwoods yield more acidic throughfall), age (older trees act as a large deposition trap because of greater biomass and crown closure), site fertility and fertilization (increases nutrient concentrations in the leaves changing canopy exchange interactions). Table 2.2 shows the nutrient concentrations of throughfall for different areas in North America.

Precipitation chemistry varies greatly from region to region depending on the origin of the air masses and types of pollution in the area. For example, precipitation from air masses coming directly off the ocean generally have a Ca:Mg ratio approaching that of sea water (0.196:1) and very high Na concentrations whereas continental precipitation generally has a much higher Ca:Mg ratio and much lower Na (Parker, 1983). Nutrient concentrations increase in TF as the trees got older throughout the year. It is believed that the younger leaves are more tightly bound to the nutrients in the leaves than leaves nearing abscission. Also deterioration of the leaves by weathering or physical damage and shifts in the form of elements from bound molecular forms to ionic forms seems to be important in the leaching ability of that element (Parker, 1983).

2.1.3 Leaf litter

Litterfall is one of the largest transfers within the nutrient cycle and represents a major mechanism for nutrient cycling and redistribution in most ecosystems (Hughes and Fahey, 1994). In young trees, N storage can be as high as 50% for the whole tree (Pregitzer et al., 1990), so loss of that N through litterfall can be a huge loss to the tree. Table 2.3 shows some nutrient values for leaf litter in poplar trees ranging in age from 4-8 years. The nutrients that are in the leaves come from either plant nutrient redistribution or nutrient uptake. The nutrients in those leaves are not immediately available to the nutrient cycle after abscission because the decomposition process needs to be completed first. The rate of decay and concentration of nutrients in the litter determines the rate of release which creates positive feedback to site fertility (Prescott, 2005).

2.1.3.1 Leaf litter decomposition

Decomposition refers to the physical breakdown of organic matter measured as mass loss. Species composition and soil fertility are the main factors determining the quality of litter on a site (physical and chemical nature and decomposability). Litter quality is based on the relative proportions of major C compounds (decreasing decomposability; sugars > cellulose > lignin > phenols).

Table 2.2. Values of throughfall nutrients determined from other nutrient cycling studies

Location and Forest Type	Nutrients N	 P	 K	 Ca	 Mg	 Na	Citation
	---------- kg ha^{-1} yr^{-1} ----------						
New Hampshire Hubbard Brook Forest,	10.6†	0.63	26.94	6.98	1.98	0.61	Eaton et al. 1973
Quebec Largetooth aspen, yellow birch etc.	22.24	-----	16.7	11.66	2.53	1.64	Belanger et al, 2002
Wisconsin Trembling aspen and largetooth aspen	3.5	-----	19.0	9.4	1.8	3.4	Pastor and Bockheim, 1984
Prince Albert, SK. Trembling aspen	2.00	1.38	-----	-----	-----	-----	Haung and Schoenau, 1997
South-central Ontario Hardwood forest	11.67	-----	9.0	5.0	1.25	0.32	Neary and Gizyn, 1994

†Total N in sample for the Hubbard Brook Forest

Table 2.3. Nutrient contents for N, P, K, Mg, and Ca in poplar leaf litter for trees ages ranging from 4 to 8 years old

Tree Species, Treatment	**Age**	**N**	**P**	**K**	**Mg**	**Ca**	**Citation**
	Year	-------------- kg ha^{-1}----------------					
Populus deltoides x trichocarpa “Beaupré”	4	69.5	11.6	41.5	9.5	115.5	Berthelot et al., 2000
	7	63.8	8.9	34.6	13.0	144.1	
Populus deltoides x *trichocarpa* “Raspalje”	4	59.6	10.4	35.0	8.3	103.8	Berthelot et al., 2000
	7	44.3	8.1	25.0	8.3	129.6	
Populus deltoides 5 x 5 m spacing	5	70.5	8.5	42.6	----	----	Lodhiyal et al., 1995
	6	80.2	9.8	46.0	----	----	
	7	87.1	10.5	49.4	----	----	
	8	96.4	11.7	51.5	----	----	
Populus deltoides 3 x 5 m spacing	4	99.3	11.6	62.8	----	----	Lodhiyal and Lodhiyal,1997

The rate of decomposition is determined by the moisture, litter quality and chemistry, which can be influenced by forestry activities (Prescott and Blevins, 2000), microclimate (Köchy and Wilson, 1997) and soil organism activity (Cárcamo et al., 2001). The activity of soil organisms determines the rate of decay and completeness of decomposition (Prescott, 2005). Decay will be uniformly slow in climates too wet, dry or cold to support decomposers operating at peak levels. Assuming adequate moisture, decomposition rates increase with increasing temperature. Litter tends to be more recalcitrant in cold and dry climates (Couteux et al., 1995).

Concentrations of N and P in the leaf litter often correlate to early decay rates. Nitrogen and P are usually retained in the litter during the initial stages and this immobilization can lead to increased content indicative of net import of N and P into litter. Moore et al. (2005) showed that most litter generally retained the majority of their original N as they decomposed; however, aspen leaves in the Prince Albert National Park, Nelson House Peatland, and Batoche, actually accumulated N in initial stages of decomposition. The tendency for N and P to increase varies with the species and site but appears to be closely related to initial leaf litter concentration, narrowing of C:N ratio (Staaf, 1986; Vesterdal, 1999), low concentration relative to requirements of decomposers (Edmonds, 1980; Kelly and Beauchamp, 1987) and increases in fungal biomass during decomposition (Berg and Soderstrom, 1979).

One well-known problem in identifying accurate results for decomposability studies is contamination of the leaf litter within the litterbags by organics and soil. Litter mass loss can be under or overestimated if not corrected for contamination. Earthworm casts, fungal hyphae, surrounding litter fragment pieces or organic matter are potential sources of contamination. The problem is identifying how much contamination is occurring in the leaf litter decomposition bags and this can be done with the use of inert material, such as fiberglass fabrics, within a decomposition bag that will not decompose, but will still collect the contaminating material. Using this method, Idol et al. (2002) showed contamination levels of 17 – 32% after 120 days due to the growth of fungal hyphae and influx of litter fragments.

2.1.3.2 Litter decomposition and fertilization

There are conflicting findings on whether fertilization has any effect on the rate of leaf litter decomposition. Litter decomposition in fertilized plots has been found to be faster (Prescott, 1992), slower (Nohrstedt et al., 1989; Prescott, 1995; 1999) or the same (Theodoru and Bowen, 1990) as litter decomposition in control plots. While fertilization may not increase the decomposition rate (Prescott, 1995; 1999) it has been shown to increase the N concentration in the leaf litter compared to control plots. Prescott (1999) showed that litter in N fertilized plots had higher N than the control plots. While litter decomposition may not be affected by fertilization, nutrient cycling may still be, because the increased leaf area in fertilized forests will create greater amounts of foliar litter with greater nutrient concentrations, resulting in greater nutrient release on a per-hectare basis (Prescott, 1999).

2.1.4 Leaching

Leaching in hardwood forests and hybrid poplar plantations are invariably linked with harvesting and fertilization. Forest fertilization commonly leads to moderate increases in stream water nutrient concentrations (Binkley et al., 1999). Nitrogen is especially scarce in soil solution in mineral soils because it is usually the most limiting nutrient in forest systems. Leaching caused by over-fertilization (Jacobs et al., 2005) can lead to increases in nitrate in the lower mineral soil (Lee and Jose, 2005) and ground water. Many plantations incorporated fertilization into their production scheme to increase yields up to five times greater than what would be there without fertilization (Jacobs et al., 2005). The greatest cause of leaching of nutrients due to over-fertilization is the use of repeated fertilization treatments (Lee and Jose, 2005), the use of high-N sewage sludge and ammonium nitrate fertilizers (Binkley et al., 1999). Lee and Jose (2005) found that repeated fertilizer treatments of over 56 kg ha^{-1} yr^{-1} resulted in leaching of between 65-95% of the fertilizer applied after seven years. While the 56 kg ha^{-1} yr^{-1} rate of N yielded the greatest biomass, it also exceeded the biological retention capacity of the system.

Most leaching occurs on sites after a harvest operation, whether it is whole-tree harvest (WTH) or stem-only harvest (SOH). In eastern forest systems the greatest nutrient depletion after WTH is that of base cations. Base cations are especially susceptible to leaching when N mineralization takes place and hydrogen ions displace cations on soil exchange sites (Hendrickson et al., 1989; Johnson et al., 1988; Silkworth and Grigal, 1982). Generally after WTH there is little nutrient uptake by vegetation (Johnson and Todd, 1987) and the mobilized nutrients in the soil solution are susceptible to leaching with downward water movement (Mroz et al., 1985). Nitrogen leaching after harvest is also of concern as it is typically the most limiting nutrient in forest systems. Leaching of N in forested systems typically is highest in sandy soils (Lee and Jose, 2005) after harvesting has occurred because of increased nitrogen mineralization and reduced uptake. Nitrogen leaching is a problem on soils that are converted from agricultural legume crops directly into tree plantations because the trees cannot utilize all of the N mineralized from the legume residue, which in turn leads to downward movement of the N in those soils (Williams, 1999). Planting a crop that can immobilize N in its roots before planting to trees may be one way to prevent nitrate leaching and ground water contamination.

2.1.5 Harvest

Tree harvesting constitutes the largest export of nutrients from a site. There are several methods that can be used for harvesting with regards to the time of year (summer or winter), and the amount of biomass exported off site. The most common methods of harvesting are SOH and WTH, which Thiffault et al. (2006) defined as the removal of the aboveground components from the harvest site. WTH accounts for about 58% of all harvesting operations on crown lands in Quebec (Thiffault et al., 2006).

There are many questions about the suitability for WTH on forest soils with inherently low fertility. Some researchers have predicted heavy losses of soil nutrients (Jorgensen et al., 1975; Mälkönen, 1976; Carey, 1980; White, 1974; Piatek and Allen, 1999), increased leaching of mineralized N (Hendrickson et al., 1989), loss of base cations (Bélanger et al., 2003; Olsson et al., 1996), and loss of yield in subsequent rotations (Cole, 1995; Thiffault et al., 2006); while others have countered these results with reports of increased sprouts of hardwoods after WTH (Hendrickson, 1988), tighter nutrient cycles, and lower N leaching than in SOH forests (Hendrickson, 1989).

The biggest concern of WTH over SOH is the amount of nutrients and organic matter exported off the site, including leaves (which could be avoided if harvested when the trees are dormant), needles, twigs and branches that are high in nutrients relative to stemwood. Although the slash only accounts for ~20% of the total dry matter, it contains about half of the total quantities of N, P, and K from the forest stand (Carey, 1980; Jorgensen et al., 1975). There are benefits to WTH as well, being that it is economically more efficient than SOH because it results in higher yields per hectare, and several studies have found that it would only affect soil fertility and limit future rotations growth on poor quality sites (Boyle et al., 1973;

Carey, 1980; Johnson et al., 1997). The general consensus is that WTH is not a practice to be used without a firm idea of the nutrient status of the site that is being harvested. For short-rotation forestry using fast growing species, the loss of nutrients may be much higher because of higher immobilization within the biomass (White, 1974; Cole, 1995).

2.2. Hybrid Poplar Production

2.2.1 Hybrid poplar growth parameters and uses

The genus *Populus* (poplars, cottonwoods and aspens) contains approximately 30 species of woody plants, all found naturally in the northern hemisphere. These trees exhibit some of the fastest growth rates observed in temperate trees (Taylor, 2002) and are now planted all over the world (Ceulemans and Deraedt, 1999). Cultivation of *Populus* species including HP, has received the greatest attention for achieving high fiber yield with short rotations (Ceulemans et al., 1992; Eckenwalder, 1996). Interspecific poplar hybrids outperform most average clones of the parental species (Ceulemans et al., 1992; Ceulemans and Deraedt, 1999). High yields of HP (upper range of 20-25 Mg ha^{-1} yr^{-1}) can be partially attributed to the selection of improved genotypes and successful cultural management (Ceulemans and Deraedt, 1999). One problem with some of the research conducted on the growth and production of HP in research plantations is that yields in small plot research settings have been shown to be 4-7 times greater than in commercial plantations (Hansen, 1991). Table 2.4 shows a range of biomass and tree growth values for hybrid poplar from Washington State, China and Meadow Lake, SK.

Short rotation forestry using HP has considerable advantages over aspen because HP is fast growing (Scaracia-Mugnozza et al., 1997), has higher yields per unit area, multiple end uses (Berthelot et al., 2000) and can be grown in pure plantations from vegetatively propagated stock (Lodhiyal et al., 1994). Plantations of HP are expected to have shorter rotations (≤ 20 yrs) (Zsuffa et al., 1996) compared to native species (> 60 yrs) and could be harvested for lumber, oriented strand board, pulp, energy production or other value-added products.

Due to high energy costs there has been a greater emphasis on producing fast growing broadleaved trees such as poplar and willow for bio-energy under

Table 2.4. Reported values for above-ground biomass, height, and diameter of four-year-old Hybrid Poplar clones according to recent studies.

Treatment and Location	Hybrid Clone	Dry Weight Biomass	Height	Diameter	Citation
			---m---	----mm----	
1.2 x 1.2 m spacing Sumner, Wash.	3 different hybrids *Populus deltoides* x *trichocarpa*	23.6 Mg ha^{-1} yr^{-1}	11.5 - 12.2	87 - 92	Heilman and Stettler, 1985
N Fertilized Puyallup, Wash.	*Populus deltoides* x *trichocarpa*	bole + branches 25.3 Mg ha^{-1} yr^{-1}	13.2	112	Heilman and Xie, 1993
1 x 1 m spacing Sumner, Wash.	*Populus deltoides* *x trichocarpa*	bole + branches 24.3 Mg ha^{-1} yr^{-1}	ND	ND	Heilman et al., 1994
1 x 1 m spacing Puyallup, Wash.	*Populus deltoides* x *trichocarpa*	whole tree 29.3 Mg ha^{-1} yr^{-1}	12	89	Scarascia-Mugnozza et al., 1997
3 x 3 m spacing Jiangsu Province, PRC	I-69 x I-63 *P. deltoides* 'Havard'	bole + branches 44 Mg ha^{-1}	13.5	130	Fang, S., et al. 1999
2.5 x 2.5 m spacing Meadow Lake, SK.	*Populus deltoides* *x petrowskyana* var. "Walker"	bole + branches 7.5 Mg ha^{-1}	4.6	42	Mistik Management unpublished, 2000
3.1 x 3.1 m spacing Meadow Lake, SK.	*Populus deltoides* *x petrowskyana* var. "Walker"	ND	4.4	46	Mistik Management Unpublished, 2000
3.7 x 3.7 m spacing Meadow Lake, SK.	*Populus deltoides* *x petrowskyana* var. "Walker"	bole + branches 6.3 Mg ha^{-1}	4.3	43	Mistik Management unpublished, 2000

ND – not determined

intensive management systems more akin to agriculture than forestry. Yields have decreased after the first rotation in over half the field trials conducted and are attributed to poor establishment, disease, and poor management techniques (Mitchell et al., 1999).

2.2.2 Hybrid poplar nutrient concentrations

Poplar and aspen trees are important stores of nutrients. Alban (1982) showed that hardwoods like poplar and aspen, due to their rapid uptake and sequestration, can lead to depletion of nutrients in soils. Typical aspen forests will immobilize 5-13 kg ha^{-1} yr^{-1} N and 0.4 – 0.8 kg ha^{-1} yr^{-1} P, whereas HP can immobilize 20 –25 kg ha^{-1} yr^{-1} N and 5-6 kg ha^{-1} yr^{-1} P or more (Bethelot et al., 2000) and are often more productive. Table 2.5 shows different values for nutrient accumulation in balsam poplar and deltoides. Younger trees have a relatively higher percentages of N, P, and K in the leaves compared to older trees (Lodhiyal and Lodhiyal, 1997) because the older trees have increased immobilization of these nutrients in the bole as they grow. The range of leaf nutrient concentrations for optimum HP nutrition are 17-30 mg g^{-1} N, 1.0-4.4 mg g^{-1} P, 7-20 mg g^{-1} K, 3.0-17 mg g^{-1} Ca and 1.4-4.0 mg g^{-1} Mg (Bungart and Hǜttl, 2004; Jug et al., 1999; McLennan, 1990). The relative contribution of nutrients in different above-ground parts in young trees is generally: foliage > bole wood > bole bark > branches. The relative contribution of nutrients in below-ground parts is generally: stump root > lateral roots > fine roots (Lodhiyal and Lodhiyal, 1997; Lodhiyal et al., 1995). As trees age the amount of N that is used for growth supplied directly from internal cycling generally increases (Millard, 1995). Internal nutrient distribution is divided into four phases: allocation of nutrients from assimilating source tissues to sinks during the growing season, reallocation during the growing season arising from metabolic recycling, resorption of nutrients from senescing tissues and remobilization to actively growing tissues in the spring (Cooke and Weih, 2005).

In the fall, HP is effective at resorbing the N that is in the leaves before abscission (Harvey and van den Driessche, 1999), and is efficient at reusing stored N. Nitrogen, P, and K are all resorbed back into the tree from the leaf before

Table 2.5. Reported values for Nitrogen, Phophorus, Potassium, Magnesium, and Calcium (kg ha^{-1}) in poplar and aspen tree components.

Tree Species,				**Nutrient**			
Age, Treatment	**Tree component**	**N**	**P**	**K**	**Mg**	**Ca**	**Citation**
				kg ha^{-1}			
Populus deltoides	Leaves	128	12	78	18	188	Switzer et al. 1976
5 x 8 m spacing	Branches	80	13	62	14	148	
20 years old	Stem	272	50	304	72	644	
Populus deltoides	Leaves	19	----	16	----	----	Blackmon et al. 1979
4.2 x 4.2 m spacing	Branches	24	----	24	----	----	
11 years old	Stem	96	----	195	----	----	
Populus deltoides	Leaves	183.2	14.8	79.4	----	----	Lodhiyal et al., 1995
5 x 5 m spacing	Branches	105.4	9.7	39.0	----	----	
5 years old	Stems	142.8	17.2	82.3	----	----	
Populus deltoides	Leaves	225.6	17.9	91.2	----	----	Lodhiyal et al., 1995
5 x 5 m spacing	Branches	135.6	15.9	53.5	----	----	
7 years old	Stems	215.0	23.6	133.3	----	----	
Populus deltoides	Leaves	259.4	21.2	117.7	----	----	Lodhiyal et al., 1997
3 x 5 m spacing	Branches	172.4	16.3	60.5	----	----	
4 years old	Stems	194.3	22.3	108	----	----	
Populus balsamifera	Leaves	29.3	3	2.3	3	15.8	Wang et al., 1995
Forest sites	Branches	7.9	1.1	2.1	2.9	15.4	
5 years old	Stems	12.7	2.2	10.3	4.5	39.4	

abscission, but P and K are typically less efficient than N in this process (Lodhiyal et al., 1995). Lodhiyal and Singh (1994) found N retranslocation of ~65%, P between 45-50% and K of ~50% in low and high density HP plantations. Lodhiyal et al. (1995) found retranslocation on the same scale for trees 5-8 years old at ~62% N, 40-45% P and 46-49% K; and Lodhiyal and Lodhiyal (1997) found retranslocation in the range of 65-68% N, 50-53% P and 51-63% for K in 1-4 year old trees. Côté and Camiré (1987) found that N retranslocation was relatively low in HP leaves at 27%, whereas P and K were either close to or above expected values at 48% and 72%, respectively. Resorption of N reduces N losses in trees and adds to tree productivity, and nutrients that remain in the leaves after abscission are important for nutrient cycling and stand productivity (Cooke and Weih, 2005).

2.3 References

Alban, D.H. 1982. Effects of nutrient accumulation by aspen, spruce, and pine on soil properties. Soil Sci. Soc. Am. J. 46: 853-861.

April, R. and R. Newton. 1992. Mineralogy and mineral weathering. p. 378-386 *In* D.W. Johnson and S.E Lindberg (ed.) Atmospheric Deposition and Forest Nutrient Cycling: A Synthesis of the Integrated Forest Study. Ecological Studies Volume 91. Springer-Verlag Inc. New York , NY.

Bain, D.C., A. Mellor, M.S.E. Robertson-Rintoul, and S.T. Buckland. 1993. Variations in weathering processes and rates with time in a chronosequence of soils from Glen Feshie, Scotland. Geoderma 57: 275-293.

Bélanger, N., F. Courchesne, B. Côté, J.W. Fyles, P. Warfvinge, and W.H. Hendershot. 2002. Simulation of soil chemistry and nutrient availability in a forested ecosystem of southern Quebec. Part 2. Application of the safe model. Environ. Modell. Software 17: 447-465.

Bélanger, N., D. Paré, and F. Courchesne. 2004. Regression equations for estimating throughfall nutrient fluxes using wet deposition data and their applicability for simulating the soil acid-base status using the dynamic forest soil-atmosphere model SAFE. Ecol. Modell. 175: 151-167.

Bélanger, N., D. Paré, and S.H. Yamasaki. 2003. The soil acid-base status of boreal black spruce stands after whole-tree and stem-only harvest. Can. J. For. Res. 33: 1874-1879.

Berg, B., and B. Soderstrom, 1979. Fungal biomass and nitrogen in decomposing Scots pine needle litter. Soil Biol. Biochem. 11: 339-341.

Berthelot, A., J. Ranger and D. Gelhaye. 2000. Nutrient uptake and immobilization in a short-rotation coppice stand of hybrid poplars in north-west France. For. Ecol. Manage. 128: 167-179.

Binkley, D., H. Burnham, and H.L. Allen. 1999. Water quality impacts of forest fertilization with nitrogen and phosphorus. For. Ecol. Manage. 121: 191-213.

Birkland, P.W. 1984. Soils and Geomorphology. Oxford Univ. Press, New York, NY.

Blackmon, B.G., J.B. Baker, and D.T. Cooper. 1979. Nutrient use by three geographic sources of eastern cottonwood (*Populus deltoides*). Can. J. For. Res. 9: 532-534.

Blum, J.D., A. Klaue, C.A. Nezat, C.T. Driscoll, C.E. Johnson, T.G. Siccama, C. Eager, T.J. Fahey, and G.E. Likens. 2002. Mycorrhizal weathering of apatite as important calcium source in base poor forest ecosystems. Nature 417: 729-731.

Boyle, J.R., J.J. Phillips, and A.R. Ek. 1973. Whole tree harvesting: nutrient budget evaluation. J. For. 71: 760-762.

Bungart, R., and R.F. Hừttl. 2004. Growth dynamics and biomass accumulation of 8-year-old hybrid poplar clones in a short-rotation plantation on a clayey-sandy mining substrate with respect to plant nutrition and water budget. Eur. J. For. Res. 123: 105-115.

Cárcamo, H.A., C.E. Prescott, C.P. Chanway and T.A. Abe. 2001. Do soil fauna increase rates of litter breakdown and nitrogen release in forests of British Columbia, Canada? Can. J. For. Res. 31: 1195-1204.

Carey, M.L. 1980. Whole tree harvesting in Sitka spruce. Possibilities and implications. Irish For. 37: 48-63.

Ceulemans, R. and W. Deraedt. 1999. Production physiology and growth potential of poplars under short rotation forestry culture. For. Ecol. Manage. 121: 9-23.

Ceulemans, R., G. Scarascia-Mugnozza, B.M. Wiard, J.H. Braatne, T.M. Hinckley, R.F. Stettler, J.G. Isebrands, and P.E. Heilman. 1992. Production physiology and morphology of Populus species and their hybrids grown under short rotation. I. Clonal comparisons of 4-year growth and phenology. Can. J. For. Res. 22: 1937-1948.

Cole, D.W. 1995. Soil nutrient supply in natural and managed forests. Plant Soil 168-169: 43-53.

Cooke, J.E.K., and M. Weih. 2005. Nitrogen storage and seasonal nitrogen cycling in *Populus*: bridging molecular physiology and ecophysiology. New Phytol. 167: 19-30.

Côté, B., and C. Camiré 1987. Tree growth and nutrient cycling in dense plantings of Hybrid Poplar and black alder. Can. J. For. Res. 17: 516-523.

Coteaux, M.M., P. Bottner, and B. Berg. 1995. Litter decomposition climate and litter quality. Trends Ecol. Evol. 10: 63-66.

Crockford, R.H. and D.P. Richardson. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrol. Process. 14: 2903-2920.

DeBell, D.S., G.W. Clendenen, C.A. Harrington, and J.C. Zasada. 1996. Tree growth and stand development in short-rotation *Populus* plantings: 7-Year results for two clones at three spacings. Biomass Bioenergy 11: 253-269.

Eaton, J.S., G.E. Likens, and F.H. Bormann. 1973. Throughfall and stemflow chemistry in a northern hardwood forest. J. Ecol. 61: 495-508.

Edmonds, R.L. 1980. Litter decomposition and nutrient release in Douglas-fir, red alder, western hemlock, and Pacific silver fir ecosystems in western Washington, U.SA. Can. J. For. Res. 17: 499-509.

Fang, S., X. Xu, S. Lu, and L. Tang. 1999. Growth dynamics and biomass production in short-rotation poplar plantations: 6-year results for 3 clones at 4 spacings. Biomass Bioenergy 17: 415-425.

Gregorich, E.G., L.W. Turchenek, M.R. Carter, and D.A. Angers. 2002. Soil and Environmental Science Dictionary. Canadian Society of Soil Science. CRC Press LLC, Boca Raton, Fla.

Hansen, E.A. 1991. Poplar woody biomass yields; a look to the future. Biomass Bioenergy 1: 1-7.

Harvey, H.P., and R. van den Driessche. 1999. Poplar nutrient resorption in fall or drought: influence of nutrient status and clone. Can. J. For. Res. 29: 1916-1925.

Heilman, P.E. and F.G. Xie. 1993. Influence of nitrogen on growth and productivity of short-rotation *Populus trichocarpa* x *Populus deltoides* hybrids. Can. J. For. Res. 23: 1863-1869.

Heilman, P.E., G. Ekuan, D. Fogle. 1994. Above- and below-ground biomass and fine roots of four-year-old hybrids of *Populus trichocarpa* x *Populus deltoides* and parental species in short-rotation culture. Can. J. For. Res. 24: 1186-1192.

Heilman, P.E., and R.F. Stettler, 1985. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. II. Biomass production in a 4-year plantation. Can. J. For. Res. 15: 384-388.

Helmisaari, H.S. Nutrient cycling in *Pinus sylvestris* stands in eastern Finland. Plant Soil 168-169: 327-336.

Helvey, J.D. and J.H. Partic. 1965. Canopy and litter interception of rainfall by hardwoods of eastern United States. Water Resour. Res. 2: 193-206.

Hendrickson, O.Q. 1988. Biomass and nutrients in regenerating woody vegetation following whole-tree and conventional harvest in a northern mixed forest. Can. J. For. Res. 18: 1427-1436.

Hendrickson, O.Q., L. Chatarpaul, and D. Burgess. 1989. Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. Can. J. For. Res. 19: 725-735.

Herwitz, S.R. and D.F. Levia Jr. 1997. Mid-winter stemflow drainage from bigtooth aspen (*Populus grandidentata* Michx.) in central Massachusetts. Hydrol. Process. 11: 169-175.

Hodson, M.E. 2002. Experimental evidence for mobility of Zr and other trace elements in soils. Geochim. Cosmochim. Acta. 66:819-828.

Hodson, M.E. and S.J. Langan. 1999. The influence of soil age on calculated mineral weathering rates. Appl. Geochem. 14: 387-394.

Huang, W.Z. and J.J. Schoenau. 1997. Seasonal and spatial variations in soil nitrogen and phosphorus supply rates in a boreal aspen forest. Can. J. Soil Sci. 77: 597-612.

Hughes, J.W. and T.J. Fahey. 1994. Litterfall dynamics and ecosystem recovery during forest development. For. Ecol. Manage. 63: 181-198.

Idol, T.W., K.A. Holzbaur, P.E. Pope, and F. Ponder Jr. 2002. Control-bag correction for forest floor litterbag contamination. Soil Sci. Soc. Am. J. 66: 620-623.

Jacobs, D.F., K.F. Salifu, and J.R. Seifert. 2005.Growth and nutritional response of hardwood seedlings to controlled release fertilization at outplanting. For. Ecol. Manage. 214: 28-39.

Janssen, B.H. 1999. Basics of budgets, buffers and balances of nutrients in relation to sustainability of agroecosystems. p. 27-55. *In* E.M.A. Smaling, O. Oenema, and L.O. Fresco (ed.) Nutrient Disequilibria in Agroecosystems. CAB International, Wallingford, Oxon, UK ; New York.

Johnson, C.E., R.B. Romanowicz, and T.G. Siccama. 1997. Conservation of exchangeable cations after clear-cutting of a northern hardwood forest. Can. J. For. Res. 27: 859-868.

Johnson, D.W., J.M. Kelly, W.T. Swank, D.W. Cole, H. Van Miegroet, J.W. Hornbeck, R.S. Pierce, ad D. Van Lear. 1988. The effects of leaching and whole-tree harvesting on cation budget of several forests. J. Environ. Qual. 17: 418-424.

Johnson, D.W. and D.E. Todd. 1987. Nutrient export by leaching and whole-tree harvesting in a loblolly pine and mixed oak forest. Plant Soil 102: 99-109.

Jorgensen, J.R., C.G. Wells, and L.J. Metz. 1975. The nutrient cycle: Key to continuous forest production. J. For. 73: 400-403.

Jug, A., C. Hofmann-Schielle, F. Makeschin, K.E. Rehfuess. 1999. Short-rotation plantations of balsam poplars, aspen and willow on former arable land in the Federal Republic of Germany. II. Nutritional status and bioelement export by harvested shoot axes. For. Ecol. Manage. 121: 67–83.

Kelly, E.F., O.A. Chadwick, and T.E. Hilinski. 1998. The effect of plants on mineral weathering. Biogeochemistry 42: 21-53.

Kelly, J.M. and J.J. Beauchamp. 1987. Mass loss and nutrient changes in decomposing upland oak and mesic mixed-hardwood leaf litter. Soil Sci. Soc. Am. J. 51: 1616-1625.

Köchy, M., and S.D. Wilson. 1997. Litter decomposition and nitrogen dynamics in aspen forest and mixed grass prairie. Ecology 78: 732-739.

Köchy, M. and S.D. Wilson. 2001. Nitrogen deposition and forest expansion in the northern Great Plains. J. Ecol. 89:807-817.

Kolka, R.K., D.F. Grigal, and E.A. Nater. 1996. Forest soil mineral weathering rates: use of multiple approaches. Geoderma 73:1-21.

Landeweert, R., E. Hoffland, R.D. Finlay, T.W. Kuyper, and N. van Breeman. 2001. Linking plants to rocks: ectomycorrhizal fungi mobilize nutrients from minerals. Trends in Ecology and Evolution 16:248-254.

Lee, K.H. and S. Jose. 2005. Nitrate leaching in cottonwood and loblolly pine biomass plantations along a nitrogen fertilization gradient. Agric. Ecosyst. Environ. 105: 615-623.

Levia Jr., D.F. and E.E. Frost. 2003. A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. J. Hydrol. 274:1-29.

Levia Jr., D.F. and S.R. Herwitz. 2000. Physical properties of water in relation to stemflow leachate dynamics: implications for nutrient cycling. Can. J. For. Res. 30: 662-666.

Lian, Y. and Q. Zhang. 1998. Conversion of a natural broad-leafed evergreen forest into pure and mixed plantation forests in a subtropical area: effects on nutrient cycling. Can. J. For. Res. 28: 1518-1529.

Lodhiyal, L.S. and R.P. Singh. 1994. Productivity and nutrient cycling in poplar stands in central Himalaya, India. Can. J. For. Res. 24: 1199-1209.

Lodhiyal, L.S., R.P. Singh, and S.P. Singh. 1994. Productivity and nutrient cycling in poplar stands in central Himalaya, India. Can. J. For. Res. 24: 1199-1209.

Lodhiyal, L.S., R.P. Singh, and S.P. Singh. 1995. Structure and function of an age series of poplar plantations in Central Himalaya. II Nutrient dynamics. Ann. Bot. 76: 201-210.

Lodhiyal, L.S. and N. Lodhiyal. 1997. Nutrient cycling and nutrient use efficiency in short rotation, high density central Himalayan Tarai poplar plantations. Ann. Bot. 79: 517-527.

Lovett, G.M., S.S. Nolan, C.T. Driscoll, and T.J. Fahey. 1996. Factors regulating throughfall flux in a New Hampshire forested landscape. Can. J. For. Res. 26: 2134-2144.

Lovett, G.M. and S.E. Lindberg. 1984. Atmospheric deposition and canopy exchange in a mixed oak forest as determined by analysis of throughfall. J. Appl. Ecol. 21: 1013-1028.

Lovett, G.M. and S.E. Lindberg. 1993. Atmospheric deposition and canopy interactions of nitrogen in forests. Can. J. For. Res. 23: 1603-1616.

Mälkönen, E. 1976. Effect of whole-tree harvesting on soil fertility. Silva Fennica 10: 157-164.

McLennan, D.S. 1990. Spatial variation in black cottonwood (*Populus trichocarpa*) foliar nutrient concentrations at seven alluvial sites in coastal British Columbia. Can. J. For. Res. 20: 1089–1097.

Melkerud, P.A., D.C. Bain, and M.T. Olsson. 2003. Historical weathering based on chemical analyses of two Spodosols in southern Sweden. Water Air Soil Pollut.: Focus 3:49-61.

Millard, P. 1995. Internal cycling of nitrogen in trees. Acta Hortic. 383: 3-15.

Mitchell, C.P., E.A. Stevens and M.P. Watters. 1999. Short-rotation forestry – operations, productivity and costs based on experience gained in the UK. For. Ecol. Manage. 121: 123-136.

Moore, T.R., J.A. Trofymow, M. Siltanen, C. Prescott, and Cidet Working Group. 2005. Patterns of decomposition and carbon, nitrogen and phosphorus dynamics of litter in upland forest and peatland sites in central Canada. Can. J. For. Res. 35: 133-142.

Mroz, G.D., M.F. Jurgensen and D.J. Frederick. 1985. Soil nutrient changes following whole tree harvesting on three northern hardwood sites. Soil Sci. Soc. Am. J. 49: 1552-1557.

Neary, A.J. and W.I. Gizyn. 1994. Throughfall and stemflow chemistry under deciduous and coniferous forest canopies is south-central Ontario. Can. J. For. Res. 24: 1089-1100.

Nohrstedt, H.O., K. Arnebrant, E. Baath and B. Soderstrom. 1989. Changes in carbon content, respiration rate, ATP content, and microbial biomass in nitrogen-fertilized pine forest soils in Sweden. Can. J. For. Res. 19: 323-328.

Oenema, O., H. Kros, W. de Vries. 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental; policies. Eur. J. Agron. 20: 3-16.

Oenema, O. and M. Heinen. 1999. Uncertainties in nutrient budgets due to biases and errors. p. 75-97. *In* E.M.A. Smaling, O. Oenema, and L.O. Fresco (ed.) Nutrient Disequilibria in Agroecosystems. CAB International, Wallingford, Oxon, UK ; New York.

Olsson, B.A., J. Bengtsson, and H. Lundkvist. 1996. Effects of different forest harvest intensities on the pools of exchangeable cations in coniferous forest soils. For. Ecol. Manage. 84: 135-147.

Olsson, M. and P.A. Melkerud. 2000. Weathering in three podzolized pedons on glacial deposits in northern Sweden and central Finland. Geoderma 94:149-161.

Olsson, M. and P.A. Melkerud. 1991. Determination of weathering rates based on geochemical properties of the soil. Geological survey of Finland, Special Paper 9:69-78.

Parker, G.G. 1983. Throughfall and stemflow in the forest nutrient cycle. Adv. Ecol. Res. 13: 57-133.

Pastor, J. and J.G. Bockheim. 1984. Distribution and cycling of nutrients in an aspen-mixed-hardwood-spodosol ecosystem in northern Wisconsin. Ecology 65: 339-353.

Piatek, K.B. and H.L. Allen. 1999. Nitrogen mineralization in a pine plantation fifteen years after harvesting and site preparation. Soil Sci. Soc. Am. J. 63: 990-998.

Pregitzer, K.S., D.I. Dickmann, R. Hendrick, P.H. Nguyen. 1990. Whole-tree carbon and nitrogen partitioning in young hybrid poplars. Tree Physiol. 7: 79-83.

Prescott, C.E. Decomposition and mineralization of nutrients from litter and humus. 2005. p. 15-32. *In* H. Bassirirad (ed.) Nutrient acquisition by plants: an ecological perspective. Ecological studies series . Springer Verlag Inc. New York , NY.

Prescott, C.E., R. Kabzems, and L.M. Zabek. 1999. Effects of fertilization on decomposition rate of *Populus tremuloides* foliar litter in a boreal forest. Can. J. For. Res. 29: 393-397.

Prescott, C.E., J.P. Corbin, and D. Parkinson. 1992. Immobilization and availability of N and P in the forest floors of fertilized Rocky Mountain coniferous forests. Plant Soil 143: 1-10.

Prescott, C.E. and L.L. Blevins. 2000. Litter decomposition in British Columbia forests; influences of forestry activities. p. 119-121. *In* C. Hollstedt, K. Sutherland, and T. Innes (ed.). Proceedings, From science to management and back: a science forum for southern interior ecosystems of British Columbia. Southern Interior Forest Extension and Research Partnership, Kamloops, B.C.

Prescott, C.E., L.M. Zabek, C.L. Staley, and R. Kabzems. 2000. Decomposition of broadleaf and needle litter in forests of British Columbia: influence of litter type, forest type and litter mixtures. Can. J. For. Res. 30: 1742-1750.

Prescott, C.E. 1995. Does nitrogen availability control rates of litter decomposition in forests? Plant Soil 168-169: 83-88.

Ranger, J., and M.P. Turpault. 1999. Input-output nutrient budgets as a diagnostic tool for sustainable forest management. For. Ecol. Manage. 122: 139-154.

Scarascia-Mugnozza, G.E., R. Ceulemans, P.E. Heilman, J.G. Isebrands, R.F. Stettler, and T.M. Hinckley. 1997. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. II. Biomass components and harvest index of hybrid and parental species clones. Can. J. For. Res. 27: 285-294.

Silkworth, D.R. and D.F. Grigal. 1982. Determining and evaluating nutrient losses following whole-tree harvesting of aspen. Soil Sci. Soc. Am. J. 46: 626-631.

Staaf, H. 1986. Release of plant nutrients from decomposing leaf litter in a south Swedish beech forest. Holarctic Ecol. 3: 129-136.

Starr, M., A.J. Lindroos, T. Tarvainen, and H. Tanskanen. 1998. Weathering rates in the Hietajärvi Integrated Monitoring Catchment. Boreal Environmental Research 3: 275-285.

Switzer, G.L., L.E. Nelson and J.B. Baker. 1976. Accumulation and distribution of dry matter and nutrients in Aigeiros poplar plantations. p. 359-369. *In* B.A. Thielges and S.B. Land (ed.) Proc. Symp. Eastern Cottonwood and related species. Louisiana State Univ. Div. Continuing, Baton Rouge, Louisiana.

Taylor, G. 2002. *Populus:* Arabidopsis for forestry. Do we need a model tree? Ann. Bot. 90: 681-689.

Theodoru, C., and G.D. Bowen. 1990. Effects of fertilizer on litterfall and N and P release from decomposing litter on a *Pinus radiata* plantation. For. Ecol. Manage. 32: 87-102.

Thiffault, E., D. Paré, N. Bélanger, A. Munson, and F. Marquis. 2006. Harvesting intensity at clear-felling in boreal forest: Impact on soil and foliar nutrient status. Soil Sci. Soc. Am. J. 70: 691-701.

Van Breeman, N., R. Finlay, U. Lundström, A.G. Jongmans, R. Giesler, and M. Olsson. 2000. Mycorrhizal weathering: A true case of mineral plant nutrition? Biogeochemistry 49: 53-67.

van Oosten, C. 2006. Hybrid poplar suitability maps. p. 186-189. *In* van Oosten, C. (ed.) Hybrid Poplar Crop Manual For the Prairie Provinces. Saskatchewan Forestry Centre. Prince Albert, SK.

Vesterdal, L. 1999. Influence of soil type on mass loss and nutrient release from decomposing foliage litter of beech and Norway spruce. Can. J. For. Res. 29: 95-105.

Wang, J.R., A.L. Zhong, P. Comeau, M. Tsze, and J.P. Kimmins. 1995. Aboveground biomass and nutrient accumulation in an age sequence of aspen (*Populus tremuloides*) stands in the Boreal White and Black Spruce Zone, British Columbia. For. Ecol. Manage. 78: 127-138.

Wesselink, L.G., G. Grosskurth, and J.J.M. van Grinsven. 1994. Measuring and Modeling Mineral Weathering in an Acid Forest Soil, Solling, Germany. p. 91-110. *In* R.B. Bryant and R.W. Arnold (Ed.) Quantitative Modeling of Soil Forming Processes: proceedings of a symposium sponsored by Divisions S-5 and S-9 of the Soil Science Society of America in Minneapolis, Minnesota, 2 Nov. 1992. SSSA Special Publication 39. Soil Science Society of America, Madison, Wis.

White, E. H. 1974. Whole-tree harvesting depletes soil nutrients. Can. J. For. Res. 4: 530-535.

Williams, T.M. 1999. Nitrate leaching from intensive fiber production on abandoned agricultural land. For. Ecol. Manage. 122: 41-49.

Zabowski, D., 1990. Role of mineral weathering in long-term site productivity. p. 55-71. *In* W.J. Dyck and C.A. Mees (Ed.). Impact if Intensive Harvesting on Forest Site Productivity. Proceedings, IES/BE A3 Workshop, South Island, New Zealand, March 1989. IEA/BE T6/A6 report no.2. FRI Bulletin No 159. Forest Research Institute, Rotorua, New Zealand.

3.0 NUTRIENT POOLS FOR HYBRID POPLAR PLANTATIONS IN SASKATCHEWAN: EFFECTS OF SITE HISTORIES AND CULTURAL PRACTICES

3.1 Introduction

Cleared agricultural land along the southern border of the boreal forest (also known as the forest fringe) in Saskatchewan is ideal for afforestation or tree plantations due to soils, climate and proximity to markets. Tree production, especially hybrid poplar (HP), has the potential to produce large amounts of biomass in relatively short time periods with lower chemical and fertilizer inputs than those used for agricultural crops. In a market of increasing input costs (fuel and fertilizer), these reduced costs can add profit to a business. However, the impact that these HP plantations may have on nutrient cycling and long-term site productivity is a question that needs to be addressed in order to ensure the sustainability of these plantation systems. Short rotation plantations such as HP have the potential to tie up large amounts of nutrients in the biomass that is then exported off site when harvested; thus, we need to understand the size of the nutrient pools (below- and above-ground) and the dynamics of nutrient fluxes and how they may be affected by site quality. However, there are no studies that have quantified nutrient pools for hybrid poplar plantations in western Canada.

Nutrient pools form the basis for extensive nutrient cycling and budgeting studies (Pastor and Bockheim, 1984; Ranger and Turpault, 1999; Silkworth and Grigal, 1982). Trees that produce large amounts of dry weight biomass in a short period of time, such as HP, and invariably immobilize high amounts of nutrients (low nutrient use efficiency), are very effective at increasing vegetative nutrient pools (Pastor and Bockheim, 1984). These nutrient-demanding trees are also important in keeping nutrients from leaching from the site, as available soil nutrients are retained in biomass instead of exiting the soil. The most efficient way of producing HP is to utilize fertile sites that can support rapid growth without copious amounts of inorganic fertilizer inputs. While young HP plantations have shown growth response to nitrogen (N) fertilizer inputs (Brown and van den Driessche, 2002), it has been shown that trees grown in the Gray Luvisol soils of the northern prairies may not respond without proper nutrient balances first (Liang and Chang, 2004; van den Driessche, 2000).

Dry matter production in Canada for HP ranges from 10-12 Mg ha^{-1} yr^{-1} oven-dry-biomass (ODB) in B.C. to 2-7 Mg ha^{-1} yr^{-1} ODB in central and eastern Canada and 1-5 Mg ha^{-1} yr^{-1} ODB in the prairies (Samson et al., 1999). The dry matter productivity of the HP plantations will depend almost exclusively on the natural fertility of the soil if no inorganic fertilizers are added (Liebeg's law of minimum), where growing conditions and moisture are good. The effects of site productivity can be directly compared by growing HP on sites of poor to high quality. Fertilizer additions can be incorporated into site quality comparisons by seeing how the trees respond to fertilizer additions at each respective site and by doing so will help identify how best to utilize the extra inputs.

Therefore this study had two objectives: the first was to determine if site quality and fertilization affect tree growth in juvenile plantations with a null hypothesis stating that fertilization and site quality will not improve tree growth. The second objective was to determine if site quality (nutrient availability) increases total nutrient pools for four- and seven-year-old HP plantations with a null hypothesis stating that site quality will not increase the total nutrient pools in HP plantations.

3.2 Materials and Methods

3.2.1 Site description

A four- (HPA) and seven- (OHPA) year-old plantation of Walker poplar (*P. deltoides* x *P. petroskyana*) established on an alfalfa field and a four-year-old plantation established on a pasture site (HPP) on agricultural land near Meadow Lake, SK. (54^{0} 7' N, 109^{0} 30' W) were used for this study.

The Alfalfa site (NW 22 – TNP 58 – Rg 19 – W3) is comprised predominantly of sandy-loam to loam textured Orthic Gray Luvisols developed from calcareous glacial till (Loon River Association) (Saskatchewan Centre for Soil Research – SCSR, 1995). The soils have moderate stoniness and the topography is gently undulating with slopes < 2%. The soils at the Pasture site (SW 31- TNP 57 – Rg 19 – W3) are comprised of Brunisolic Gray Luvisols and Orthic Gray Luvisols with loam to clay-loam textured glacial till overlain by sandy glaciofluvial material (Bittern Lake association) with significant additions of sandy Orthic Regosols and Eluviated Eutric Brunisols (Pine Association) (SCSR, 1995). Stoniness is light to moderate and slopes are less than 3% with the topography slightly undulating. For more information regarding site description see Block (2004).

3.2.2 Experimental design, plantation establishment and maintenance

The four-year-old plantations were designed as a three-factor factorial experiment arranged in a randomized complete block design, with three nursery stock types (cuttings, rooted cuttings and rooted plugs), two rates of fertilizer (0 and 100 kg ha^{-1} in a split plot with one application of fertilizer occurring in 2003 and one application of fertilizer occurring in 2005), and pruning (pruned and unpruned) (Block, 2004). The study was initiated in 2002 and the treatments were replicated three times. The seven-year-old plantation was initiated in 1997 and was designed as a two-factor factorial experiment arranged in a randomized complete block design (replicated three times) with spacing (2.5 x 2.5 m, 3.1 x 3.1 m, and 3.7 x 3.7 m) and pruning (pruned and unpruned) treatments**.**

The current study regarding tree growth, nutrient cycling and budgeting in HPA and HPP sites used the fertilized treatments only and was conducted solely in the rooted cuttings and unpruned plots. The OHPA plantation the unpruned and 3.1 x 3.1m spacing was used which was the closest spacing to the four-year-old plantations (Appendix A – experimental design diagrams for four- and seven-year-old plantations).

The HPA and HPP plantations were planted in June 2002 at a spacing of 3.2 x 2.4 m. For more information on plantation establishment see Block (2004). For plantation maintenance in 2003, the main weed control method used was tillage to a depth of 7.5 cm with and against the rows. In 2004 and 2005 glyphosate was applied semi-annually at a rate of 2.5 L ha^{-1} in both spring and fall, with an Enviromist™ sprayer (Enviromist Industries, Berri, South Australia) to control extensive perennial weed infestation of quackgrass (*Agropyron repens*) and dandelion (*Taraxacum officinale*). In June 2004, the pasture site was treated with 2 L ha^{-1} Venture™ (fluazifop-p-butyl) for control of quackgrass (*Agropyron repens*). In August 2004, both sites were treated with Lontrel™ (clopyralid) for control of dandelion and volunteer alfalfa (*Medicago sativa*). During the 2004 and 2005 seasons, the four-year-old plantations were mowed for additional weed control.

The older plantation was treated with pre-emergent herbicide, Treflan™ (Trifluralin) + Sencor™ (metribuzin) at a rate of 4 kg active ingredient ha^{-1}, prior to hand planting in the spring of 1997. The previous fall the alfalfa was sprayed with glyphosate and tilled. No other weed control had been done in this plantation and the major weed species in the plots was dandelion.

3.2.3 Soil sampling

In May 2004, soil cores were collected to a depth of 1.2 m for baseline data on soil mineralogy and soil exchangeable nutrients. A depth of 1.2 m was chosen to ensure that the rooting zone was characterized. Kolka et al. (1996) found that *Populus* species fine roots can go as deep as 1 m. Three cores per block were taken for each of the 3 plantations. Soil cores were taken with a soil auger (7 cm dia.) and separated into 10 cm depth increments to 60 cm, and in 20 cm depth increments to a 120 cm (i.e. 60-80, 80-100, and 100-120 cm). Soil samples were then air-dried and sieved (2 mm mesh) before being analyzed for exchangeable N, P, K, Mg, Ca, and Na.

Bulk density cores were collected to a depth of 60 cm (10 cm depth increments) in the fall of 2002 at the HPA, HPP, and OHPA plantations. The bulk density values derived from these samples were used to convert soil nutrient concentrations to a kg ha^{-1} basis.

3.2.4 Tree harvesting, tree measurements and understory vegetation sampling

In early August 2004, one tree from each block of the unpruned 3.1 x 3.1 m spacing treatment plots in the OHPA plantation were harvested for biomass and nutrient contents (total of 3 trees). Each harvested tree was measured for height, diameter at breast height (DBH) at 1.3 m, and root collar diameter (RCD). Trees were sectioned into 1 m bolts (Pastor and Bockheim, 1984) in order to determine biomass and nutrient contents spatially within the tree. Tree components for each 1 m section were separated into leaves, branches and boles to determine fresh weights using a Mettler PM 30-K balance (Mettler-Toledo International Ltd., Columbus, OH.) in the field. Coarse roots were excavated from a 3 m^2 area around the stem of the tree to a 60 cm depth and measured for fresh weight. The 3 m^2 area was chosen for the excavation because it was assumed that the majority of roots would occupy this area as well as minimize site disturbance for the rest of the plantation. In 2005, the understory vegetation, which consisted mostly of dandelion and some wild oats (*Avena fatua*), was harvested from three 1 m^2 plots for each of the unpruned 3.1 x 3.1 m spacing plots (for a total of nine separate samples). Fine roots were sampled by collecting one core (8.5 cm diameter) in each of the plots to a depth of 45 cm using 15 cm depth increments. The root cores were frozen to prevent decomposition until the roots were washed to remove soil, and then dried and weighed.

Hybrid poplar trees from the four-year-old plantation were harvested in August 2005, following the same procedure for the seven-year-old plantation. One tree was harvested from both the fertilized (fertilized in 2003) and unfertilized treatments in all three blocks at both the Alfalfa and Pasture sites for a total of 12 trees. In October of 2004 and 2005, tree heights and DBH were recorded in the measurement plots (20 trees and 18 trees per plot of the four-year-old and seven-year-old plantations respectively).

3.2.5 Plant and soil analysis

After harvesting the bolewood, barkwood, branches, leaves and roots of the hybrid poplar and understory shoots and roots (dandelion) were subsampled to determine fresh weights. The samples were then dried at 45^0C for two weeks to determine dry weights. The subsamples were then ground in a Wiley mill (20 mesh). The plant samples were digested using the H_2SO_4-H_2O_2 ashing method (Thomas et al., 1967) and analyzed for total N, P, K, Ca, Mg and Na. Nitrogen and P were analyzed using the Technicon AutoAnalyzer (Technicon Industrial Systems, Tarrytown, N.Y.) and K, Ca, Mg, and Na using the Varian Spectra AA 220 atomic absorption spectrometer (Varian Inc., Palo Alto, CA). Total C in the biomass was analyzed using the LECO CNS 2000 analyzer (LECO Instruments Ltd., St. Joseph, MI). Nutrient concentrations were converted to contents using the dry weight to fresh weight conversion from the subsamples to give units in kg ha $^{-1}$. Biomass was converted to Mg ha^{-1} of carbon using a conversion of 0.47 based on the carbon percentage found in seven-year-old trees harvested in 2004.

Soil analysis for PO_4 was done using a 0.5*M* $NaHCO_3$ extraction and analyzing it colorimetrically after adding the Murphy and Riley color development solution (Murphy and Riley, 1962). Soil exchangeable Ca, Mg, K, and Na were extracted using a neutral 1*M* NH_4OAc solution (Simard, 1993) and analyzed using the atomic absorption spectrometer. Inorganic N (NO_3 and NH_4) was extracted using 2*M* KCl (Maynard and Kalra, 1993) and analyzed colorimetrically using the Technicon AutoAnalyzer. Extractable nutrient contents were converted to an area basis using the bulk densities for the plots.

3.2.6 Environmental conditions

Soil temperature and soil moisture were measured hourly using Campbell Scientific (Edmonton, AB) soil monitoring equipment. Soil temperature and soil moisture were measured hourly in rooted cutting, unfertilized and unpruned plots of each block in the two four-year-old plantations at varying depths: 5, 10, 20, 30, 40, 50, 70 cm and 5, 10, 20, 30, 40, 50, 63 cm, respectively. A Campbell Scientific climate station was also installed at each site (Alfalfa and Pasture) to record environmental conditions including air temperature and precipitation (Appendix E).

3.2.7 Statistical approach and analysis

The descriptive statistics function in SPSS for windows (Version 14.0, SPSS Inc. Chicago, Illinois, USA) was used to describe the nutrient data for the seven-year-old plantation. The statistical analysis for the four-year-old plantations at both the Alfalfa and Pasture sites involved determining the differences in growth measurements for the unpruned rooted cuttings between the Alfalfa site and Pasture site and between fertilized and unfertilized treatments. Tree heights were analyzed using a one-way analysis of variance with Fishers protected least significant difference (LSD) reported as significant ($P < 0.1$) and highly significant ($P < 0.05$). The DBH was analyzed using a one-way analysis of variance with Dunnett's T3 test (with significance at $P < 0.1$) because the data did not have a homogenous variance. A one-way analysis of variance was also used for nutrient accumulation and total tree biomass for the harvested trees from the four-year-old sites. Probability values for Dunnett's T3 test were used again because of non-homogenous variance, and were reported as significant ($P < 0.1$) or highly significant ($P < 0.05$).

3.3 Results

3.3.1 Four-year-old plantations

3.3.1.1 Tree height and diameter at breast height

Tree heights for the four-year-old Alfalfa plantation averaged 3.5 and 2.8 m for unfertilized and fertilized treatments, respectively, while both the fertilized and unfertilized treatments at the Pasture site averaged 2.9 m in height in 2005 (Fig. 3.1). Tree heights in the unfertilized Alfalfa treatment were significantly greater than those for all other treatments ($p < 0.10$). Harvested trees from the four-year-old plantation had heights that ranged from 2.7 to 4.0 m, with the fertilized treatments at the Alfalfa site having the largest average height of 3.3 m. Tree DBH for the Alfalfa and Pasture sites ranged from 2.3 to 3.1 cm with the DBH of the unfertilized treatment at the Alfalfa site being significantly greater than both of the Pasture treatments. Harvested trees had an average DBH that ranged from 2.6 to 3.0 cm.

3.3.1.2 Tree dry weight biomass, carbon accumulation and nutrient immobilization

Harvested trees from the four-year-old plantations in 2005 showed no statistically significant differences in total dry biomass, carbon accumulation or nutrient immobilization (N, P, Ca, Mg, K, Na) between fertilized and unfertilized plots for both the Alfalfa (Table 3.1) and Pasture (Table 3.2) sites. The unfertilized treatments had slightly higher amounts of N, P, Ca, Mg, Na, and C compared to the fertilized treatment at the Alfalfa site (K was slightly higher for the fertilized treatment), while the opposite trend occurred at the Pasture site. Nitrogen was the dominant nutrient in the tree biomass followed by K. Calcium is typically the nutrient either in highest volume or second to N (Silkworth and Grigal, 1982; Pastor

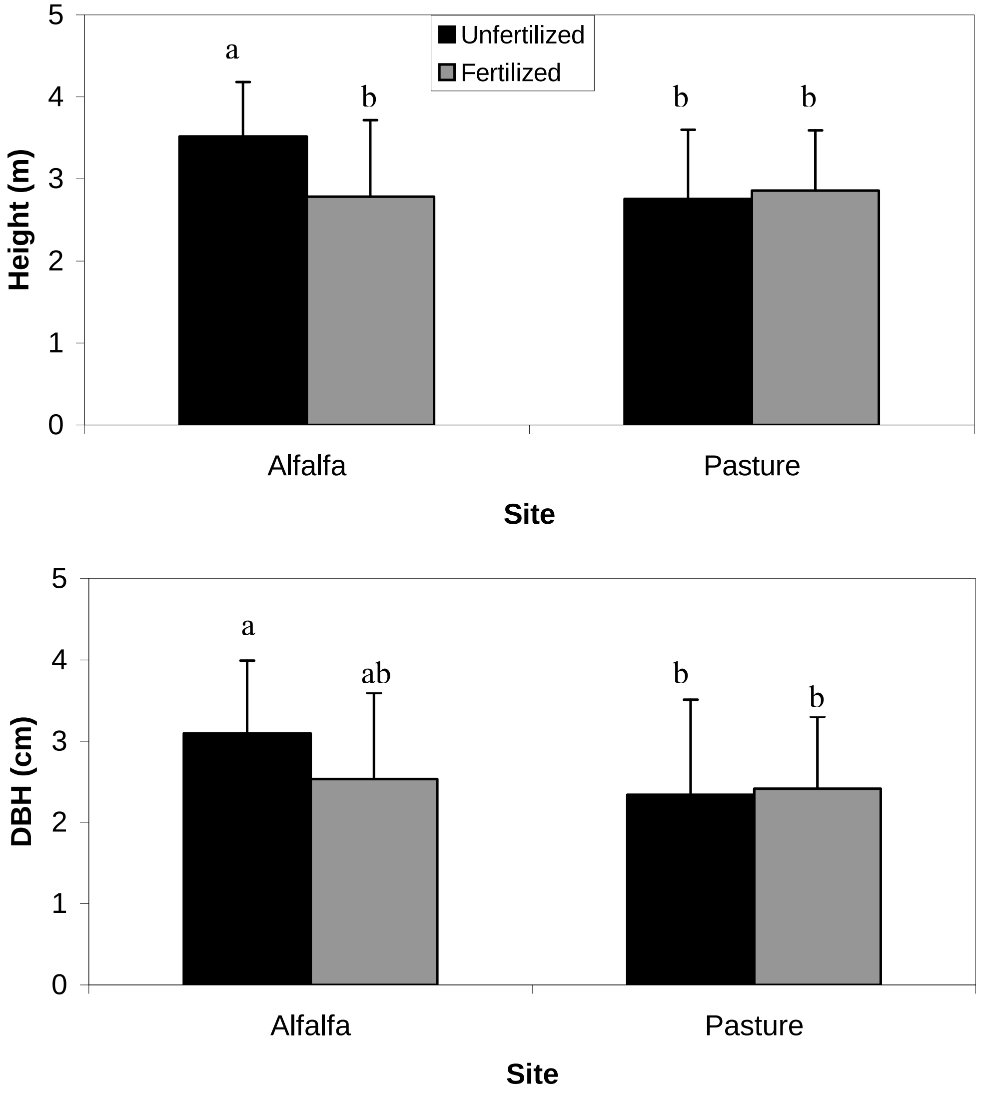

Figure 3.1. Heights and diameter at breast height (DBH) of four-year-old trees in unpruned and fertilized plots at Alfalfa and Pasture sites measured October 5, 2005. Vertical bars and lines represent mean + one standard deviation. Levels of significance are denoted with letters with "a" being significantly greater ($P < 0.1$) than "b" according to Fisher's protected LSD.

Table 3.1. Nutrient pools for soils and trees for fertilized and unfertilized plots at the four-year-old Alfalfa plantation

Site	Component	Dry Matter	C†	N§	P	Ca	Mg	K	Na
		----------Mg ha^{-1}----------		---kg ha^{-1}---					
Alfalfa	**Soil††**								
	0 - 30cm	n.a.¶	36.9	142.8	71.6	4674	562	599	730
	30-60cm	n.a.	13.3	73.8	23.2	7255	1507	510	717
	60-120 cm	n.a.	n.a.	86.1	41.5	10553	3160	852	1449
	Total (a)	**n.a.**	***50.2***	***302.9***	***134.4***	***22485***	***5227***	***1961***	***2896***
Alfalfa Fertilized									
	Leaves	1.0	0.5	33.7	1.9	4.7	1.6	22.6	0.2
	Bole	0.8	0.4	1.8	0.3	0.9	0.7	4.3	0.2
	Bark	0.3	0.1	3.2	0.3	1.6	0.4	3.1	0.1
	Branches	1.0	0.5	8.1	1.3	4.4	1.4	12.6	0.2
	Roots	0.9	0.4	11.3	1.7	3.4	1.1	12.8	0.2
	Total (b)	***4.1***	***1.9***	***58.1***	***5.4***	***15.1***	***5.2***	***55.4***	***0.8***
Alfalfa Unfertilized									
	Leaves	1.0	0.5	35.1	2.0	5.2	2.0	19.6	0.2
	Bole	0.6	0.3	1.7	0.2	0.6	0.5	3.1	0.1
	Bark	0.2	0.1	2.6	0.2	1.2	0.3	2.0	0.0
	Branches	1.1	0.5	9.2	1.4	4.9	1.7	12.0	0.2
	Roots	1.2	0.5	17.2	1.9	4.5	1.6	15.5	0.3
	Total (c)	***4.1***	***1.9***	***65.8***	***5.7***	***16.5***	***6.1***	***52.2***	***0.9***
Total Fert. (a+b)			**52.1**	**361.0**	**139.8**	**22500**	**5232**	**2016**	**2897**
Total Unfert. (a+c)			**52.1**	**368.7**	**140.1**	**22502**	**5233**	**2013**	**2897**

† Carbon pools for soils are based on % total carbon * a hectare furrow slice, and carbon for plant material is % total carbon per component * dry weight biomass of that component ha^{-1}. Values based on soil sampling done in 2003.

‡ Nitrogen is total inorganic nitrogen (NO_3 + NH_4) for soils and total nitrogen for plant material.

§ Soil sampled in May 2004 and soil nutrients represent extractable levels.

¶ n.a. means data is not available

Table 3.2. Nutrient pools for soils and tree biomass for fertilized and unfertilized plots at the four-year-old Pasture plantation

Site	Component	Dry Matter	C†	N§	P	Ca	Mg	K	Na
		----------Mg ha^{-1}----------		----------kg ha^{-1}----------					
Pasture Soil††									
	0 - 30cm	n.a. ¶	31.7	84.8	29.3	3847	793	432	671
	30-60cm	n.a.	12.9	79.4	20.5	6329	3006	568	1209
	60-120 cm	n.a.	n.a.	92.8	44.9	10262	7094	1067	2677
	Total (a)	**n.a.**	***44.6***	***257.0***	***94.7***	***20439***	***10895***	***2068***	***4558***
Pasture Fertilized									
	Leaves	0.8	0.4	22.4	1.5	3.8	1.8	13.9	0.2
	Bole	0.7	0.3	1.2	0.2	0.6	0.5	2.8	0.1
	Bark	0.2	0.1	2.3	0.2	1.2	0.4	1.9	0.0
	Branches	0.7	0.3	5.5	0.8	2.8	1.3	7.8	0.1
	Roots	0.6	0.3	7.8	1.1	1.9	0.4	7.6	0.2
	Total (b)	**3.0**	**1.4**	**39.0**	**3.8**	**10.3**	**4.5**	**33.9**	**0.6**
Pasture Unfertilized									
	Leaves	0.7	0.3	19.6	1.3	3.2	1.5	11.3	0.1
	Bole	0.7	0.3	1.3	0.2	0.7	0.5	3.0	0.1
	Bark	0.2	0.1	2.3	0.2	1.2	0.4	2.1	0.0
	Branches	0.6	0.3	4.4	0.6	2.4	1.0	6.0	0.1
	Roots	0.6	0.3	6.6	1.1	2.0	0.7	6.4	0.1
	Total (c)	***2.8***	***1.3***	***34.1***	***3.5***	***9.6***	***4.2***	***28.7***	***0.6***
Total Fert. (a+b)			**46.0**	**296.0**	**98.5**	**20449**	**10900**	**2102**	**4559**
Total Unfert (a+c)			**45.9**	**291.1**	**98.2**	**20449**	**10899**	**2097**	**4559**

† Carbon pools for soils are based on % total carbon * a hectare furrow slice, and carbon for plant material is % total carbon per component * dry weight biomass of that component ha^{-1}. Values based on soil sampling done in 2003.

‡ Nitrogen is total inorganic nitrogen (NO_3 + NH_4) for soils and total nitrogen for plant material.

§ Soil sampled in May 2004 and soil nutrients represent extractable levels.

¶ N.A. means data is not available

and Bockheim, 1984). Nutrient contents at the Alfalfa site were up to two times higher that those for the Pasture site. In the four-year-old plantations, leaves comprised the largest single component (24-27% of ODB) of the total ODB biomass of the tree for the Alfalfa and Pasture sites, respectively (Table 3.1 and 3.2). While leaves had the largest ODB, they also had the largest amount of sequestered nutrients compared to the other tree components for both the Alfalfa and Pasture sites.

3.3.2 Nutrient pools in soil and biomass

The exchangeable soil nutrient pools for the two four-year-old plantations vary between sites depending on the nutrient (Tables 3.1 and 3.2). A detailed breakdown of the nutrient pools by depth increments can be found in Appendix B. Nitrogen was different between the two four-year-old plantations in both biomass and soil availability. The four-year-old trees from the fertilized and unfertilized plots at the Alfalfa site (58.1 and 65.8 kg ha^{-1}, respectively) contain higher amounts of N than the Pasture sites (39 and 34.1 kg ha^{-1}, respectively) in the biomass and inorganic N in the soil (302.9 and 257 kg ha^{-1}, respectively). The plant components with the most N for both of the four-year-old plantations were the leaves > roots > branches > bark > bole. Soil carbon in the four-year-old plantations is similar between the Pasture and the Alfalfa plantation (44.6 and 50.2 Mg ha^{-1} C, respectively). In the Alfalfa fertilized and unfertilized plantations the amount of biomass C (1.9 and 1.9 Mg ha^{-1}, respectively) is greater than the biomass C in the Pasture fertilized and unfertilized plantations (1.4 and 1.3 Mg ha^{-1}, respectively).

3.3.3 Seven-year-old plantation

3.3.3.1 Tree heights and diameter at breast height

Average height for harvested trees from the OHPA plantation in 2004 was 9.1 ± 1.3 m, and the average DBH was 9.7 ± 2.4 cm. Average tree height in 2005 for OHPA was 9.3 ± 0.8 m and the average DBH was 9.7 ± 1.2 cm.

3.3.3.2 Tree dry weight biomass, carbon accumulation and nutrient storage

In 2004, a total of three trees from the seven-year-old plantation were harvested for determination of the total dry weight biomass, carbon accumulation, and nutrient immobilization. Trees from the OHPA plantation had dry weight biomass averaging 31.6 ± 8.4 Mg ha^{-1}, and 14.8 ± 4.0 Mg ha^{-1} C sequestered in the biomass (Table 3.3), which is 10 times greater than that for the four-year-old plantations. As the trees get older the amount of biomass that goes into the bole and bark substantially grows compared to the other biomass components. In the seven-year-old trees at the Alfalfa site, the bole and bark components make up 50% of the total biomass, with the leaves only contributing 11% to the total.

Looking at the dry weight biomass from the weeds in the OHPA plantation, there is more root biomass from the weeds than there is in the trees. They also hold a high percentage of the total biomass nutrient content, especially for N (25%).

3.3.3.3 Nutrient pools in soil and biomass

The seven-year-old plantation soils contain low inorganic N (133.1 kg ha^{-1}), relative to the organic N in the biomass. Total C at the seven-year-old plantation totaled 44.0 Mg ha^{-1} C. The seven-year-old trees have accumulated a large amount of K and N in the tree biomass (204.1 and 168.8 kg ha^{-1}, respectively). The leaves held the most N out of all the tree components (95.6 kg ha^{-1}) followed by the bark and bole > branches > roots. Carbon sequestered in the tree biomass is large in the alfalfa seven-year-old plantation (14.8 Mg ha^{-1}). The bole and bark contain more C in the seven-year-old trees than the branches, roots and leaves (7.5, 2.9, 2.7 and 1.6 kg ha^{-1}, respectively).

The understory vegetation was sampled only in the seven-year-old plantation because the weeds in the four-year-old plantations were being controlled with herbicides. The roots of the understory vegetation (mostly dandelion) are a large pool of N, P, Ca, Mg, and K (Table 3.3) in the seven-year-old plantation. The vegetation roots are the largest nutrient holder on the site after the leaves; greater than the stem, roots and branches.

3.4 Discussion

3.4.1 Tree growth

Results for the fourth year of tree growth at the HPA (3.3 m) and HPP (2.9 m) sites in this study are lower than those reported elsewhere in the literature (Table 2.4) At the Alfalfa site, the seven-year-old plantation at four years of age had

Table 3.3. Nutrient pools for soils and tree biomass for the seven-year-old Alfalfa plantation

Site	Component	Dry Matter	C†	N§	P	Ca	Mg	K	Na
		----------Mg ha^{-1}----------		---kg ha^{-1}---					
Alfalfa	**Soil††**								
	0 - 30cm	n.a.¶	31.1	27.0	76.5	5441	1203	678	701
	30-60cm	n.a.	12.9	37.6	34.2	7848	2906	701	938
	60-120 cm	n.a.	n.a.	68.5	62.9	12902	5381	1214	1733
	Total (a)	***n.a.***	***44.0***	***133.1***	***173.6***	***26192***	***9491***	***2594***	***3374***
Alfalfa	**Seven-year-old**								
	Leaves	3.6	1.6	95.6	8.0	27.5	8.2	80.3	0.3
	Bole and Bark	15.6	7.5	31.2	7.7	23.9	7.5	62.0	0.2
	Branches	6.2	2.9	23.5	6.3	34.0	6.4	28.5	0.4
	Roots	6.2	2.7	18.5	8.6	14.3	3.9	33.3	0.3
	Total (b)	***31.6***	***14.8***	***168.8***	***30.5***	***99.7***	***26.0***	***204.1***	***1.2***
Under	Shoots $_{c}$	**0.6**	n.a.	**7.6**	**1.2**	**2.7**	**1.4**	**27.4**	**0.1**
Story	Roots $_{d}$	**7.9**	n.a.	**57.2**	**10.6**	**33.4**	**10.8**	**42.6**	**3.4**
Total	**(a+b+c+d)**		**58.8**	**366.7**	**215.9**	**26328**	**9529**	**2868**	**3379**

† Carbon pools for soils are based on % total carbon * a hectare furrow slice, and carbon for plant material is % total carbon per component * dry weight biomass of that component ha^{-1}. Values based on soil sampling done in 2003.

‡ Nitrogen is total inorganic nitrogen (NO_3 + NH_4) for soils and total nitrogen for plant material.

§ Soil sampled in May 2004. Available soil nutrients in more detailed depth increments available in Appendix B.

¶ N.A. means data is not available.

tree heights and DBHs averaging 4.4 m and 4.6 cm, respectively for the 3.1 x 3.1 m spacing (Mistik Management, Unpublished, 2000). In Fort Frances and Thunder Bay, ON., the average height of 68 different *Populus deltoides* clones and hybrids was 5.54 m and 4.42 m, respectively after four years (Farmer et al., 1994). Heights ranged from 2.6 to 7.1 m at Fort Frances and 2.0 to 5.9 m at Thunder Bay. Four-year-old *Populus deltoides* x *trichocarpa* from Washington State had tree heights and DBHs ranging from 11.5 to 13.2 m and 8.7 to 11.2 cm, respectively (Heilman and Stettler, 1985; Heilman and Xie, 1993; Heilman et al., 1994; Scaracia-Mugnozza et al., 1997). These sites have about 200 frost-free days yr^{-1} (average of 100-110 days more than Meadow Lake, SK.) and substantially more moisture (1000 mm yr^{-1}) than what occurs in northwestern Saskatchewan (Ceulemans et al., 1992). The smaller growth of the four-year-old trees at the Alfalfa and Pasture sites could be attributed to the extreme drought conditions the plantation experienced during the year of establishment (2002), poor weed control in the first two years as well as the die back (also known as “cutting back”) that occurred after the first growing season. This die-back resulted in most trees resprouting from the base of the tree in the second year. Five year results (which would actually represent four years of growth) showed average heights and DBHs for rooted cuttings of 3.9 m and 4.0 cm for both sites and maximum heights of 6.6 to 6.9 m (unpublished data).

For the seven-year-old plantation at the Alfalfa site, I could find no studies to compare with in Canada. DeBell et al. (1996) reported that seven-year-old trees from Washington State had heights of 13.1 m and DBH of 10.8 cm in a 2 m spacing trial. Again, the higher growth can be related to increased precipitation, irrigation and frost-free days for that region.

The Alfalfa site is likely the better of the two sites in terms of growth response to natural fertility. The N benefit from fixation that was made available from growing alfalfa previously at the site may have benefited early growth. Neither site had any significant response to fertilizer additions; in fact, tree heights from the fertilized Alfalfa site were significantly smaller than the unfertilized trees. This negative response suggests that there may have been an inhibition of other macronutrient uptake caused by an over-supply of N. Liang and Chang (2004) found that in Gray Luvisolic soils, P and S when added to hybrid aspen (*Populus tremuloides x P. tremula*), in the absence of N limitations, increased N, P, and S uptake, leaf concentrations, and growth parameters such as leaf area, height and basal diameter. The available P content of the Alfalfa and Pasture soils in the top 30 cm were 50 and 21 μg g^{-1}, respectively (data not shown), and according to van den Driessche (2000) and subsequently confirmed by Liang and Chang (2004), the optimum soil concentration of available P should be at or above 37 μg g^{-1} for maximum HP growth. The Alfalfa site was above this critical level for P suggesting that another element may have been inadequate resulting in the growth reduction. At the Pasture site, however, the low P levels may be the cause of the poor growth response to applied N.

3.4.2 Total biomass, biomass partitioning and carbon sequestration

The ODB of the four-year-old plantations ranged from 2.8 (unfertilized Pasture) to 4.1 Mg ha^{-1} (unfertilized Alfalfa) or between 0.75 and 1.0 Mg ha^{-1} yr^{-1} and these values are again lower than those reported in the literature. The seven-year-old plantation at the Alfalfa site at four years of age averaged 6.3 Mg ha^{-1} and 7.5 Mg ha^{-1} for the 2.4 and 3.7 m spacings, respectively (Mistik Management, 2000) which is six times greater than that for the two four-year-old plantations in this study. The seven-year-old trees at the Alfalfa plantation had ODB of 31.6 Mg ha^{-1} or 4.5 Mg ha^{-1} yr^{-1}, which is comparable to the rate of 1-5 Mg ha^{-1} yr^{-1} that Samson et al. (1999) reported for HP on the prairies. Oven dry biomass rates ranged from 9-12 Mg ha^{-1} yr^{-1} for the west coast and 2-7 Mg ha^{-1} yr^{-1} for central and eastern Canada (Samson et al., 1999). The lower yield in the first several years of growth is not unusual, especially with the two years of drought that plagued the plantations for the first two years after establishment. Samson et al. (1999) found that low annual growth increments occur for the first 2-3 years and then increase to peak accumulation by mid-rotation for HP.

Carbon sequestration by the four-year-old harvested trees for the unfertilized Pasture, fertilized Pasture, unfertilized Alfalfa, and fertilized Alfalfa plots was 1.3, 1.4, 1.9 and 1.9 Mg ha^{-1} respectively. Considering that the trees had only really grown for 3 years due to die back in the first year, the amounts of C accumulation range between 0.4 and 0.6 Mg ha^{-1} yr^{-1}. The larger amount of C accumulated at the Alfalfa site is a product of the higher total growth of these trees at the site. For the seven-year-old trees at the Alfalfa site, the C sequestration in the total tree was 14.8 Mg ha^{-1}. Not included in the estimates of carbon sequestration is fine root production, which from estimates at the same sites used for this study (Block, 2004) could add up to 0.2 – 1.2 Mg C ha^{-1} yr^{-1}. Between above and below ground biomass, C accumulation was between 0.5 and 2.0 Mg ha^{-1} yr^{-1}.

3.4.3 Tree nutrient immobilization and partitioning

The unfertilized Alfalfa plots had the greatest nutrient immobilization among the four-year-old trees harvested, with almost twice the amount of N immobilized compared to the treatments at the Pasture site. The N uptake of the trees was somewhat surprising especially as the unfertilized treatments had more N immobilized than the fertilized trees at the Alfalfa site. In many cases nutrient immobilization is increased with increasing rates of fertilization for poplars (Brown and van den Driessche, 2002; Liang and Chang, 2004). Based on the nutrient availability from the soil, it is not surprising that the trees in the Pasture site were smaller trees. Based on the 37 μg g^{-1} (van den Driessche, 2000) available P that is best for optimal growth in HP, the Pasture site was limited with 21 μg g^{-1} in the top 30 cm. The leaf nutrient concentrations of the trees (Appendix C) for all treatments, were all within what Bungart and Hüttl (2004) deemed necessary for optimum nutrition of *Populus* species with values for N (28.5 – 35 mg g^{-1}), P (2.2 – 2.4 mg g^{-1}), K (18 – 23 mg g^{-1}), Ca (4.0 – 4.3 mg g^{-1}), and Mg (1.6 – 2.1 mg g^{-1}). The partitioning of the nutrients showed a trend towards the leaves containing about half of the N, P, and K in the whole tree, and a large portion of Ca and Mg as well. Lodhiyal et al. (1994) showed that 35% N, 30 % P and 35% K of the total tree amounts were contained in the leaves.

The seven-year-old plantation at the Alfalfa site had a large component of N contained in the biomass: 170 kg ha^{-1} N, 30.5 kg ha^{-1} P, 100 kg ha^{-1} Ca and 204 kg ha^{-1} K are immobilized in the biomass, 24 kg ha^{-1} yr^{-1} N, 4.5 kg ha^{-1} yr^{-1} P, 12.5 kg ha^{-1} yr^{-1} Ca and 29 kg ha^{-1} yr^{-1} K. Berthelot et al. (2000) found similar accumulation of K in the aboveground biomass, although the trees in the study also accumulated 100 kg ha^{-1} more Ca than K, which is opposite from what was seen at the Meadow Lake plantations. The proportions of uptake are different from those typically reported. Calcium accumulation is usually twice as much as K in biomass (Berthelot et al., 2000; Pastor and Bockheim, 1984). In contrast to the seven-year-old trees, the four-year-old trees are only immobilizing roughly 15 and 10 kg ha^{-1} yr^{-1} N, 1.5 and 1 kg ha^{-1} yr^{-1} P and 13 and 8 kg ha^{-1} yr^{-1} K at the Alfalfa plantation and Pasture plantations, respectively. The seven-year-old plantation was similar to what was calculated by Berthelot et al (2000) for eight-year-old trees in France (20-25 kg ha^{-1} yr^{-1} N and 5-6 kg ha^{-1} yr^{-1} P), but not comparable to what was being immobilized by seven-year-old trees in India with 100 kg ha^{-1} yr^{-1} N and 7 kg ha^{-1} yr^{-1} P (Lodhiyal et al., 1995). What is different from the trees at the Alfalfa site from other areas is that the leaves contain 55% of the total N for the whole tree, where Lodhiyal et al (1995) showed only a 28% share of N in leaves compared to the whole tree.

The amount of N held by the leaves as the trees got older (comparing the HPA and OHPA trees) did not change (~50%) even though the percentage biomass that the leaves represented decreased (25% to 11%). Typically the amount of N in the leaves relative to the rest of the biomass will decrease as the tree gets older (Blackmon et al., 1979; Lodhiyal et al., 1994: Lodhiyal et al., 1995; Switzer et al., 1976). The largest shift from the four-year-old trees to the seven-year-old trees at the Meadow Lake plantations was the shift from the leaves containing most of the P, Ca and Mg (> 30%) compared to the bole and branches to holding a relatively equal amount (~25%).

3.4.4 Available soil nutrients

The available soil nutrients have a great deal to do with the potential growth of the trees in the juvenile stage. The four-year-old Alfalfa site, with 302.9 kg ha^{-1} extractable N and 134.4 kg ha^{-1} extractable P, had more than the four-year-old Pasture site (257.0 kg ha^{-1} N and 94.7 kg ha^{-1} P) in the top 1.2 m of soil. The available P in the soil could be restricting the growth in the trees at the Pasture site, as the soil concentrations (Appendix C) are well below what is considered good for optimum growth potential for HP (Liang and Chang, 2004; van den Driessche, 2000). The exchangeable base cations (Ca, Mg, and K) were measured in all the plantations to a depth of 1.2 m and showed similar results to those found in Alban (1982) and Silkworth and Grigal (1982). Alban (1982) measured exchangeable cations to a depth of 60 cm and found Ca, Mg, and K at amounts of 9796, 1741 and 1066 kg ha^{-1} respectively which compares well to the exchangeable cations to 60 cm in the four-year-old HPA and HPP plantations. Pennock and van Kessel (1997) found 4500 and 10160 kg ha^{-1} exchangeable Ca in the top 45 cm of two separate soils under mature mixedwood sites within the Prince Albert Model Forest.

The four-year-old sites both had more available N in the top 1.2 m of soil than the seven-year-old plantation (133 kg ha^{-1}). This is not surprising as the older trees at the Alfalfa plantation with a more extensive root mass would be much more effective at taking up available NO_3^- in the upper horizons than the four-year-old plantations (Appendix B). Understory vegetation, both roots and shoots, were only measured in the seven-year-old Alfalfa plantation because in the two four-year-old plantations, understory vegetation was being controlled with herbicides. In a plantation setting such as this, there is no real competing tree species that is growing up from the understory, most of what is comprised of perennial weed species. The largest weed species by observation was dandelion. The dandelion did not have a very high shoot mass (58.4 g m^{-2}), but the root mass was very large (790 g m^{-2}), leading to a very large pool of nutrients tied up below the soil surface. This pool is not likely to increase because of the lack of sunlight and competition for nutrients that the trees provide. This pool of immobilized nutrients is one other factor in the reduced inorganic N that is found in the upper horizons of the seven-year-old plantation (Table 3.6) compared to the four-year-old plantations (Tables 3.4, 3.5). This available nutrient pool is then immobilized in the tree biomass (bole, bark, branches) or returned to the soil as organic N held within the leaf litter. The lack of available N in the upper soil horizons in the seven-year-old plantation is apparent when the N in the tree biomass is looked at (Table 3.6). The turnover rate of the leaf litter is what is going to drive the available soil N for the plantations as they mature (Berthelot et al., 2000; Prescott, 2005).

3.5 Conclusion

Broadcast applications of N fertilizer for the plantations at year 2 (in the HPP and HPA plantations) did not improve tree growth, and in the case of the Alfalfa site, actually reduced tree height growth. Biomass and nutrient accumulations of the trees at the Alfalfa site were not significantly greater than those from the Pasture site; therefore, the null hypothesis that fertilization and improved site quality do not improve tree growth and nutrient immobilization in newly established plantations is not disproved. Site quality did affect total nutrient pools for the Alfalfa and Pasture plantations where the Alfalfa site accumulated more C, N and P than the Pasture site in the four-year-old plantation. Therefore the null hypothesis that site quality will not increase total nutrient pools is rejected. Prior site management and natural soil fertility seemed to have a large effect on the productivity and nutrient pools of the plantations.

This study demonstrates the value of good quality sites for the production of HP in plantation management. It also provides the baseline data needed for the construction of nutrient budgets that will help determine if HP grown in plantations can be produced without sustainability issues in northwestern Saskatchewan, Canada.

3.6 References

Anderson, A. 1995. The soils of Loon Lake rural municipality No. 561. Saskatchewan Centre of Soil Research – Soil Survey Staff, University of Saskatchewan, Saskatoon, SK.

Berthelot, A., J. Ranger and D. Gelhaye. 2000. Nutrient uptake and immobilization in a short-rotation coppice stand of hybrid poplars in north-west France. For. Ecol. Manage. 128: 167-179.

Blackmon, B.G., J.B. Baker, and D.T. Cooper. 1979. Nutrient use by three geographic sources of eastern cottonwood (*Populus deltoides*). Can. J. For. Res. 9: 532-534.

Block, R.M.A. 2004. Fine root dynamics and carbon sequestration in juvenile hybrid poplar plantations in Saskatchewan, Canada. Master's Thesis, University of Saskatchewan.

Brown, K.R. and R. van den Driessche. 2002. Growth and nutrition of hybrid poplars over 3 years after fertilization at planting. Can. J. For. Res. 32: 226-232.

Bungart, R., and R.F. Hȕttl. 2004. Growth dynamics and biomass accumulation of 8-year-old hybrid poplar clones in a short-rotation plantation on a clayey-sandy mining substrate with respect to plant nutrition and water budget. Eur. J. For. Res. 123: 105-115.

Ceulemans, R., G. Scarascia-Mugnozza, B.M. Wiard, J.H. Braatne, T.M. Hinckley, R.F. Stettler, J.G. Isebrands, and P.E. Heilman. 1992. Production physiology and morphology of Populus species and their hybrids grown under short rotation. I. Clonal comparisons of 4-year growth and phenology. Can. J. For. Res. 22: 1937-1948.

DeBell, D.S., G.W. Clendenen, C.A. Harrington, and J.C. Zasada. 1996. Tree growth and stand development in short-rotation *Populus* plantings: 7-Year results for two clones at three spacings. Biomass Bioenergy 11: 253-269.

Farmer, R.E. Jr., C.L. Palmer, and G.J. O'Reilly. 1994. Four-year performance of *Populus deltoides* Bartr. and some of its hybrids in northwestern Ontario. NODA/NFP Tech. Rep. TR-2. Nat. Resour. Can., Can. For. Serv., Ont. Region, Sault Ste. Marie, Ont.

Heilman, P.E. and F.G. Xie. 1993. Influence of nitrogen on growth and productivity of short-rotation *Populus trichocarpa* x *Populus deltoides* hybrids. Can. J. For. Res. 23: 1863-1869.

Heilman, P.E., G. Ekuan, D. Fogle. 1994. Above- and below-ground biomass and fine roots of four-year-old hybrids of *Populus trichocarpa* x *Populus deltoides* and parental species in short-rotation culture. Can. J. For. Res. 24: 1186-1192.

Heilman, P.E., and R.F. Stettler, 1985. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. II. Biomass production in a 4-year plantation. Can. J. For. Res. 15: 384-388.

Kolka, R.K., D.F. Grigal, and E.A. Nater. 1996. Forest soil mineral weathering rates: use of multiple approaches. Geoderma 73:1-21.

Liang, H. and S.X. Chang. 2004. Response of trembling and hybrid aspens to phosphorus and sulfur fertilization in a Gray Luvisol: growth and nutrient uptake. Can. J. For. Res. 34: 1391-1399.

Lodhiyal, L.S., R.P. Singh, and S.P. Singh. 1995. Structure and function of an age series of poplar plantations in Central Himalaya. II Nutrient dynamics. Ann. Bot. 76: 201-210.

Maynard, D.G. and Y.P. Kalra. 1993. Nitrate and exchangeable ammonium nitrogen. p. 25-32. *In* M.R. Carter (ed.) Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. Lewis Publishers. Boca Raton, FL.

Murphy, J. and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta. 27: 31-36.

Pastor, J. and J.G. Bockheim. 1984. Distribution and cycling of nutrients in an aspen-mixed-hardwood-spodosol ecosystem in northern Wisconsin. Ecology 65: 339-353.

Pennock, D. J. and C. van Kessel. 1997. Clear-cut forest impacts on soil quality indicators in the mixedwood forest of Saskatchewan, Canada. Geoderma 75: 13-32.

Prescott, C.E. 2005. Decomposition and mineralization of nutrients from litter and humus. p. 15-32. *In* H. Bassirirad, (ed.) Nutrient Acquisition by Plants: an Ecological Perspective. Ecological Studies series. Springer Verlag, New York, NY.

Ranger, J., and M.P. Turpault. 1999. Input-output nutrient budgets as a diagnostic tool for sustainable forest management. For. Ecol. Manage. 122:139-154.

Samson, R., P. Girouard, C. Zan, B, Mehdi, R. Martin and J. Henning. 1999. The implications of growing short-rotation tree species for carbon sequestration in Canada: Final Report. For joint forest sector table/sinks table. Afforestation #5. Natural Resources Canada. Ottawa, ON.

Scarascia-Mugnozza, G.E., R. Ceulemans, P.E. Heilman, J.G. Isebrands, R.F. Stettler, and T.M. Hinckley. 1997. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. II. Biomass components and harvest index of hybrid and parental species clones. Can. J. For. Res. 27: 285-294.

Schoenau, J.J. and R.E. Karamanos. 1993. Soil bicarbonate extractable P, K, and N. Pp. 51-58. *In* M.R. Carter (Ed). Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. Lewis Publishers. Boca Raton, FL.

Simard, R.R. 1993. Ammonium acetate extractable elements. p. 39-41. *In* M.R. Carter (Ed). Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. Lewis Publishers. Boca Raton, FL.

Switzer, G.L., L.E. Nelson and J.B. Baker. 1976. Accumulation and distribution of dry matter and nutrients in Aigeiros poplar plantations. p. 359-369. *In* B.A. Thielges and S.B. Land (ed.) Proc. Symp. Eastern Cottonwood and Related Species Louisiana State Univ. Div. Continuing Ed., Baton Rouge, Louisiana.

Thomas, R.L., R.W. Sheard and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. Agron. J. 59: 240-243.

van den Driessche, R. 2000. Phosphorus, copper, and zinc supply levels influence growth and nutrition of a young *Populus trichocarpa* (Torr. and Gray) x *P. deltoides* (Bartr. ex Marsh) hybrid. New. For. 19: 143-157.

4.0 NUTRIENT FLUXES FOR FOUR- AND SEVEN-YEAR OLD HYBRID POPLAR PLANTATIONS IN MEADOW LAKE, SASKATCHEWAN, CANADA

4.1 Introduction

Maintaining the soil's capacity for crop production from inherent soil fertility without the use of fertilizer inputs is a distinct advantage that tree production could have over other current production systems on the Prairies. Hybrid poplar (HP), however, are fast growing and thus nutrient demanding and often require 20-25 years to reach economic harvest size when grown on agricultural land. Conifer species such as white spruce (*Picea glauca*) and Siberian larch (*Larix siberica*) have longer rotations (40-60 years) on agricultural land and use nutrients more efficiently. During a rotation, many nutrients will enter, exit and cycle through the production system from both internal and external sources and when all of the fluxes entering and exiting the system are measured, a reasonable estimate of the soil fertility and production capacity can be evaluated to determine long-term sustainability (Ranger and Turpault, 1999). While many studies have investigated the various fluxes of a nutrient cycle on natural forested landscapes (Pastor and Bockheim, 1984; Silkworth and Grigal, 1982), none have focused on HP production in the Prairies.

Input fluxes to any production system include soil mineral weathering and atmospheric deposition, but HP may be able to forage more nutrients from the atmosphere than most crop systems because of its large canopy area and biomass. Hybrid poplar likely cycles a lot of nutrients through the plantation with its high uptake rates and subsequent litterfall and decomposition. While this does not add any new nutrients to the soil, it moves nutrients from soil depths inaccessible to other plant roots to enrich the soil surface. However, even though HP may be able to pump nutrients from the subsoil, there is a concern that HP production with its increased nutrient demand will deplete soil nutrients when trees are harvested over shorter rotations. The question that is asked is whether the inputs to the site via weathering and deposition are enough to counter the site exports via harvest and leaching after harvest. The best way to address this question is to measure the input and output fluxes and thus, to assess whether these shorter rotations are sustainable.

The two objectives, therefore, of this study were to: (1) quantify the fluxes for nutrient inputs and outputs for young hybrid poplar stands in northwestern Saskatchewan; and (2) compare the fluxes between two sites of contrasting production capability. The null hypothesis for this study is that fertilization and site quality will not affect the nutrient fluxes in these hybrid poplar plantations.

4.2 Materials and Methods

4.2.1 Site description, experimental design and plantation establishment

For information on the site description, experimental design and plantation establishment see sections 3.2.1 and 3.2.2.

4.2.2 Soil sample collection

In May 2004, soil cores were collected to a depth of 1.2 m to gather baseline data on soil mineralogy for each plantation. A depth of 1.2 m was chosen to ensure that the rooting zone was characterized because Kolka et al. (1996) found that *Populus* species fine roots can reach depths of 1 m. Three samples per block in the unfertilized, unpruned, rooted plug plots were taken from the four- and seven-year-old plantation. Soil cores were taken with an auger (7 cm dia.) and separated into 10 cm increments to a depth of 60 cm, and in 20 cm increments to the 120 cm depth.

4.2.3 Mineral weathering determination

Mineral weathering rates for the sites was determined using the Zirconium (Zr) depletion method (Bain et al., 1993; Melkerud et al., 2003). Bulk densities of the sites were determined in the fall of 2002. Samples were taken from the 12 separate plots in each block at each site and averaged. The samples were taken from each soil horizon (data not shown) in each plot.

Soil samples from the OHPA, HPA and HPP plantations were dried, ground and sieved to 2 mm and then ball ground to a fine powder. This powder was sent to

Geochemical Laboratories at McGill University for X-Ray fluorescence analysis with a Phillips PW2400 Spectrometer (PANalytical, Almelo, The Netherlands). The analysis identified the total concentrations of Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P_2O_5, Ba, Cu, Ni, Zn, and Zr. The values derived from the x-ray fluorescence analysis were used to calculate cumulative weathering rates as follows:

$$X_l = (X_c * Zr_w / Zr_c) - X_w \qquad [4.1]$$

Where X_l is the loss of element X (g m^{-2}), which for this study included Ca, Mg, K and Na; X_c is the concentration of element X as a percentage of soil material in the parent material; Zr_w and Zr_c are the present amounts of Zr in the weathered horizon and the concentration of Zr in the parent material, respectively. X_w is the present amount of element X in the weathered horizon (g m^{-2}), and is calculated by:

$$X_w = X_c * \rho_b * \text{Horizon depth} \qquad [4.2]$$

Where ρ_b is the bulk density. The cumulative mineral weathering rate (X^1) is then divided by the age of the soil in years since deglaciation based on glacial history for the site resulting in:

$$\text{Average weathering rate} = X_l / \sim 12{,}000 \text{ years} \qquad [4.3]$$

Equation 4.3, therefore results in the average annual historical mineral weathering rate, which is not the current weathering rate, but is based rather on the past weathering since deglaciation.

4.2.4 Atmospheric deposition sampling

Atmospheric deposition (bulk) was collected with 1L Nalgene bottles (fitted with funnels) on 1m high posts (Appendix D) at the Alfalfa and Pasture sites for each block without any canopy interception or vegetative interference, in order to avoid any changes in the water chemistry from throughfall effects (Pastor and Bockheim, 1984). The samples were collected and measured every two weeks (from May to October for 2004 and 2005) or after rainfall events, and were refrigerated and transported back to Saskatoon, SK. The samples were then measured for volume, subsampled, filtered through Whatman #2 filter paper and frozen until analysis took place in the fall of each year with the throughfall, stemflow, and lysimeter samples.

Throughfall collectors (Appendix D) were placed on wooden fence posts below the tree canopy, about 50 cm away from the tree stem, to collect rainfall after it had passed through the tree foliage (Pastor and Bockheim, 1984; Rode, 1995). A collector was placed in every block (unfertilized, unpruned, rooted plugs treatment for the HPA and HPP plantations and in the 3.1 x 3.1 m spacing, unpruned treatments in the OHPA plantation) and were collected every two weeks (from May to October for 2004 and 2005).

Stemflow collection took place only in the 3.1 x 3.1 m spacing, unpruned, seven-year-old plantation at the Alfalfa site because the boles of the trees in the four-year-old plantations were not large enough in diameter install collectors. To collect the stemflow, flexible plastic tubing (3.2 cm dia.) was cut in half longitudinally and stapled to the bole of the tree in a downward spiral (Appendix D) starting at 1.5 m up the stem and winding down to roughly 0.5 m above the ground (Mahendrappa, 1983; Lian and Zhang, 1998; Levia and Herwitz, 2000). The tubing was also caulked with silicon sealant to the bole so that no water could run between the tree and the tubing and the stemflow drained into a 10 L plastic bottle situated under the tree. The samples were collected every two weeks (from May to October for 2004 and 2005) or after rainfall events to be analyzed for nutrient concentration. The samples were handled the same way as the bulk deposition and throughfall samples for storage.

4.2.5 Leaf litter sampling

Leaf litter traps were placed in the HP plantations to measure litter fall in September and October of each year. The litter traps were placed in the unfertilized and fertilized plots of each block in both the HPA and HPP plantations and in the 3.1 x 3.1 m spacing plots in the OHPA plantation. The litter traps for the HPA and HPP plantations had a 0.16 m^2 area and the OHPA plantation litter traps were 1 m^2 in size. Both sized traps had a wood frame with 15 cm sides and 2 mm mesh screens stapled to the bottom and were raised 10 cm above the soil surface (Keenan et al., 1995) to keep microorganisms from decomposing the leaves. The leaves were collected several times during September and October of both 2004 and 2005, weighed fresh, then dried at 45°C for two weeks before determining dry weights.

4.2.6 Leaf litter decomposition sampling

Litterbags were used in the fall of 2002 and 2003 to determine litter decomposition and nutrient composition (Kochy and Wilson, 1997; Mudrick et al., 1994). Leaf litter was collected in the fall of 2002 and 2003, air dried and weighed in the lab, and then placed in 2 mm mesh bags (20 x 20 cm) to allow for microbial decomposition of the leaf material in the field. Twelve litterbags per site were placed in both four-year-old plantations in the unfertilized, unpruned, and rooted plug treatment plots (replicated three times) and in the seven-year-old OHPA plantation (3.1 x 3.1 m spacing, unpruned plots, replicated three times), and the aspen forest adjacent to the Alfalfa site in the fall of 2002 and 2003. In 2003, three litterbags per site and one sample from the forest from the 2002 leaf litter decomposition bags were collected, for a total of ten, and measured for weight lost. In 2004 and 2005, 10 samples from the 2002 and 2003 (for a total of 20 bags each year) leaf litter decomposition bags were collected from all four sites, cleaned (to eliminate as much soil and other organic contaminants as possible), oven-dried at 45°C for 14 days, weighed and compared to their original weights from 2002 and 2003 to determine the mass loss and rate of decomposition. The samples were then ground to pass through a 2 mm sieve for nutrient content analysis.

Decomposition rate constants (K_{decomp}) was determined by the following equation

$$X_1/X_0 = e^{kt} \tag{4.4}$$

Where X_0 is initial dry weight and X_1 is the dry weight remaining at collection time (t) in years (Olson, 1963).

4.2.7 Lysimeter soil water samples

Soil solution lysimeters (SoilMoisture Equipment Corp., Santa Barbara, CA.) were installed in the four-year-old HPA and HPP plantations at depths of 20 and 60 cm in both the unfertilized and fertilized, unpruned, rooted plug treatment (replicated three times) plots. Solution samples were taken every four weeks from June - October for 2004 and May - October for 2005. The samples were measured for volume, sub-sampled (125 mL) and filtered through Whatman #2 filter paper and frozen until analysis took place in the fall of each year. The samples provided estimates of soil nutrient concentrations for each depth (20 cm data in Appendix F because of low and highly variable water volumes collected over the two years of the study) and differences between the fertilized (N) and unfertilized treatments within the four-year-old plantation. The amount of water that could potentially be leached through the soil profile in a given year was estimated with a soil water balance model (Koerner and Daniel, 1997) and the values presented in Appendix G. The total amount of water that was leached through the soil in a year (determined from the water balance model) was multiplied by the nutrient concentrations from the lysimeters to provide total amounts of nutrients leached per year.

4.2.8 Nutrient analysis

All litter samples were digested using the H_2SO_4-H_2O_2 method (Thomas et al., 1967) and were then analyzed for N, P, K, Ca, Mg, and Na. Nitrogen and P were analyzed using the Technicon AutoAnalyzer (Technicon Industrial Systems, Tarrytown, N.Y.) and K, Ca, Mg, and Na were determined using the Varian Spectra 220 atomic absorption spectrometer (Varian, Inc., Palo Alto, CA, USA).

All filtered water samples from the lysimeters and atmospheric bulk deposition collectors were frozen until analysis in the fall of 2004 and 2005. The samples were analyzed for NO_3^-, NH_4^+, and P on the Technicon Autoanalyzer, and Ca, Mg, K, and Na on the Varian Spectra 220 atomic absorption spectrometer.

Nutrient resorption from leaves back to trees was calculated by measuring nutrient values in green leaves at harvest, subtracting the amount of nutrient in leaf litter and dividing by the amount in the green leaves.

i.e. (N content $_{\text{green leaves}}$ – N content $_{\text{leaf litter}}$) / N content $_{\text{green leaves}}$ = % resorption

4.2.6 Statistical approach and analysis

The descriptive statistics function in SPSS for windows (Version 14.0, SPSS Inc. Chicago, Illinois, USA) was used to describe the nutrient content data for the leaf litter of the seven-year-old Alfalfa plantation, leaf litter decomposition (mass remaining) for the litter bags placed in the field in 2002 and 2003 and nutrient concentrations of the atmospheric deposition for both four-year-old plantations in 2004 and 2005.

The statistical analysis for the atmospheric deposition (bulk deposition and throughfall) between the Alfalfa site and Pasture site for N, P, Ca, Mg, K and Na was done using the Independent Samples T-Test determining differences in nutrient fluxes for each component of deposition between sites. Samples were reported as significant ($P < 0.10$) or highly significant ($P < 0.05$). Leaf litter nutrient content was analyzed using a one-way analysis of variance with Fishers protected least significant difference (LSD) reported as significant ($P < 0.1$) and highly significant ($P < 0.05$). The nutrient concentrations of the 60 cm depth leachate for 2004 and 2005 was analyzed using a one-way analysis of variance with Dunnett's T3 test because Levene's statistic showed that the values did not have homogeneity of variance.

4.3 Results

4.3.1 Leaf litter nutrient content and nutrient resorption

Leaf litter nutrient contents in 2004 were not different between fertilizer treatments and sites (P=0.10) (Table 4.1). In 2005, however, only litter N contents for the unfertilized treatment at the Alfalfa site were greater than the other treatments at both sites while litter P and K contents from the unfertilized treatment were greater than both fertilizer treatments at the Pasture site. Litter Ca contents for the unfertilized treatment at the Alfalfa site were also greater than those for the unfertilized treatment at the Pasture site. As a comparison, the older seven-year-old plantation at the Alfalfa site had litter nutrient contents that were approximately doubled those of the younger Alfalfa plantation (Fig. 4.1). Surprisingly, leaf litter K contents are generally greater than N leaf litter contents in the younger plantations, but were almost doubled that in the seven-year-old plantation. Magnesium in the leaf litter was quite low in all treatments in both years. Tree resorption of N from abscising leaves for the two treatments in 2005 for the four-year-old trees ranged from 56-59% for the Alfalfa site and 62-63% for the Pasture site (Table 4.2). Phosphorus resorption was slightly higher than N ranging from 62 to 66% and 69 to 71% for the Alfalfa and Pasture sites, respectively. Resorption of K was considerably less than N or P and ranged from 13 to 20% for both treatments and sites. At the seven-year-old plantation at the Alfalfa site, resorption of N, P and K

Table 4.1. Nutrient contents for leaf litter in four-year-old Alfalfa and Pasture plantations collected in the fall of 2004 and 2005 for fertilized and unfertilized treatments.

Year	Element	Alfalfa		Pasture	
		Fertilized	Unfertilized	Fertilized	Unfertilized
		------------kg ha^{-1} yr^{-1}------------			
2004	N	13.35 ± 5.16	6.97 ± 2.27	15.13 ± 12.70	8.70 ± 6.68
	P	0.45 ± 0.21	0.27 ± 0.06	0.63 ± 0.49	0.43 ± 0.29
	Ca	3.65 ± 2.61	1.70 ± 0.70	4.10 ± 3.64	2.00 ± 1.56
	Mg	0.95 ± 0.78	0.33 ± 0.12	0.93 ± 0.67	1.03 ± 0.81
	K	4.45 ± 3.04	4.17 ± 2.31	14.29 ± 13.37	6.23 ± 4.82
2005	N	14.06 ± 2.37b	20.66 ± 4.50a	8.45 ± 6.12bc	7.51 ± 1.34c
	P	0.77 ± 0.28ab	1.17 ± 0.35a	0.47 ± 0.35b	0.59 ± 0.18b
	Ca	6.36 ± 0.33ab	9.60 ± 0.62a	7.07 ± 5.65ab	4.77 ± 1.09b
	Mg	1.42 ± 0.16	1.90 ± 0.18	1.55 ± 1.27	1.47 ± 0.40
	K	18.13 ± 4.2ab	23.74 ± 5.87a	13.0 ± 10.8b	10.72 ± 1.53b

†Means with the same letter within a row and year are not significantly different at P= 0.1 according to Fisher's protected LSD. Standard deviations follow all means.

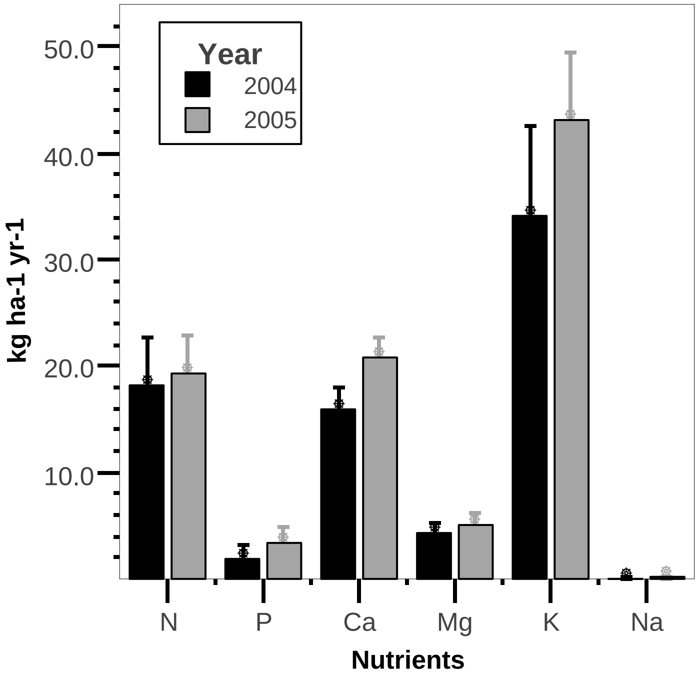

Figure 4.1. Nutrient content of leaf litter in the seven-year-old alfalfa plantation collected in the fall of 2004 and 2005. Comparisons were not made between years for the nutrient content of the leaf litter. Whiskers on bars represent 1 standard deviation.

Table 4.2. Tree resorption of N, P, and K before leaf abscission for the fertilized and unfertilized treatments at the four-year-old Alfalfa and Pasture plantations in 2005.

Element	Alfalfa		Pasture	
	Fertilized	Unfertilized	Fertilized	Unfertilized
	-------------	------------- %	-------------	-------------
N	59.4	55.9	62.3	63.2
P	65.8	61.7	71.2	69.1
K	19.2	18.3	19.6	12.5

was similar to the younger plantation at this site with values of 62, 56 and 12%, respectively.

4.3.2 Leaf litter decomposition and nutrient loss

Leaf litter decomposition bags placed in the OHPA and aspen forest in 2002 showed a much greater mass loss (48 and 40 %, respectively) than that for the litter bags in the two four-year-old plantations HPA and HPP (17 and 20%, respectively) after the first year (Fig. 4.2). After the second year, mass loss reached 65% of the initial for the OHPA and aspen forest and 35% for HPA and HPP.

By the third year, mass loss for all four sites began to converge; however, mass loss was greatest for the HPP site. When litter was placed in the field starting in 2003, similar trends were observed again after the first year with mass loss highest for the OHPA and forest sites (51 and 62%, respectively) compared to the 4 year old plantations HPA and HPP (29 and 36%, respectively) (Fig. 4.3). After the second year, mass loss for the OHPA and HPA sites were similar while the forest and HPP sites were higher at 77 %.

Decomposition rate constants (K_{decomp}) were higher for litter bags placed in the field in 2002 in the OHPA and aspen forest compared to the four-year-old plantations (HPA and HPP) for the first two years of decomposition (Table 4.3, Table 4.4). In the third year, rates of decomposition were different only between HPA and HPP. For litter bags placed in the field in 2003, decomposition rates were differed between all sites after the first year and in the second year the decomposition rates were higher for HPP compared to the HPA and OHPA sites (Table. 4.4) which was similar to the 2002 placement study (Table 4.3). Nitrogen contents for the litter in the litter bags increased (up to 2 times) after the first year of decomposition for all sites with the 2002 placement (Fig. 4.4) and up to 1.3 times for all sites except the forest when litter bags were placed in 2003 (Fig. 4.5). By the end of the third or second year for the 2002 and 2003 placements, respectively, N contents had decreased to the initial levels. Phosphorus contents decreased for the

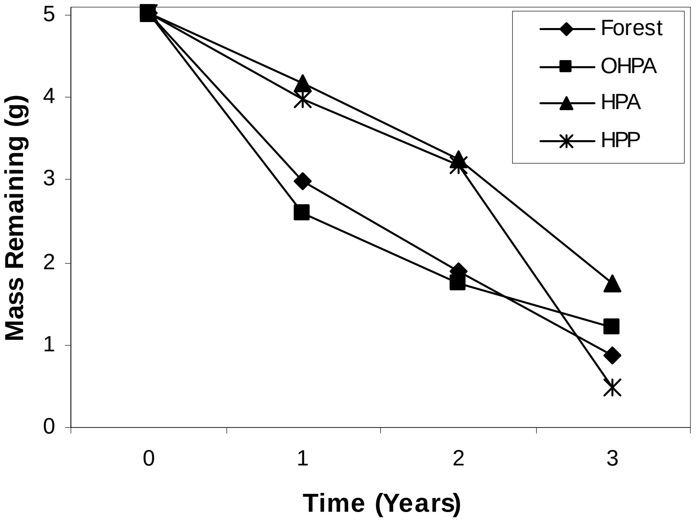

Figure 4.2. Leaf litter decomposition for litterbags placed in different locations in the fall of 2002.

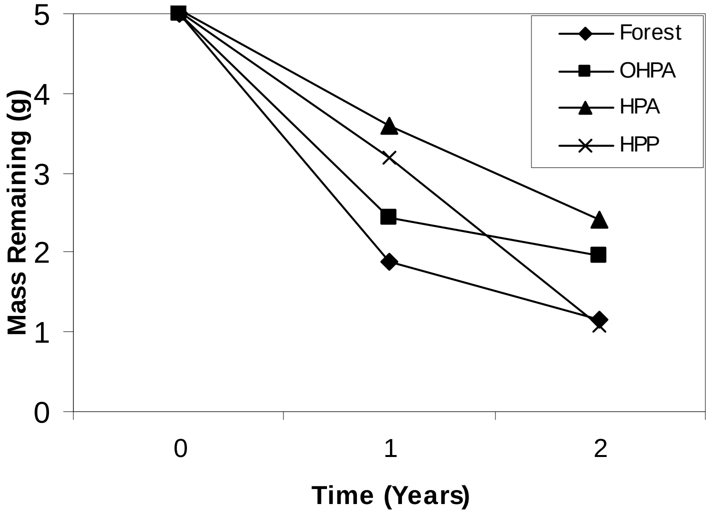

Figure 4.3. Leaf litter decomposition for litterbags placed in different locations in the fall of 2003.

Table 4.3. K_{decomp} values for decomposition (2003-2005) for litterbags placed in the field in 2002. K_{decomp} values are based on decomposition from year of initiation (2002) to year one, year one to year two and year two to year three.

Site	Year 1	Year 2	Year 3
Forest	-0.5215	-0.4858	-0.5804
OHPA	-0.6631	-0.5260	-0.4734
HPA	-0.1823	-0.2153	-0.3525
HPP	-0.2313	-0.2283	-0.7756

Table 4.4. K_{decomp} values for decomposition (2004-2005) for leaf litterbags placed in the field in 2003. K_{decomp} values are based on decomposition from year of initiation (2003) to year one and year one to year two.

Site	Year 1	Year 2
Forest	-0.9749	-0.7358
OHPA	-0.7181	-0.4701
HPA	-0.3393	-0.3703
HPP	-0.4492	-0.7636

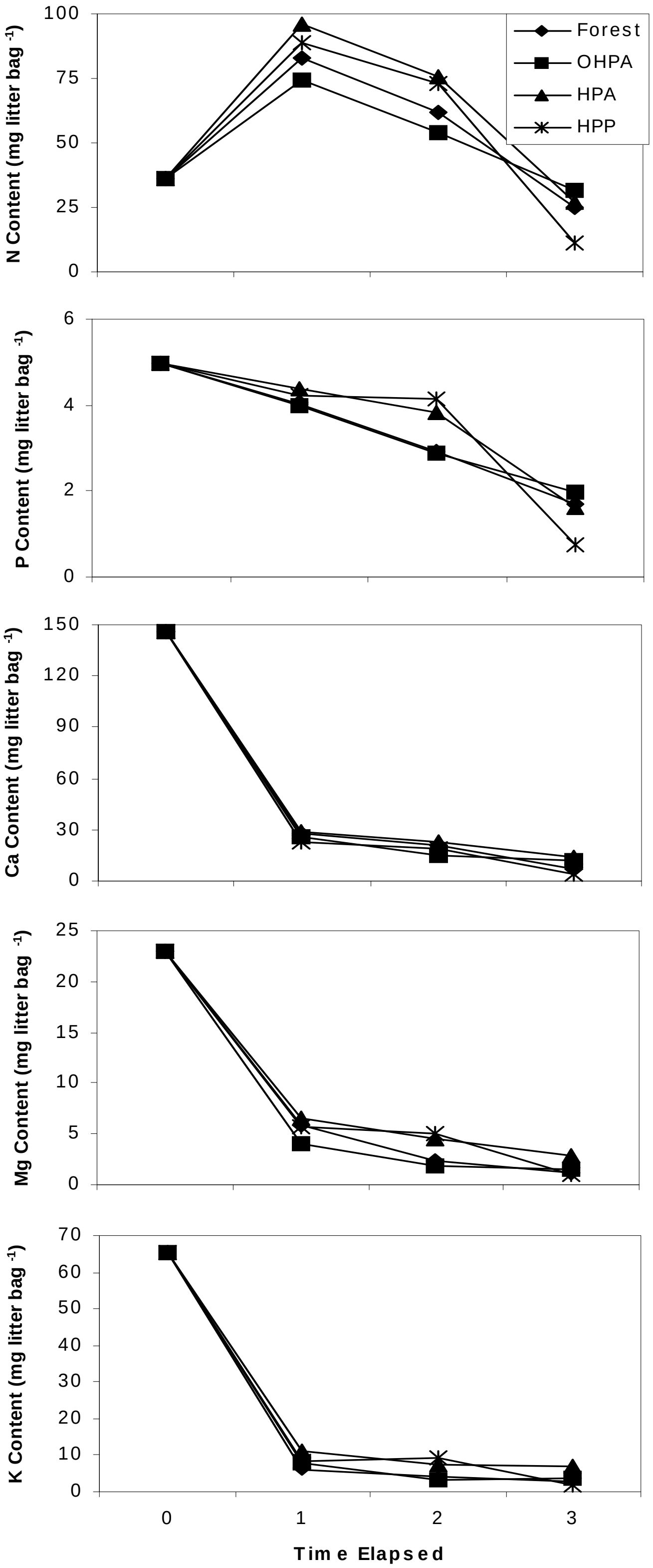

Figure 4.4. Nutrients remaining in leaf litter after three years of decomposition (2002 placement) from the OHPA, HPA and HPP plantations and the adjacent aspen forest.

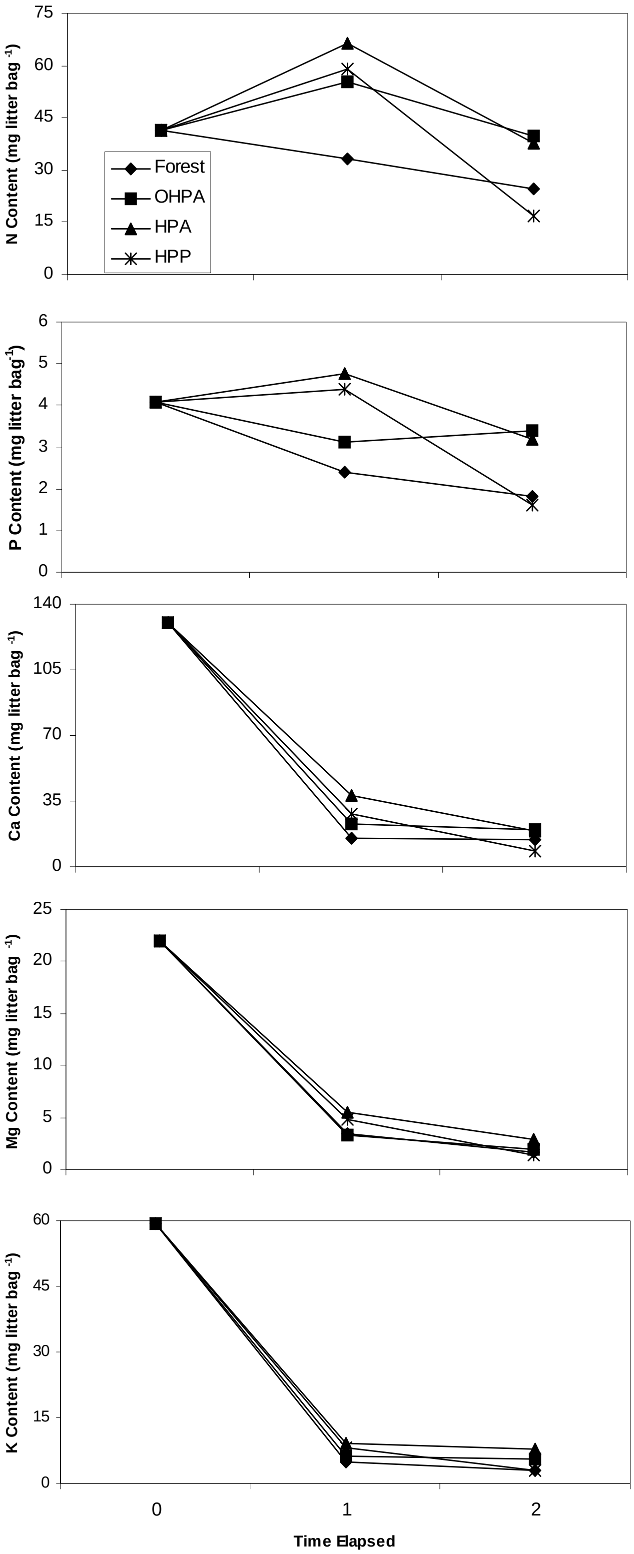

Figure 4.5. Nutrients remaining in leaf litter after two years of decomposition (2003 placement) from the OHPA, HPA and HPP plantations and the adjacent aspen forest.

three-year study and had lost about 60% of the total P after three years of decomposition (Fig. 4.4). In the two-year study, however, P levels remained constant after the first year for the four-year-old plantations but decreased in the OHPA and forest sites and in the second year P contents decreased except for the OHPA site (Fig. 4.5). The base cations Ca, Mg and K all showed large decreases in nutrient contents (80, 78, 85 %, respectively) after the first year of decomposition for both the 2002 (Fig. 4.4) and 2003 (Fig. 4.5) litter bag placements. There was little nutrient loss in the subsequent years for both placements.

4.3.3 Mineral weathering

Historical weathering rates for the base cations Ca, Mg, K and Na were estimated for the Alfalfa and Pasture sites using the elemental depletion method (Table 4.5). Mineral weathering rates were highest for Ca ranging from 13.4 to 22.9 kg ha^{-1} yr^{-1}, intermediate for Mg (3.9-8.1 g ha^{-1} yr^{-1}) and lowest for K and Na (1.2 – 2.5 g ha^{-1} yr^{-1}). Phosphorus weathering rates were calculated and included but weathering values were negligible. Weathering rates for the OHPA site were about two times smaller than that for the four-year-old plantations.

4.3.4 Atmospheric bulk deposition

Atmospheric deposition for both sites and years (2004 and 2005) followed a general trend where the bulk deposition lost NO_3^-, NH_4^+, and P to the tree canopy as throughfall but gained Ca, Mg, K, and Na when passing through the canopy (Table 4.6). Ammonium showed the greatest decrease of 72 and 63% for 2004 and 2005, respectively between the bulk deposition and throughfall for both of the four-year-old plantations. Phosphorus decreased by 73% and 49% for 2004 and 2005, respectively for both sites while NO_3 losses were smaller averaging 7% in 2004 for both sites and only HPA showing a loss of 43% in 2005. The largest increase in nutrient content from bulk deposition to throughfall occurred with K which increased from 1.5 to 2.0 times at the HPA and HPP sites in 2004 and from 3 to 3.3 times for the HPA and HPP sites in 2005. Nutrient concentrations for atmospheric deposition and throughfall can be found in Appendix D. The amount of nutrients that are contained in stemflow in the OHPA was almost negligible compared to throughfall (Table 4.7). Stemflow rates of NO_3^-, NH_4^+ and P were 0.01 kg ha^{-1} yr^{-1},

Table 4.5. Historical mineral weathering rates to a depth of 1 m based on the elemental depletion method.

Site	**Ca**	**Mg**	**K**	**Na**	**P**
	-------------------------------	---------	kg ha^{-1} yr^{-1}	---------	------------------------------
HPA	21.2	7.2	2.1	2.5	0.13
HPP	22.9	8.1	2.4	1.8	0.13
OHPA	13.4	3.9	1.2	1.4	0.05

Table 4.6. Mean atmospheric deposition (± standard deviation), which includes bulk deposition (BDep) and throughfall (TF) for 2004 and 2005 for four-year-old alfalfa and four-year-old pasture sites.

Element	Atmos. Dep.	----------2004--------		---------2005---------	
		HPA	HPP	HPA	HPP
		------------------------- kg ha^{-1} yr^{-1}	-------------------------		
H_2O†	BDep	2.8 x 10^6	3.0 x 10^6	4.4 x 10^6	4.7 x 10^6
	TF	2.5 x 10^6	3.1 x 10^6	3.6 x 10^6	4.3 x 10^6
NO_3	BDep	1.58±0.54	1.51±0.73	1.92±0.93	1.76±0.34
	TF	1.56±0.67	1.31±0.51	1.09±0.15	2.01±0.91
NH_4	BDep	7.41±7.95	6.12±2.57	6.15±1.69	9.33±3.80
	TF	2.10±0.81	1.78±0.25	2.35±1.27	3.37±0.81
P	BDep	1.30±1.45	1.73±0.95	1.09±0.18	1.37±0.22
	TF	0.45±0.17	0.33±0.08	0.49±0.32	0.80±0.53
Ca	BDep	3.51±0.95	2.86±0.56	1.89±0.56	1.59±0.36
	TF	4.93±0.73	5.41±1.15	3.62±0.74	6.35±5.42
Mg	BDep	0.41±0.30	0.52±0.34	0.66±0.06	0.77±0.13
	TF	0.48±0.12	0.55±0.30	1.01±0.12	1.62±0.93
K	BDep	3.44±2.20	3.76±1.29	4.66±0.09	4.16±0.24
	TF	9.11±4.23	5.60±2.61	13.96±3.15	13.80±5.41
Na	BDep	8.21±2.77	6.95±1.24	9.57±0.77	9.71±1.05
	TF	8.76±1.54	11.26±1.38	10.04±1.21	11.88±1.61

† Water additions are measured as L ha^{-1} yr^{-1}

Table 4.7. Mean atmospheric deposition (± standard deviation), which includes bulk deposition (BDep) throughfall (TF) and stemflow (SF) for 2004 and 2005 for seven-year-old Alfalfa site.

Element	Atmos. Dep.	2004	2005
		-------------------kg ha^{-1} yr^{-1}-----------------	
H_2O†	BDep	2.6×10^6	4.4×10^6
	TF	2.7×10^6	3.9×10^6
	SF	3.9×10^4	8.3×10^4
NO_3	BDep	1.58±0.54	1.92±0.93
	TF	1.43±0.50	2.09±1.59
	SF	0.01±0.002	0.01±0.002
NH_4	BDep	7.41±7.95	6.15±1.69
	TF	2.08±0.43	2.13±1.77
	SF	0.01±0.004	0.01±0.002
P	BDep	1.30±1.45	1.09±0.18
	TF	0.98±0.51	0.64±0.19
	SF	0.11±0.07	0.01±0.002
Ca	BDep	3.51±0.9	1.89±0.56
	TF	6.35±2.10	5.86±1.82
	SF	3.70±1.03	0.53±0.10
Mg	BDep	0.41±0.30	0.66±0.06
	TF	1.02±0.62	1.68±0.58
	SF	1.08±0.35	0.14±0.02
K	BDep	3.44±2.20	4.66±0.09
	TF	11.88±4.92	23.10±7.87
	SF	11.18±6.24	1.42±1.11
Na	BDep	8.21±2.77	9.57±0.77
	TF	12.20±2.32	12.29±0.22
	SF	0.74±0.15	0.22±0.05

† Water volumes are measured as L ha^{-1} yr^{-1}

and thus are not considered a large contributor to the soil. Although stemflow may not have a large accumulation of nutrients during the year, the solution concentrations are quite high in Ca, Mg, and K relative to bulk deposition and throughfall (Appendix D).

4.3.5 Soil solution nutrient concentrations and leaching

Soil solution concentrations at the 60 cm depth showed significant differences between the Alfalfa and the Pasture sites in 2004 and 2005 for N, Ca, and Mg (Table 4.8). In 2004 the HPA fertilized, HPA unfertilized, and HPP fertilized treatments had significantly greater N concentrations than the HPP unfertilized treatment. HPA fertilized and HPA unfertilized were significantly greater than HPP fertilized and HPP unfertilized treatments for Ca and the HPA unfertilized treatment was significantly greater than the HPP unfertilized treatment for Mg. In 2005 the HPA fertilized and unfertilized treatments were significantly greater than the HPP fertilized and unfertilized treatments for N, Ca, and Mg concentrations in the leachate. The concentrations of N, Ca, Mg, and K were more than double for all treatments in 2004 compared to 2005. Soil solution nutrient concentrations for the 20 cm depth lysimeters at both the Alfalfa and Pasture sites are presented in Appendix F.

The leaching amounts, determined from the 60 cm lysimeter nutrient concentrations and the evapotranspiration model, were generally higher in 2004 compared to 2005 and usually higher for the Alfalfa site compared to the Pasture site (Table 4.9). In 2004, the nutrients lost from leaching were highest in the HPA fertilized plots followed by the HPA unfertilized, HPP fertilized and HPP unfertilized for N, Ca, and K with the exception of Mg where the HPA unfertilized had greater leaching losses (Table 4.9). HPP plots had the lowest leaching losses for all nutrients in 2004. In 2005 the same trend occurred, except that Mg was lost in greater amounts in the HPA fertilized than the HPA unfertilized. The most obvious difference between nutrient losses in 2004 and 2005 is the quantities lost with the losses in 2005 being vastly lower than those in 2004.

Table 4.8. Mean soil solution concentrations (± standard deviation) for N, P, Ca, Mg and K at a 60 cm depth for 2004 and 2005 for four-year-old Alfalfa and four-year-old Pasture sites in both fertilized and unfertilized treatments.

Year	Element	Alfalfa		Pasture	
		Fertilized	Unfertilized	Fertilized	Unfertilized
		------------------------------μg mL^{-1}---------------------------			
2004	N	273 ± 105a	218 ± 81a	185 ± 118a	21 ± 17b
	P	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1
	Ca	316 ± 228a	256 ± 126a	140 ± 97b	32 ± 20c
	Mg	68 ± 46ab	90 ± 42a	59 ± 40ab	35 ± 50 b
	K	8.1 ± 13.4	1.9 ± 0.6	2.5 ± 1.4	1.8 ± 1.4
2005	N	100 ± 89a	76 ± 66a	11.3 ± 14.8b	5.8 ± 6.9b
	P	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Ca	154 ± 104a	126 ± 98a	23.2 ± 17.4b	16.8 ± 8.7b
	Mg	39 ± 28a	37 ± 31a	8.6 ± 5.4b	6.5 ± 4.3b
	K	1.3 ± 0.6	1.1 ± 0.5	1.1 ± 0.5	0.9 ± 0.2

Means with the same letter within a row and year are not significantly different at *P* = 0.1

Table 4.9. Mean leaching amounts (± standard deviation) for N, P, Ca, Mg and K at a 60 cm depth for 2004 and 2005 for four-year-old alfalfa and four-year-old pasture sites in both fertilized and unfertilized treatments.

Year	Element	Alfalfa		Pasture	
		Fertilized	Unfertilized	Fertilized	Unfertilized
		------------------------kg ha^{-1} yr^{-1}----------------------			
2004	N	93.1 ± 35.9	74.1 ± 27.4	70.2 ± 44.7	7.9 ± 6.5
	P	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Ca	107.5 ± 7.7	87.1 ± 42.9	53.2 ± 36.7	12.0 ± 7.8
	Mg	23.3 ± 15.7	30.5 ± 14.1	22.2 ± 15.1	13.1 ± 18.8
	K	2.8 ± 4.6	0.7 ± 0.2	1.0 ± 0.5	0.7 ± 0.5
2005	N	6.8 ± 6.1	5.2 ± 4.5	0.9 ± 1.2	0.5 ± 0.5
	P	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Ca	10.6 ± 7.1	8.6 ± 6.7	1.8 ± 1.4	1.3 ± 0.7
	Mg	2.7 ± 1.9	2.6 ± 2.1	0.7 ± 0.4	0.5 ± 0.3
	K	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0

4.4 Discussion

4.4.1 Factors affecting leaf litter nutrient content and decomposition

The litterfall from the four-year-old plantations was highly variable, making any conclusions about nutrient trends difficult. In 2004, the nutrient content of the leaves from the Pasture site were higher in N, P, Ca, and K than the Alfalfa site but in 2005 the opposite was true. Some reasons for the variation in leaf nutrient contents from year to year may include tree productivity and also the way the leaves fall. Storms may induce leaf fall earlier than would normally occur and cause nutrient content in the leaves to increase (Gosz et al., 1972). Wind may also affect the direction of litterfall away from litter traps (Ferrari and Sugita, 1996), and the tree productivity will affect the nutrient content of the leaf litter collected as more leaves will equate to a greater nutrient deposition.

The seven-year-old trees had consistent litterfall from 2004 to 2005. In all cases the nutrient content of the leaf litter in 2005 was greater than in 2004. The small increase in leaf litter nutrient content indicates that the leaf mass is close to reaching its maximum nutrient level and leaf biomass.

Nutrient contents in the leaves at the point of abscission is highly dependant on the amount of nutrient resorption back into the woody portions of the tree biomass. Trees at the Pasture site had higher resorption of N and P than the Alfalfa site (Table 4.2), and the resorption of the OHPA was close to both the HPA and HPP plantations. The resorption of N, P and K for the leaf litter was equal to, greater than and lower than that found in other studies, respectively. Cote and Camire (1987), Das and Chaturvedi (2005), Lodhiyal et al. (1994), Lodhiyal et al. (1995), and Lodhiyal and Lodhiyal (1997) found similar results of 60% N, 50% P and between 50-70% K resorption for similarly aged HP. The K resorption may be even lower in the leaves due to the fact that most of the K leaching from leaves in throughfall occurs just before abscission (Parker, 1983). The leaves at this age may be losing much of the K assumed to be resorbed as leaching in throughfall.

The leaf litter bags that were placed in the field in 2002 and 2003 showed some similarities in the first year of leaf litter decomposition. The leaf litter placed in the older plantation and aspen forest decomposed faster than the leaf litter in the

HPA and HPP plantations. The litter in the older stands may have decomposed faster because of different microclimate conditions in these closed-canopy stands. The increased humidity and temperature in these plantations would have improved the conditions for decomposition (Meentemeyer, 1978; Santa Regina, 2001). The rapid decomposition of the HP litter is backed up by other studies that have found that broadleaf litter decomposes rapidly after abscission (Peterson et al., 1997; Prescott et al., 2000). The litter decomposes fast because of low lignin content, high N concentrations and possibly due to high labile content that leads to leachable losses (Prescott et al., 2000; Prescott, 2005). In 2005 (year 3 of decomposition for the 2002 bags and year 2 of decomposition for the 2003 bags) the litter decomposition of the HPP plantation was far greater than the other treatments and this was likely due to contamination and trouble with the cleaning of the litter bags at the time of collection. The bags contained high amounts of outside organic material that had grown through the mesh and soil that had accumulated on top of the bags. The results obtained for the HPP litter bags were expected to be similar to the decomposition found at the Alfalfa site, and due to difficulty cleaning and processing, some litter may have been lost in this process, resulting in greater decomposition rates.

The N content of the leaf litter in the decomposition bags increased in the first year of decomposition. Moore et al. (2005) and Köchy and Wilson (1997) reported that aspen leaves increased in total N content during the year. The P content also increased slightly in the 2002 litter decomposition bags in the HPA and HPP plantations. Nitrogen and P are usually retained in the litter in the early stages of decomposition and Prescott (2005) found that it may actually lead to an import of N and P into the litter, possibly as a result of increased fungal biomass (Berg and Soderstrom, 1979).

4.4.2 Mineral weathering rates

The weathering rates of Ca and Mg compared well to those reported by Likens et al. (1977), which took place in the Hubbard Brook forest in New Hampshire. Potassium and Na were lower than those reported by Likens et al (1977). Compared to Watmough and Dillon (2003), though, the Ca (10 kg ha^{-1} yr^{-1})

and Mg (4.4 kg ha^{-1} yr^{-1}) values are high in regards to K (7 kg ha^{-1} yr^{-1}) and low for Na (6.8 kg ha^{-1} yr^{-1}). Phosphorus weathering was very low, and in some studies (Bain et al., 1993; Melkerud et al., 2003) is not accounted for because of the low values.

The historical mineral weathering rates that were calculated for the nutrient fluxes have some uncertainty surrounding how close they represent current mineral weathering values. The historical mineral weathering rates do not take into account the effect that the trees may have on the mineral weathering rate over the life of the plantation. Several studies have linked fast-growing tree species to increased rates of mineral weathering. Bormann et al. (1998), Augusto et al. (1998) and Nordberg and Olsson (1999) all showed that trees (Red Pine and Norway spruce) had increased the rate of mineral weathering by different biological processes. The result was that tree immobilization was not reducing base cations, particularly Ca and Mg, in available nutrient pools as fast as what was expected.

The mineral weathering rates determined from the elemental depletion method showed some very large differences between the HPA and OHPA plantations and no difference between the HPA and HPP plantations (Table 4.5). The main difference between the sites is the difference in bulk density on the sites. The OHPA plantation has a reduced bulk density to that of the HPA plantation even though both plantations are on the same site, with only a dirt path separating them. This can be explained by increased root and undergrowth biomass and organic matter building more stable soil aggregates and decreasing soil bulk density. Considering that the mineralogy is similar between the sites, the difference in the average mineral weathering rate was unexpected. The estimates of mineral weathering for these sites show that there is a steady source of base cations for nutrient replenishment.

4.4.3 Bulk deposition, throughfall and stemflow chemistry

The total inorganic N that was deposited at the HPA and HPP plantations (~9 kg ha^{-1} yr^{-1}) were relatively close to that found by Köchy and Wilson (2001) in the Prince Albert National Park area in north-central Saskatchewan (14.0 kg ha^{-1} yr^{-1}), and was within the range of values 4.8 – 27 kg ha^{-1} yr^{-1} reported by Lovett and

Lindberg (1993) for sites across the continental U.S. Sites in their study located closest to urban areas had high deposition and the rural sites had deposition ranging between 6 – 10 kg ha^{-1} yr^{-1}. Ammonium-N was the main form of N that was deposited at the HPA and HPP plantations which is in line with Lovett and Lindberg (1993), but contradictory to what Köchy and Wilson (2001) found for northern SK.

Nutrient concentrations (Table 4.7) and the total fluxes for precipitation showed that NO_3^-, NH_4^+ and P were retained in the tree biomass when incident precipitation passed through the canopy. The loss of these nutrients to the tree biomass suggests that the ions are responding to a nutrient gradient between the incoming precipitation and the absorption sites in the plants (Lovett et al., 1996; MacDonald et al., 1993). This process is called canopy exchange (C.E.). Calcium, Mg and K are gained and N lost from water in the C.E. process. Some of the increases are due to dry deposition washing off of leaves and the remainder is from C.E. or canopy leaching (Eaton et al., 1973). The increase in Ca, Mg and K from wet deposition to throughfall has been recorded in other studies using deciduous trees (Bélanger et al., 2002; Pastor and Bockheim, 1984).

Stemflow results showed that the only elements added to the forest floor were K, Ca, and Mg (Table 4.6). Nitrate, NH_4^+, and P added negligible amounts to the soil from stemflow and are not considered important nutrient fluxes (Neary and Gizyn, 1994; Levia Jr. and Frost, 2003).

4.4.4 Factors affecting leachate amounts

Inorganic N and Ca leached from the root zone in 2004 was very high in the HPA fertilized and unfertilized treatments and the HPP fertilized plots and lower in the HPP unfertilized plot. The loss in 2004 was a result of several different factors. Both sites experienced drought conditions in the 2002 and 2003 growing seasons, in which the trees grew little (Chapter 3) and had very little N uptake, followed by a year of above average rainfall. At the HPA plantation, the trees were planted where there had been alfalfa production for the previous six years. This provided a high level of organic and inorganic N that would have remained in the soil in the two years of drought with little uptake. This N was leached out of the root zone with the increased water flow in year three. This is similar to the effects of harvesting a forest site, as the organic N would mineralize (Mroz et al., 1985; Piatek and Allen, 1999), leach from the slash (Hendrickson et al., 1989) and leach through the root zone (Johnson et al., 1988). In the 2003 growing season, the plots were also fertilized leading to even more available N. The HPP unfertilized plots were the only plots to deviate from the high leaching trend in 2004 with smaller leaching losses than the HPA fertilized, HPA unfertilized and HPP fertilized plots (Table 4.9). The fertilizer treatments on the HPP and HPA plantations had a larger influence on the N lost through leaching, which is suggested in several other studies (Binkley et al. 1999; Lee and Jose, 2005; Williams, 1999). Calcium and Mg also had high leaching losses in 2004 with losses ranging from 53.2 – 107.5 kg ha^{-1} yr^{-1} for Ca (HPA fertilized and unfertilized plots, respectively) and 22.2 – 30.5 kg ha^{-1} yr^{-1} for Mg (HPA unfertilized and HPP fertilized, respectively).

In 2005, rainfall was high and led to another flux of nutrients past the root zone, although much smaller than in 2004 (Table 4.8). This rate of leaching is a more reasonable yearly rate to expect at the plantations as tree uptake would likely limit the large fluxes that occurred in 2004.

4.5 Conclusion

The nutrient fluxes from the HPA, HPP and OHPA sites were quantified in almost all cases, excluding stemflow for HPA and HPP plantations because the small stem diameters of the trees did not allow for proper stemflow collection. The magnitude of the fluxes showed than the level of nutrient inputs and outputs were dependant on site quality.

Several factors contributed to the difference in site quality between the HPP and HPA plantations. The HPA plantation site was rated as a higher quality production site than the HPP plantation, and past management on the two sites contributed to higher fertility at the HPA plantation than the HPP plantation. The HPA site had been alfalfa for six years prior to planting contributing to higher soil N compared to the HPP site being in pasture for 17 years.

Fluxes that differed between the two plantations were nutrient contents of leaf litter and soil leachate. The nutrient availability at the HPP plantation was lower than at HPA and presumably held nutrients tighter in the biomass. This was reflected in nutrient resorption from green leaves before abscission, with the HPP plantation trees resorbing 3-8% more N and 5-8% more P (fertilized and unfertilized plots respectively) than the HPA plantation. This same trend was observed with the nutrients added to the soil from the leaf litter. The amount of nutrient addition to the soil from the leaves was not significantly different in 2004, but greater in the HPA than the HPP plantation in 2005. Nutrient content from leaching was higher at the HPA site than the HPP site in both 2004 and 2005. The fluxes from mineral weathering and deposition were not significantly different from each other and in the case of deposition were quite variable over both years of the study.

Fertilization affected the scale of nutrient fluxes at both sites. On fertilized plots, at both the HPA and HPP plantations, nutrient content in leaf litter was higher in 2004 (the year immediately after fertilization). Leachate nutrient content was high for 2004 and 2005 at both the HPA and HPP plantations.

The results from this study showed that site quality and fertilization do make a difference on nutrient inputs and outputs to a HP plantation. Higher site quality and fertilization increased litterfall and losses (leachate) at both sites in both years. These results disprove the null hypothesis that site quality and fertilization would not have an effect on quantity of inputs and outputs for HP plantations.

4.6 References

Augusto, L., P. Bonnaud and J. Ranger. 1998. Impact of tree species of forest acidification. For. Ecol. Manage. 105: 67-78.

Bain, D.C., A. Mellor, M.S.E. Robertson-Rintoul, and S.T. Buckland. 1993. Variations in weathering processes and rates with time in a chronosequence of soils from Glen Feshie, Scotland. Geoderma 57: 275-293.

Bélanger, N., F. Courchesne, B. Côté, J.W. Fyles, P. Warfvinge, and W.H. Hendershot. 2002. Simulation of soil chemistry and nutrient availability in a forested ecosystem of southern Quebec. Part 2. Application of the safe model. Environ. Model. Software 17: 447-465.

Berg, B. and B. Soderstrom. 1979. Fungal biomass and nitrogen in decomposing Scots pine needle litter. Soil Biol. Biochem. 11: 339-341.

Binkley, D., H. Burnham, and H.L. Allen. 1999. Water quality impacts of forest fertilization with nitrogen and phosphorus. For. Ecol. Manage. 121: 191-213.

Block, R.M.A. and K.C.J. Van Rees. 2004. Characterization of aspen ash, sand and log-yard waste mixtures from an aspen-based oriented strand board mill for use as an intermediate landfill cover. Water Air Soil Pollut. 158: 223-235.

Bormann, B.T., D. Wang, F.H. Bormann, G. Benoit, R. April and M.C. Snyder. 1998. Rapid, plant-induced weathering in an aggrading experimental ecosystem. Biogeochemistry 43: 129-155.

Côté, B., and C. Camiré 1987. Tree growth and nutrient cycling in dense plantings of hybrid poplar and black alder. Can. J. For. Res. 17: 516-523.

Das, D.K. and O.P. Chaturvedi. 2005. Structure and function of *Populus deltoides* agroforestry systems in eastern India: 2. Nutrient dynamics. Agrofor. Syst. 65: 223-230.

Eaton, J.S., G.E. Likens, and F.H. Bormann. 1973. Throughfall and stemflow chemistry in a northern hardwood forest. J. Ecol. 61: 495-508.

Ferrari, J.B. and S. Sugita. 1996. A spatially explicit model of leaf litter fall in hemlock-hardwood forests. Can. J. For. Res. 26: 1905-1913.

Gosz, J.R., G.E. Likens and F.H. Bormann. 1972. Nutrient content of litterfall on Hubbard Brook experimental forest, New Hampshire. Ecology 53: 769-784.

Hendrickson, O.Q., L. Chatarpaul, and D. Burgess. 1989. Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. Can. J. For. Res. 19: 725-735.

Johnson, D.W., J.M. Kelly, W.T. Swank, D.W. Cole, H. Van Miegroet, J.W. Hornbeck, R.S. Pierce, and D. Van Lear. 1988. The effects of leaching and whole-tree harvesting on cation budget of several forests. J. Environ. Qual. 17: 418-424.

Köchy, M., and S.D. Wilson. 1997. Litter decomposition and nitrogen dynamics in aspen forest and mixed grass prairie. Ecology 78: 732-739.

Köchy, M. and S.D. Wilson. 2001. Nitrogen deposition and forest expansion in the northern Great Plains. J. Ecol. 89: 807-817.

Koerner, R.M. and D.E. Daniel. 1997. Water balance analysis. p. 113-157. *In* Koerner, R.M. and D.E. Daniel (Ed.) Final covers for solid waste landfills and abandoned dumps. American Society of Civil Engineers. Thomas Telford Limited. London, UK.

Lee, K.H. and S. Jose. 2005. Nitrate leaching in cottonwood and loblolly pine biomass plantations along a nitrogen fertilization gradient. Agric. Ecosyst. Environ. 105: 615-623.

Levia Jr., D.F. and E.E. Frost. 2003. A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. J. Hydrol. 274: 1-29.

Levia, D.F. Jr., and S.R. Herwitz. 2000. Physical properties of water in relation to stemflow leachate dynamic: implications for nutrient cycling. Can. J. For. Res. 30: 662-666.

Lian, Y., and Q. Zhang. 1998. Conversion of a natural broad-leafed evergreen forest into pure and mixed plantation forests in a subtropical area: effects on nutrient cycling. Can. J. For. Res. 28: 1518-1529.

Likens, G.E., F.H. Bormann, R.S. Pierce, J.S. Eaton and N.M. Johnson. 1977. Biogeochemistry of a Forested Ecosystem. Springer-Verlag.; New York; USA

Lodhiyal, L.S., R.P. Singh, and S.P. Singh. 1994. Productivity and nutrient cycling in poplar stands in central Himalaya, India. Can. J. For. Res. 24: 1199-1209.

Lodhiyal, L.S., R.P. Singh, and S.P. Singh. 1995. Structure and function of an age series of poplar plantations in Central Himalaya. II Nutrient dynamics. Ann. Bot. 76: 201-210.

Lodhiyal, L.S. and N. Lodhiyal. 1997. Nutrient cycling and nutrient use efficiency in short rotation, high density central Himalayan Tarai poplar plantations. Ann. Bot. 79: 517-527.

Lovett, G.M., S.S. Nolan, C.T. Driscoll, and T.J. Fahey. 1996. Factors regulating throughfall flux in a New Hampshire forested landscape. Can. J. For. Res. 26: 2134-2144.

MacDonald, N.W., J.A. Witter, A.J. Burton, K.S. Pregitzer and D.D. Richter. 1993. Relationships among atmospheric deposition, throughfall, and soil properties in oak forest ecosystems. Can. J. For. Res. 23: 2348-2357.

Mahendrappa, M.K. 1983. Chemical characteristics of precipitation and hydrogen input in throughfall and stemflow under some eastern Canadian forest stands. Can. J. For. Res. 13: 948-955.

Melkerud, P.A., D.C. Bain, and M.T. Olsson. 2003. Historical weathering based on chemical analyses of two Spodosols in southern Sweden. Water Air Soil Pollut.: Focus 3: 49-61.

Moore, T.R., J.A. Trofymow, M. Siltanen, C. Prescott, and Cidet Working Group. 2005. Patterns of decomposition and carbon, nitrogen and phosphorus dynamics of litter in upland forest and peatland sites in central Canada. Can. J. For. Res. 35: 133-142.

Mroz, G.D., M.F. Jurgensen and D.J. Frederick. 1985. Soil nutrient changes following whole tree harvesting on three northern hardwood sites. Soil Sci. Soc. Am. J. 49: 1552-1557.

Mudrick, D.A., M. Hoosein, R.R. Hicks Jr. and E.C. Townsend. 1994. Decomposition of leaf litter in an Appalachian forest: effects of leaf species, aspect, slope position and time. For. Ecol. Manage. 68: 231-250.

Nordberg, F. and S. Olsson. 1999. Changes on soil mineralogy and exchangeable cation pools in stands of Norway spruce planted on former pasture land. Plant Soil 207: 219-229.

Olson, J.S. 1963. Energy storage and balance of producers and decomposers in ecological ecosystems. Ecology 44: 322-331.

Parker, G.G. 1983. Throughfall and stemflow in the forest nutrient cycle. Adv. Ecol. Res. 13: 57-133.

Pastor, J. and J.G. Bockheim. 1984. Distribution and cycling of nutrients in an aspen-mixed-hardwood-spodosol ecosystem in northern Wisconsin. Ecology 65: 339-353.

Petersen, E.B., N.M. Peterson, S.W. Simard and J.R. Wang. 1997. Paper birch managers' handbook for British Columbia. B.C. Ministry of Forests, Victoria, B.C.

Piatek, K.B. and H.L. Allen. 1999. Nitrogen mineralization in a pine plantation fifteen years after harvesting and site preparation. Soil Sci. Soc. Am. J. 63: 990-998.

Prescott, C.E. 2005. Decomposition and mineralization of nutrients from litter and humus. p. 15-32. *In* H. Bassirirad (ed.). Nutrient acquisition by plants: an ecological perspective. Ecological Studies series. Springer Verlag, New York, NY.

Prescott, C.E., L.M. Zabek, C.L. Staley, and R. Kabzems. 2000. Decomposition of broadleaf and needle litter in forests of British Columbia: influences of litter type, forest type, and litter mixtures. Can. J. For. Res. 30: 1742-1750.

Ranger, J., and M.P. Turpault. 1999. Input-output nutrient budgets as a diagnostic tool for sustainable forest management. For. Ecol. Manage. 122: 139-154.

Rode, M.W. 1995. Aboveground nutrient cycling and forest development on poor sandy soil. Plant Soil 168-169: 337-343.

Silkworth, D.R. and D.F. Grigal. 1982. Determining and evaluating nutrient losses following whole-tree harvesting of aspen. Soil Sci. Soc. Am. J. 46: 626-631.

Watmough, S.A. and P.J. Dillon. 2003. Base cation and nitrogen budgets for a mixed hardwood catchment in south-central Ontario. Ecosystems 6: 675-693.

Williams, T.M. 1999. Nitrate leaching from intensive fiber production on abandoned agricultural land. For. Ecol. Manage. 122: 41-49.

5. HARVESTING OF HYBRID POPLAR PLANTATIONS: IMPACTS ON LONG-TERM SOIL PRODUCTIVITY

5.1 Introduction

Nutrient budgets have been developed for investigating nutrient loss after harvesting (Silkworth and Grigal, 1982), nutrient uptake and cycling in mature native forests (Pastor and Bockheim, 1984; Forster and Morrison, 1988) and tree plantations (Ranger et al., 1995). The basis for these studies was to determine if there were nutrient imbalances by comparing the nutrient inputs and outputs of the ecosystem. These studies also looked at whether moving to shorter rotations would deplete soil nutrients at the sites. Silkworth and Grigal (1982) suggested that harvesting of aspen forests on reduced rotation lengths could led to nutrient depletion (in their case Ca). Imbalances are typically not sustainable and can be used as the force to change production practices and policy regarding best management practices (Oenema et al., 2003). Imbalances shown from short rotation forestry are caused by nutrients being lost quicker than they can be replaced by natural processes (atmospheric deposition, mineral weathering).

Almost all ecosystem nutrient budgets use inputs from atmospheric deposition (wet and dry) and mineral weathering, and outputs from soil leaching and tree harvest to determine the final balances. Budgets are based on either one-year observations (Silkworth and Grigal, 1982), multi-year measurements (Pastor and Bockheim, 1984) or stand chronosequences. The budgets for this study are based on the data collected over a two-year time period and then projected to a 20-year HP plantation rotation.

The objectives of this chapter were to 1) estimate nutrient budgets for 20-year-old HP plantations grown on the Alfalfa and Pasture sites using the data from chapters 3 and 4; 2) determine the impacts of different harvesting scenarios (stem-only and whole-tree) on the nutrient budget with and without fertilizer additions, and 3) determine the best management practices for the Pasture and Alfalfa sites at Meadow Lake.

5.2 Materials and Methods

5.2.1 Site description, experimental design and plantation establishment

For information on the site description, experimental design and plantation establishment see sections 3.2.1 and 3.2.2.

5.2.2 Soil, tissue and water sampling

For information on the collection and analysis of soil samples, water samples and tissue samples for mineral weathering determination, atmospheric deposition and lysimeter nutrient concentrations, leaf litter and leaf litter decomposition measurements see sections 4.2.2 through 4.2.8.

5.2.3 Nutrient budget data

The numbers that were used as inputs for the nutrient budget were collected from several different sources. All of the flux data that were used in chapter 4 was averaged for the two years of collected data and has been multiplied by 20 to estimate the rotation length inputs. Nutrient budgets were calculated for eight different scenarios with the variables consisting of the harvest type (WTH, SOH), fertilization of N at 100 kg ha^{-1} and site quality (pasture and alfalfa) (Table 5.2). The site quality is indicative of the two sites that the study was carried out on in Meadow Lake, SK., with the Pasture site being low quality, and the Alfalfa site being medium quality.

The data for the bulk deposition, throughfall and stemflow (Table 5.1) was averaged from all of the data taken between May 2004 and October 2005. Added to the data tables for the budget are estimates of dry deposition (DD) and canopy exchange (CE) to show transfers of nutrients within the system. These values are calculated using the sodium adsorption ratio (SAR) equation (Parker, 1983), which separates the extra sodium in throughfall into the two sources (dry deposition and canopy exchange):

$$\text{SAR} = (\text{Na TF} - \text{Na B.dep.}) * ((\text{Na TF} - \text{Na B. dep.}) / \text{Na B. dep.}) \qquad [5.1]$$

Where Na TF is the sodium throughfall and Na B. dep. is the sodium bulk deposition. The DD is equivalent to equation [5.1] and CE can be calculated as 1-DD.

The leaching data from Table 4.8 in section 4.2.7 was separated into two components: year 1 and years 2-20. Year 1 was separated out because of the high leaching rates during that first year and years 2-20 were represented by the flux data from year 2 (assuming that the fluxes are relatively stable for the remainder of the rotation). The four-year-old plantations and seven-year-old plantations could not be compared here to determine if the leaching rates were stable, because in 2005, leachate could not be collected from the seven-year-old plantation. Thus the total leaching flux was the summation of the various fluxes over a 20-year period.

Litterfall is estimated for the 20 years by averaging the amounts of nutrients from the litterfall from the seven-year-old Alfalfa plantation from 2004 and 2005. At 7-years old, it is assumed that the canopy has reached crown closure (Nicolas Bélanger, pers. comm., March, 2006) and that the litterfall is at a steady state for the remainder of the plantation life.

Since there were no 20-year-old HP plantations to obtain biomass and nutrient contents, the amount of nutrients harvested in the biomass was estimated using biomass values from Peterson et al. (1999) and multiplied by nutrient concentrations determined from the tree harvest completed in 2004 for the seven-year-old HP plantation (section 3.2.4). Peterson et al. (1999) calculated biomass estimates for HP trees on the prairies for low, medium and high quality soils to 50 years of age. For the nutrient budgets in this chapter, the tree biomass at 20 years, for low and medium productivity sites, was interpolated from Peterson et al. (1999) data and with the nutrient concentrations from this study the total amount of nutrients in the harvestable biomass was calculated.

The nutrient budget was calculated as the difference between all the inputs and outputs. Harvesting losses were determined by two different scenarios: stem-only (SOH) and whole-tree (WTH) harvesting. The biomass totals for SOH were determined by moving the leaves from an output to an input because the leaves in stem-only harvest remain on the site after harvesting. The final balance of the budgets used the means from all of the components, both inputs and outputs, of the budgets (Table 5.1):

$$\text{Total} = (AD + MW + F) - (\Delta H + L) \quad [5.2]$$

where AD is atmospheric deposition, MW is mineral weathering, F is fertilization, ΔH is harvest (SOH or WTH) and L is leaching.

In Table 5.6 and Appendix H (Table H.1) the ranges of possible budget values were calculated using the means ± standard deviations of the different inputs and outputs. The reason for taking this approach was to show the range of means if the standard deviations are included in the calculations. The equations used for Table 5.6 were as follows:

$$[(AD + s.d. + MW + s.d. + F + s.d.) - (\Delta H - s.d. + L - s.d.)] = \text{total} \quad [5.3]$$

$$[(AD - s.d. + MW - s.d. + F - s.d.) - (\Delta H + s.d. + L + s.d.)] = \text{total} \quad [5.4]$$

and the equations used for Table H.1 in Appendix H were as follows:

$$[(AD + s.d. + MW + s.d. + F + s.d.) - (\Delta H + s.d. + L + s.d.)] = \text{total} \quad [5.5]$$

$$[(AD - s.d. + MW - s.d. + F - s.d.) - (\Delta H - s.d. + L - s.d.)] = \text{total} \quad [5.6]$$

5.3 Results

5.3.1 Atmospheric deposition

Nitrogen and P in the precipitation decreased as they passed through the canopy as throughfall, whereas Ca, Mg, and K all increased after passing through the canopy (Table 5.2). This increase in the base cations is a combination of dry deposition (D.D.) and canopy exchange (C.E.). Stemflow, over the two years, was not a major contributor as an input except for the nutrients K and Ca.

5.3.2 Nutrient budgets

The medium quality site was estimated to have 167 tdm ha^{-1} biomass after 20 years and the low quality site was estimated to have 133 tdm ha^{-1} biomass after 20 years based on the projections from Peterson et al. (1999). Scenarios 1 and 2 represent the impact of WTH and SOH, respectively on the medium quality site without fertilizer while scenarios 3 and 4 are for the medium quality site with fertilizer additions (Table 5.3). Scenario 1 with WTH showed that there would be very high losses in N (425.8 kg ha^{-1}), P (64.3 kg ha^{-1}) and K (335.8 kg ha^{-1}) over the

Table 5.1 A table indicating the different factors that separate the different scenarios

Scenario	**Factors** Fertilizer	No Fertilizer	WTH†	SOH‡	Med. Q§	Low Q.
1		**x**	**x**		**x**	
2		**x**		**x**	**x**	
3	**x**		**x**		**x**	
4	**x**			**x**	**x**	
5		**x**	**x**			**x**
6		**x**		**x**		**x**
7	**x**		**x**			**x**
8	**x**			**x**		**x**

† Whole-tree harvesting
‡ Stem-only harvesting
§ Quality

Table 5.2. Average nutrient fluxes (2004-2005) for bulk deposition, throughfall and stemflow in an seven-year-old hybrid poplar plantation

Element	Deposition Type	2004-2005 Alfalfa	2004-2005 Pasture
		--------------------------kg ha^{-1} yr^{-1}--------------------------	
NO_3	Bulk	1.78 ± 0.72	1.64 ± 0.53
	Throughfall	1.33 ± 0.51	1.66 ± 0.77
	Stemflow	0.01 ± 0.00	0.01 ± 0.00
NH_4	Bulk	6.78 ± 5.19	7.76 ± 3.37
	Throughfall	2.23 ± 0.96	2.58 ± 1.02
	Stemflow	0.01 ± 0.00	0.01 ± 0.00
P	Bulk	1.20 ± 0.93	1.55 ± 0.65
	Throughfall	0.47 ± 0.23	0.57 ± 0.42
	Stemflow	0.06 ± 0.07	0.06 ± 0.07
Ca	Bulk	2.70 ± 1.13	2.22 ± 0.81
	Throughfall	4.28 ± 0.97	5.88 ± 3.54
	Stemflow	2.11 ± 1.86	2.11 ± 1.86
Mg	Bulk	0.54 ± 0.24	0.65 ± 0.26
	Throughfall	0.75 ± 0.31	1.09 ± 0.85
	Stemflow	0.61 ± 0.56	0.61 ± 0.56
K	Bulk	4.05 ± 1.55	3.96 ± 0.86
	Throughfall	11.54 ± 4.26	9.70 ± 5.88
	Stemflow	5.66 ± 7.22	5.66 ± 7.22
Na	Bulk	8.89 ± 1.97	8.33 ± 1.83
	Throughfall	9.40 ± 1.42	11.57 ± 1.38
	Stemflow	1.09 ± 0.80	1.09 ± 0.80

20-year rotation, whereas with the SOH N, P, Ca, Mg and K losses were reduced by 190 kg ha^{-1}, 15 kg ha^{-1}, 55 kg ha^{-1}, and 15 kg ha^{-1} and 160 kg ha^{-1}, respectively. The amount of N lost in the WTH scenario represents 141% of the available N present in the soil at the beginning of the study, and the loss of N in the SOH (234.7 kg ha^{-1}) represents 77% of what was available at the beginning of the study. The loss of Ca, Mg, and K in the two harvesting scenarios, however, represents only a small proportion of the total soil nutrient pool measured at the beginning of the study.

The addition of N fertilizer resulted in both the WTH and SOH (scenarios 3 and 4) having reduced losses of N compared to scenarios 1 and 2 (Table 5.3). Although the fertilizer reduced the N loss, the difference between the fertilized and unfertilized scenarios, were not as large as would be expected because the fertilized scenarios had greater N leaching losses than the unfertilized scenarios (Table 5.3). The loss of Ca was larger in scenarios 3 and 4 than that for the unfertilized scenario due to the higher leaching losses resulting from fertilization. There was little change in the harvesting losses for P, Ca and Mg with the addition of fertilizer compared to no fertilizer additions.

Scenarios 5 and 6 represent nutrient budgets for the low quality site with no fertilizer additions (Table 5.4). The largest difference between the low quality site scenario and the medium quality site scenarios is the nutrient sequestration in the tree biomass. The low quality Pasture site sequestered 80% less N, P, Ca, Mg and K in the biomass relative to the medium quality Alfalfa site. The lower amounts of nutrients sequestered in the tree resulted in smaller losses after harvest with the low quality site than the medium quality site. Losses were observed with WTH for N (187.1 kg ha^{-1}), P (43.0 kg ha^{-1}) and K (242.6 kg ha^{-1}); however, gains were observed for Ca (195 kg ha^{-1}) and Mg (7.6 kg ha^{-1}). With SOH, the losses of N were reduced to 22%, P losses by 29%, and K losses were reduced to 4% while gains for Ca and Mg were similar to those of WTH (Table 5.4).

The last scenarios using the low quality site with fertilizer additions had the lowest nutrient losses of all the scenarios with WTH losing 157.8 kg ha^{-1} N, 40.4 kg

Table 5.3 Nutrient budget for soils and tree biomass for a medium quality alfalfa 20-year-old HP plantation with WTH, SOH and with or without fertilizer

Site	Component	N	P	Ca	Mg	K
		--------kg ha^{-1}--------				
Baseline Data						
Soil (1.2 m)		302.9	134.4	22485	5227	1961
Tree Roots		111.3	51.9	80.0	23.2	190.7
Inputs						
Fertilization		100.0	-----	-----	-----	-----
A.D.	B.D.	171.2	24.0	54.0	10.8	81.0
	D.D.	0.0	0.0	12.0	1.6	59.7
	Stemflow	0.3	1.2	42.2	12.2	126.2
Mineral Weathering[†]		-----	2.6	423.2	77.0	24.0
Transfers						
C.E. [‡]		(100.0)[§]	(14.6)	19.6	2.6	92.8
Litterfall		376.0	56.0	370.0	94.0	776.0
Outputs						
Tree Harvest						
	Leaves[¶]	95.6	8.0	27.5	8.2	80.3
	Wood	328.9	83.9	348.3	83.7	544.2
Leaching w/o fert						
	Year 1	74.1	0.2	87.1	30.5	0.7
	Remaining years	98.7	0.0	162.6	48.6	1.5
Leaching w/ fert						
	Year 1	93.1	0.0	107.5	23.3	2.8
	Remaining years	129.2	0.0	200.7	51.2	1.9
Balance						
Scenario						
(1) Whole-tree Harvest		**(425.8)**	**(64.3)**	**(93.5)**	**(69.4)**	**(335.8)**
(2) Stem-only Harvest		**(234.7)**	**(48.4)**	**(38.5)**	**(53.1)**	**(175.2)**
With Fertilization						
(3) Whole-tree Harvest		**(375.7)**	**(64.2)**	**(152.0)**	**(64.8)**	**(338.1)**
(4) Stem-only Harvest		**(184.6)**	**(58.2)**	**(96.9)**	**(48.5)**	**(177.5)**

[¶] In stem-only harvest the leaves would be considered an input in year 20 because they would be left on the site as green leaves

[†] N weathering cannot be measured

[‡] C.E. is described in section 5.2.3

[§] () indicate negative values

Table 5.4 Nutrient budget for a poor quality pasture 20-year-old HP plantation with WTH, SOH and with or without fertilizer

Site	Component	N‡	P	Ca	Mg	K
		--	kg ha^{-1}	----------------------------------		
Baseline Data						
Pasture Soil (1.2 m)		257.0	94.7	20439	10895	2068
Tree Roots		89.0	41.5	64.0	18.6	152.6
Inputs						
Fertilization		100.0	-----	-----	-----	-----
A.D.	B.D.	188.0	30.9	44.4	12.9	79.2
	D.D.	0.0	0.0	29.2	3.5	45.8
	Stemflow	0.3	1.2	42.3	12.2	126.1
Mineral Weathering†		-----	2.6	423.2	78.0	24.0
Transfers						
C.E.‡		(103.2)§	(19.6)	44.0	5.3	69.0
Litterfall		376.0	56.0	370.0	94.0	776.0
Outputs						
Tree Harvest						
	Leaves	95.6	8.0	27.5	8.2	80.3
	Wood	263.1	67.1	278.7	67.0	435.4
Leaching w/o fert						
	Year 1	7.9	0.0	12.0	13.1	0.7
	Remaining years	8.8	0.0	25.3	9.8	1.3
Leaching w/ fert						
	Year 1	70.2	0.0	53.2	22.2	1.0
	Remaining years	17.2	0.0	34.9	12.9	1.6
Balance						
Scenario						
(5) Whole-tree Harvest		**(187.1)**	**(40.4)**	**195.6**	**7.6**	**(242.6)**
(6) Stem-only Harvest		**(66.7)**	**(24.4)**	**199.9**	**11.7**	**(82.5)**
With Fertilization						
(7) Whole-tree Harvest		**(157.8)**	**(40.4)**	**144.8**	**(4.6)**	**(243.1)**
(8) Stem-only Harvest		**104.0**	**(24.4)**	**250.6**	**23.9**	**(81.9)**

***** In stem-only harvest the leaves would be considered an input in year 20 because they would be left on the site as green leaves

† N weathering cannot be measured

‡ C.E. is described in section 5.2.3

§ () indicate negative values

ha^{-1} P, 4.6 kg ha^{-1} Mg, and 243.1 kg ha^{-1} K with Ca gaining 144.8 kg ha^{-1}. The addition of fertilizer did not result in a direct 100 kg ha^{-1} increase in N, as the N leaching losses again increased with the fertilizer addition. Leaching losses of Ca and Mg also increased with the fertilizer addition compared to the unfertilized treatment (Table 5.4). The SOH with added fertilizer was the only scenario to show a gain in N (104 kg ha^{-1}) along with gains in Mg and Ca (23.9 and 250 kg ha^{-1}, respectively); however, losses were observed for P (24.4 kg ha^{-1}) and K (81.9 kg ha^{-1}). The final rankings for the scenarios for all nutrients are shown in Table 5.5 from best to worst (left to right, respectively).

Table 5.6 shows the range of values of gains and losses that could also occur with the budgets if the standard deviations of all of the different components were taken into account either added to the means or subtracted from the means. Appendix H also shows a range of values around the mean that would be considered extreme cases.

5.4 Discussion

5.4.1 Nutrient budget

With the growing interest in establishing HP in Saskatchewan, there is a need to understand how the fast growth rates and nutrient accumulations by these plantations will impact the long-term productivity of these sites when harvested on shorter rotations of 20 years. This chapter has shown that in most cases there will be substantial losses of nutrients from agricultural sites following harvest of trees especially when WTH is employed. The eight different scenarios that were presented in Tables 5.2 and 5.3 showed that the smallest amount of nutrients exported off of the sites occurred with SOH. Therefore, external inputs will likely be needed in order for these sites to maintain fertility over long time periods, or sites will need to be fallow after harvest to regain lost fertility through natural inputs.

Nitrogen and P losses are high enough to raise concern about the long-term sustainability of these HP plantations. With atmospheric inputs totaling about 9 kg ha^{-1} yr^{-1} (Table 5.1), it would take between 8 and 50 years, depending on the type of plantation management, to replenish the soil N without the use of inorganic

Table 5.5 Final rankings of nutrient loss over 20 years relative to each site scenario. Nutrients that are bolded represent gains over the plantation rotation length.

Site	Harvest Type	Fertilization	Nutrient loss ranking
Alfalfa	WTH	N	N > K > Ca > Mg >P
Alfalfa	SOH	N	N > K > Mg > P > Ca
Alfalfa	WTH	Y	N > K > Ca > P > Mg
Alfalfa	SOH	Y	N > K > Ca > P > Mg
Pasture	WTH	N	K > N > P > **Mg** > **Ca**
Pasture	SOH	N	K > N > P > **Mg** > **Ca**
Pasture	WTH	Y	K > N > P > Mg > **Ca**
Pasture	SOH	Y	K > P > **Mg** > **N** > **Ca**

Table 5.6 Range of gains and losses that budgets could be based on calculations using means +/- standard deviations

Scenario	Range‡	N	P	Ca	Mg	K
		--	----------	kg ha^{-1}	----------	--
Alfalfa, unfertilized	Inputs +, Outputs –	(139.9)†	(50.0)	190.8	22.0	34.3
WTH	Inputs -, Outputs +	(711.8)	(78.7)	(377.8)	(160.8)	(705.9)
Alfalfa, fertilized	Inputs +, Outputs –	(52.0)	(49.7)	174.6	25.4	32.1
WTH	Inputs -, Outputs +	(699.4)	(78.6)	(478.6)	(154.9)	(708.4)
Alfalfa, unfertilized	Inputs +, Outputs –	51.2	(34.0)	245.8	38.3	195.0
SOH	Inputs -, Outputs +	(520.7)	(62.7)	(322.8)	(144.5)	(545.3)
Alfalfa, fertilized	Inputs +, Outputs –	139.1	(33.8)	229.7	41.7	192.8
SOH	Inputs -, Outputs +	(508.3)	(62.7)	423.5)	(138.6)	(547.7)
Pasture, unfertilized	Inputs +, Outputs –	(48.3)	(16.8)	314.4	67.1	79.4
WTH	Inputs -, Outputs +	(330.4)	(64.0)	76.8	(51.9)	(564.5)
Pasture, fertilized	Inputs +, Outputs –	35.7	(16.8)	305.6	52.8	79.3
WTH	Inputs -, Outputs +	(351.3)	(64.0)	(16.0)	(62.0)	(565.5)
Pasture, unfertilized	Inputs +, Outputs –	247.3	(0.8)	369.4	83.4	240.0
SOH	Inputs -, Outputs +	(39.3)	(48.0)	131.8	(35.6)	(403.9)
Pasture, fertilized	Inputs +, Outputs –	126.8	12.1	360.6	69.1	239.9
SOH	Inputs -, Outputs +	(260.1)	(48.0)	39.1	(45.7)	(404.9)

‡ Range is the values around the mean calculated by adding and subtracting standard deviation

† ( ) indicates negative values

fertilizers. Neither mineral weathering nor atmospheric deposition adds appreciably to the P pool; thus, it would require some type of fertilizer amendment to replenish the losses. Calcium, Mg, and K losses from harvesting a 20-year-old plantations represent a much smaller percentage of the total available nutrients in the soil (Tables 5.2 and 5.3). Even though these nutrients have large soil reserves, it would still take between 3-5 years to replenish Ca, 1-10 years to replenish Mg and 6 – 26 years to replenish K, depending on the site management practices before and after harvest.

While all scenarios experienced some losses, there is the potential for increased losses of nutrients several years after the harvest has taken place. Silkworth and Grigal (1982), using a balance-sheet approach, found that there was accelerated leaching of Ca for five years after harvest, while N, P, K, and Mg losses were less than inputs from atmospheric deposition and weathering. There is potential for greater losses after harvest than what was seen in this study. Nitrogen showed high leaching losses in the first year of the study, which was a product of both the previous site history (alfalfa stubble left high nitrogen levels in the soil), reduced tree growth and uptake caused by drought, which combined with the high inorganic N levels left by the alfalfa to conditions favoring N leaching with increased precipitation.

The loss of nutrients can be compounded by the type of harvesting practice where WTH will export all nutrients off-site at harvest time, whereas SOH will leave branches add leaves on site that are nutrient rich. Silkworth and Grigal (1982) found that leaving the leaves (aspen) on site during harvest reduced N and P losses by 10%. In this study, the savings were much greater for SOH over WTH with up to 50% savings in N and about 20% savings in P at the alfalfa site and N savings of 60% (actual site increases in scenario 8) and ~40% for P at the pasture site.

Hybrid poplars are very effective at retaining N, Ca and K as observed by the nutrients immobilized in the tree biomass in this study. Alban (1982) and Pastor and Bockheim (1984) concluded similar findings with N and Ca, but to a lesser extent with K on Aspen trees. This effective retention of nutrients, while good for the growing tree, is not good for the growing site's long-term sustainability as the vast majority of the nutrients held in the tree biomass (bole) are exported off site for harvest purposes. Both WTH and SOH will export the same amount of bolewood off of a site, so there is no advantage to one harvest method over another with regards to exporting bolewood nutrients.

While the scenarios for the Pasture site exported the least amount of nutrients, this site also exported smaller amounts of merchantable biomass. In this respect, a balance needs to be struck between productivity and sustainability where the most production is gained from the least amount of nutrient loss. The value of the wood would need to outweigh the increased cost of fertilization, with urea fertilizer at \$520 tonne^{-1} as of Feb., 2007 (Personal Communication, Darren Camm P.Ag., Agricore United). With this in mind, the eight scenarios with nutrient loss and productivity as the main factors in determining a quality production method are ranked in terms of best to worst: 4 > 2 > 8 > 6 > 3 > 1 > 7 > 5. The general trend in this ranking is that the SOH scenarios (2, 4, 6, 8) are better than the WTH scenarios (1, 3, 5, 7), the value of the extra production of the medium quality sites outweighs the costs of its losses, and fertilized scenarios are better than the unfertilized.

5.5 Conclusions

The budgets produced for this chapter show how the productivity of the sites and the type of harvest practices affect the nutrients exported off of a site and the balances of nutrients after a 20-year rotation. The greatest nutrient export occurred with the medium quality sites using WTH, and the smallest export of nutrients occurred with the low quality sites using SOH and fertilizer additions. Based on the values that were found for losses in Tables 5.2-5.3, the time it would take to replenish nutrients would be: Nitrogen (8 – 50 yr), P (30-50 yr), K (6 – 23 yr), Ca (2 – 6 yr) and Mg (9 – 14 yr).

The replenishment of site fertility by natural occurrences is more desirable than fertilization because of the costs associated with fertilization, both economic and ecological (Ranger and Turpault, 1999). This replenishment could be sped up with subsequent crops grown on the sites such as atmospheric N fixing crops such as alfalfa or application of organic wastewaters and manures (Mitchell et al., 1999).

The production of HP requires large amount of nutrients from the soil. The inputs from atmospheric deposition, mineral weathering and fertilizers would cancel a large proportion of the outputs from leaching and harvest, but not all, as most of the scenarios in Tables 5.2 and 5.3 show losses of N, P, Ca, Mg, and K. From analyzing the rankings of the different scenarios discussed in section 5.5.1 it can be concluded that the best management practices for the production of HP include fertilizing with nitrogen and using SOH to reduce the amount of nutrients exported off of the sites with the branch and leaf biomass thereby taking the most marketable products for sale (bolewood) and leaving the slash residue and its nutrients on site.

5.6 References

Alban, D.H. 1982. Effects of nutrient accumulation by aspen, spruce, and pine on soil properties. Soil Sci. Soc. Am. J. 46: 853-861.

Camiré, C. and Brazeau, M. 1998. Cultures des genres Populus et Larix au Québec: sols, exigences nutritionnelles et productivité. Report # C-122. Ministère des ressources naturelles, Direction de l'environnement forestier., Québec.

Mitchell, C.P., E.A. Stevens and M.P. Watters. Short-rotation forestry – operations, productivity and costs based on experience gained in the UK. For. Ecol. Manage. 121: 123-136.

Oenema, O., H. Kros, W. de Vries. 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental; policies. Europ. J. Agron. 20: 3-16.

Parker, G.G. 1983. Throughfall and stemflow in the forest nutrient cycle. Adv. Ecol. Res. 13: 57-133.

Pastor, J. and J.G. Bockheim. 1984. Distribution and cycling of nutrients in an aspen-mixed-hardwood-spodosol ecosystem in northern Wisconsin. Ecology 65: 339-353.

Peterson, E.B., G.M. Bonnor, G.C. Robinson, and N.M. Peterson. 1999. Carbon Sequestration aspects of an afforestation program in Canada's prairie provinces. Nawitka Renewable Resource Consultants, Victoria, B.C., Canada.

Ranger, J., R. Marques, M. Colin-Belgrand, N. Flammang and D. Gelhaye. 1995. The dynamics of biomass and nutrient accumulation in a Douglas-fir (*Pseudotsuga menziesii* Franco) stand studied using a chronosequence approach. For. Ecol. Manage. 72: 167-183.

Silkworth, D.R. and D.F. Grigal. 1982. Determining and evaluating nutrient losses following whole-tree harvesting of aspen. Soil Sci. Soc. Am. J. 46: 626-631.

6.0 GENERAL SUMMARY AND CONCLUSIONS

A nutrient cycling and budgeting study was established to investigate the effects of site quality, fertilization and harvest type on tree growth and site sustainability. Two sites (Alfalfa and Pasture) with four-year-old trees and one site with seven-year-old trees (Alfalfa) were sampled for baseline soils data (total C, extractable N, P, K, Ca, Mg), tree growth parameters (height, diameter), and tree biomass. Nutrient cycling in these plantations was also measured by assessing input (atmospheric deposition, mineral weathering) and output fluxes (leaching, harvest) for both the Alfalfa and Pasture sites. The fluxes that were determined for the sites were used to estimate 20-year totals for the individual sites to be used in budgets, and the budgets constructed gave a reasonable estimation of the site's ability to sustain HP plantations and the nutrient losses that the sites incurred.

Investigation of the tree growth parameters showed that the Alfalfa site had significantly larger trees than the Pasture site in the four-year-old plantations, but fertilizer additions did nothing to increase growth. The trees in the four-year-old Alfalfa plantations, both fertilized and unfertilized, contained more N, P, Ca, Mg and K ha^{-1} than the four-year-old trees at the Pasture plantation. The Alfalfa site had more available soil N and P (302.9 and 134.4 kg ha^{-1}, respectively) than the Pasture site (257.0 and 94.7 kg ha^{-1}, respectively), which is likely reflected in the tree growth and immobilization figures.

Nutrient fluxes were examined in the two four-year-old plantations as well as the seven-year-old plantation at the Alfalfa site. One of the most interesting findings was the leaf litter decomposition results which showed that the four-year-old plantations both had slower initial decomposition rates than the seven-year-old plantation and the adjacent aspen forest stand, but caught up in decomposition by the third year of the litterbag study. Nitrogen content of the leaf litter in the decomposition study also showed a surprising increase in the first year of decomposition (Figures 4.4 and 4.5), while P showed a slow steady decline and Ca, Mg and K all showed sharp early declines in content. The atmospheric deposition flux showed an average of roughly 9 kg ha^{-1} yr^{-1} N being added (as NO_3^- and NH_4^+) to the sites in both 2004 and 2005. Leaching of N was extremely high in 2004 (Table 4.8), likely due to the drought years in 2002 and 2003 combined with high soil N followed by very high precipitation in 2004, leaching the N through the HP root zone.

From the data collected for the nutrient cycling study, 20-year estimates of the total inputs and outputs for low and medium quality sites were produced, and from those nutrient budgets were constructed. The budgets showed that whole-tree harvest (WTH) exported much more N, P, Ca, Mg and K off of sites than stem-only harvest (SOH), and also showed that because of greater biomass production, medium quality sites export much more nutrients off of sites compared to low quality sites.

Table 6.1 (Paré et al., 2002) shows a rating for N, P, Ca, Mg and K for each scenario examined in chapter five regarding the export losses that would be expected for each management type (harvest and fertilization). It shows that the WTH scenarios generally receive poor ratings for export losses for N and K while SOH scenarios receive either medium or good ratings indicating low losses or even gains. The ratings were given based on the amount of gains or losses from the site relative to what was stored in the soil at the beginning of the study. So while the losses of Ca may be relatively high compared to P, they are not a large proportion of the exchangeable Ca in the soil.

These ratings do not take into account the amount of merchantable wood produced from the site. From an ecological perspective the scenarios rated as poor due to high losses would be unacceptable, but from a production standpoint, some producers and foresters may look at them differently if the cost of fertilizing to replace lost nutrients is less than the profits made from the more extensive harvest practices.

Growing trees on higher quality sites will yield more biomass than other sites and regardless of losses these sites are the best for production of HP. The nutrients lost can be replaced by fallowing the sites before putting them back into intensive production again: N fixing perennial crops could be established prior to tree planting to increase N faster, and/or have amendments such as manures, wastewaters, or inorganic fertilizers added to the site

As a recommendation for farmers that are choosing to place land into long-term production of HP, the best route is likely to choose the most productive land that they can use, that will bring them the best growth for their trees. Proper management of the HP plantations such as soil fertility management (soil testing, fertilizing), weed control, and stem-only harvesting should be employed to reduce the amount of nutrients lost due to weed uptake, leaching and harvest export.

Future research in the area of HP production and nutrient balances should continue in long-term trials that can better predict final rotation nutrient balances. This would include measurements that were not conducted during this study including nutrient mineralization, nitrogen losses due to volatilization and denitrification, litter turnover times; and measurements that were studied such as atmospheric deposition and leaching. Tree biomass should also be looked at again for the Alfalfa and Pasture sites at maturity to validate or discredit current model predictions of tree growth and nutrient export, and to determine if budget predictions are legitimate.

6.1 Reference

Paré, D. P. Rochon and S. Brais. 2002. Assessing the geochemical balance of managed boreal forests. Ecological Indicators 1: 293-311.

Table 6.1 Ratings of the plantation scenarios based on nutrient export relative to baseline nutrient stocks

Site quality	Harvest Type	Fertilizer	N	P	Ca	Mg	K
Medium	WTH	Fert	■	▩	▩	□	■
	WTH	Unfert	■	▩	▩	□	■
	SOH	Fert	□	▩	▩	□	▩
	SOH	Unfert	▩	▩	□	□	▩
Low	WTH	Fert	■	▩	□	□	■
	WTH	Unfert	■	▩	□	□	■
	SOH	Fert	□	□	□	□	□
	SOH	Unfert	□	□	□	□	□

■ Indicates a poor rating for heavy export losses

▩ Indicates a intermediate rating for medium export losses

□ Indicates a good rating for low losses or nutrient gains

Appendix A

Supplementary Data Showing Plot Design and Treatments at HPA, HPP and OHPA Plantations in Meadow Lake, SK.

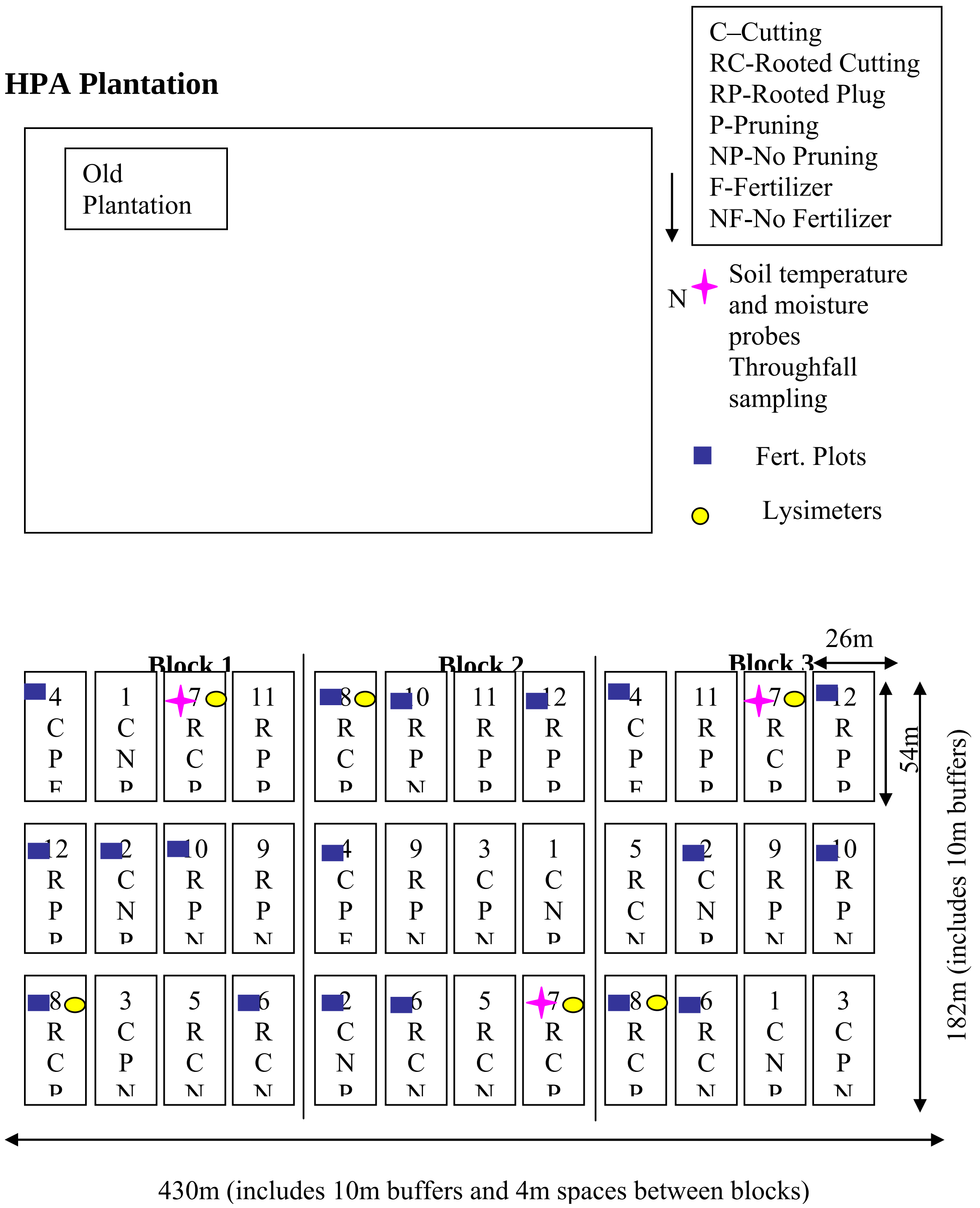

Figure A.1. Plot design for HPA and HPP plantations , as well as plots where measurements will be taken.

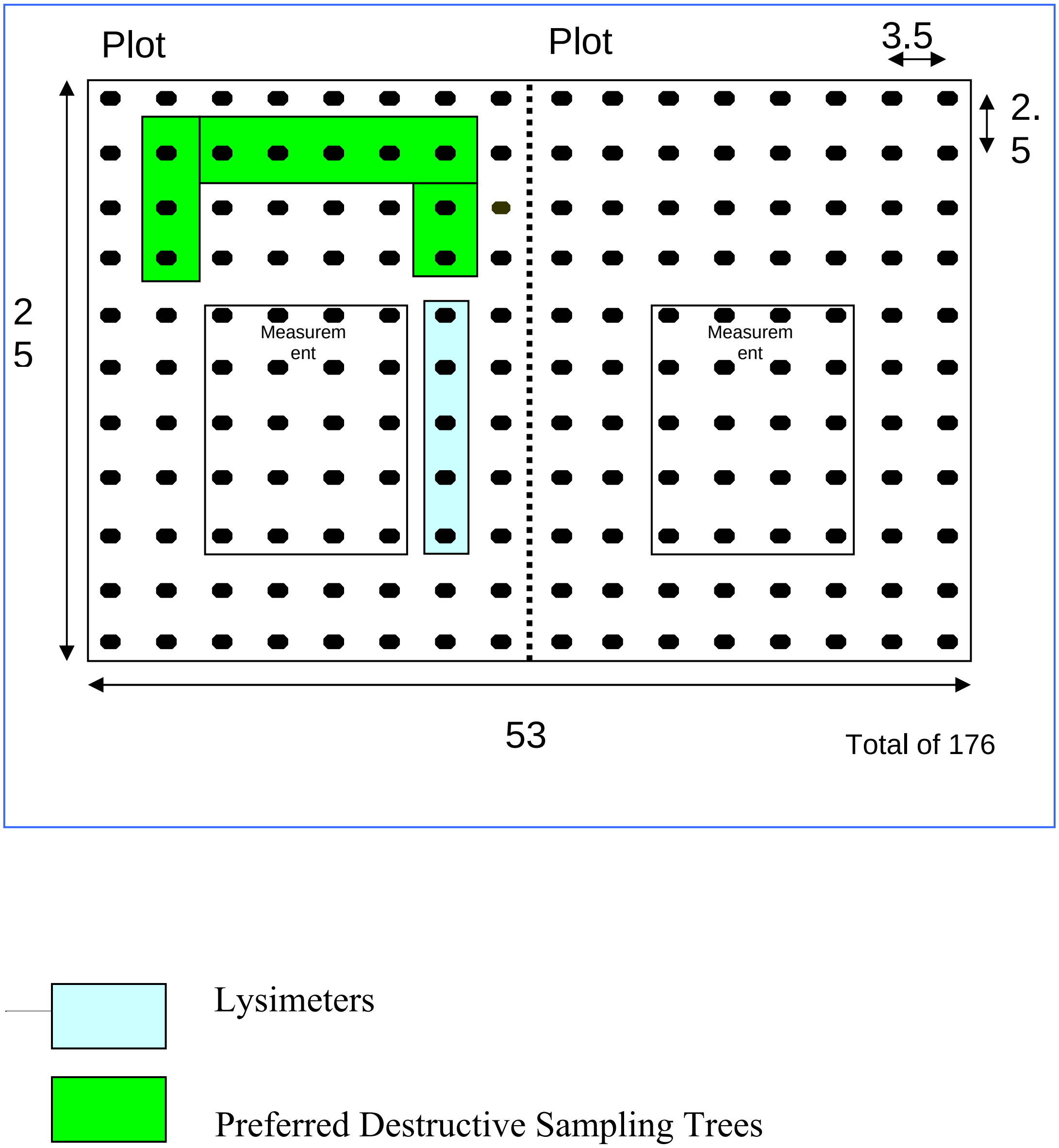

Figure A.2. Individual plot design for plots in HPA and HPP

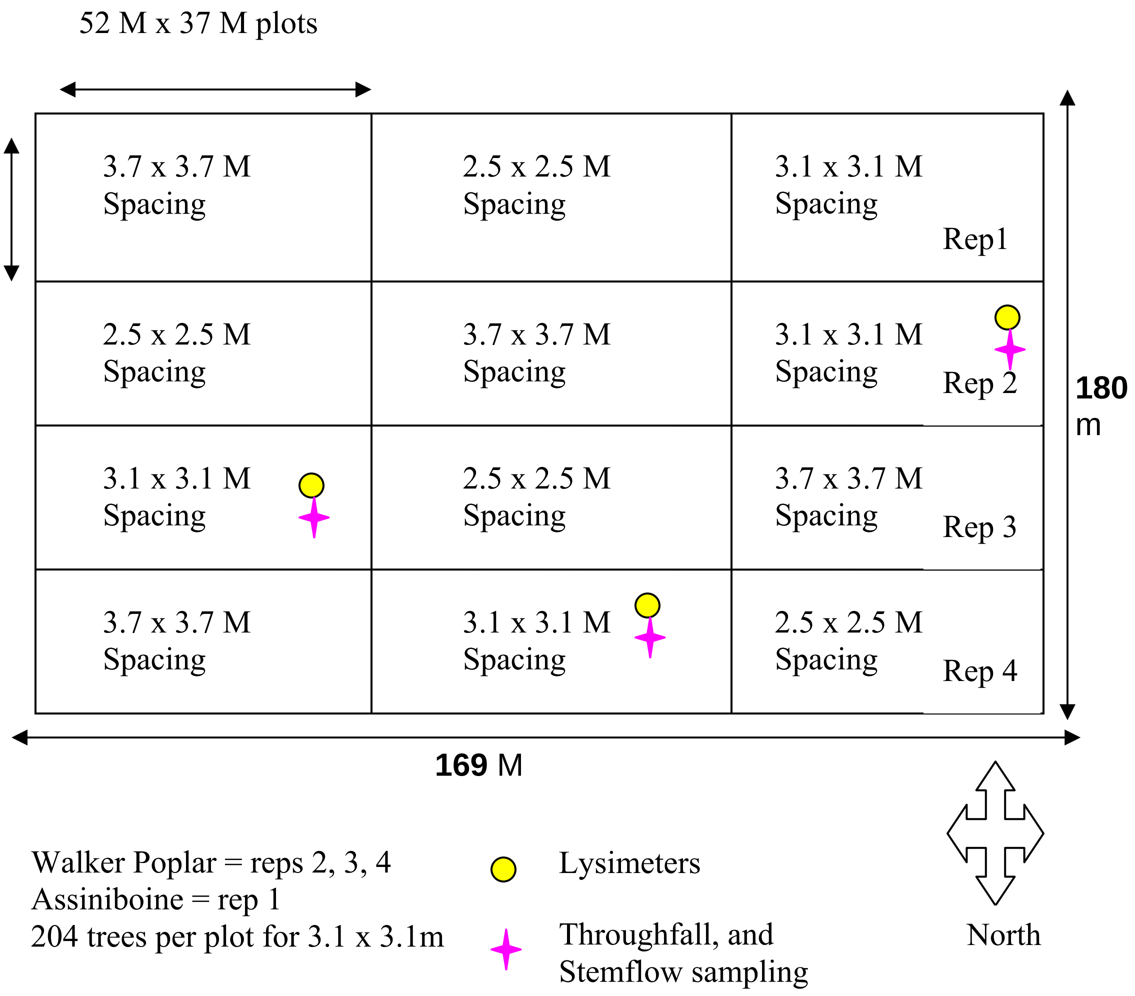

Figure A.3. OHPA plantation design and setup as well as plots were measurements and sampling will take place.

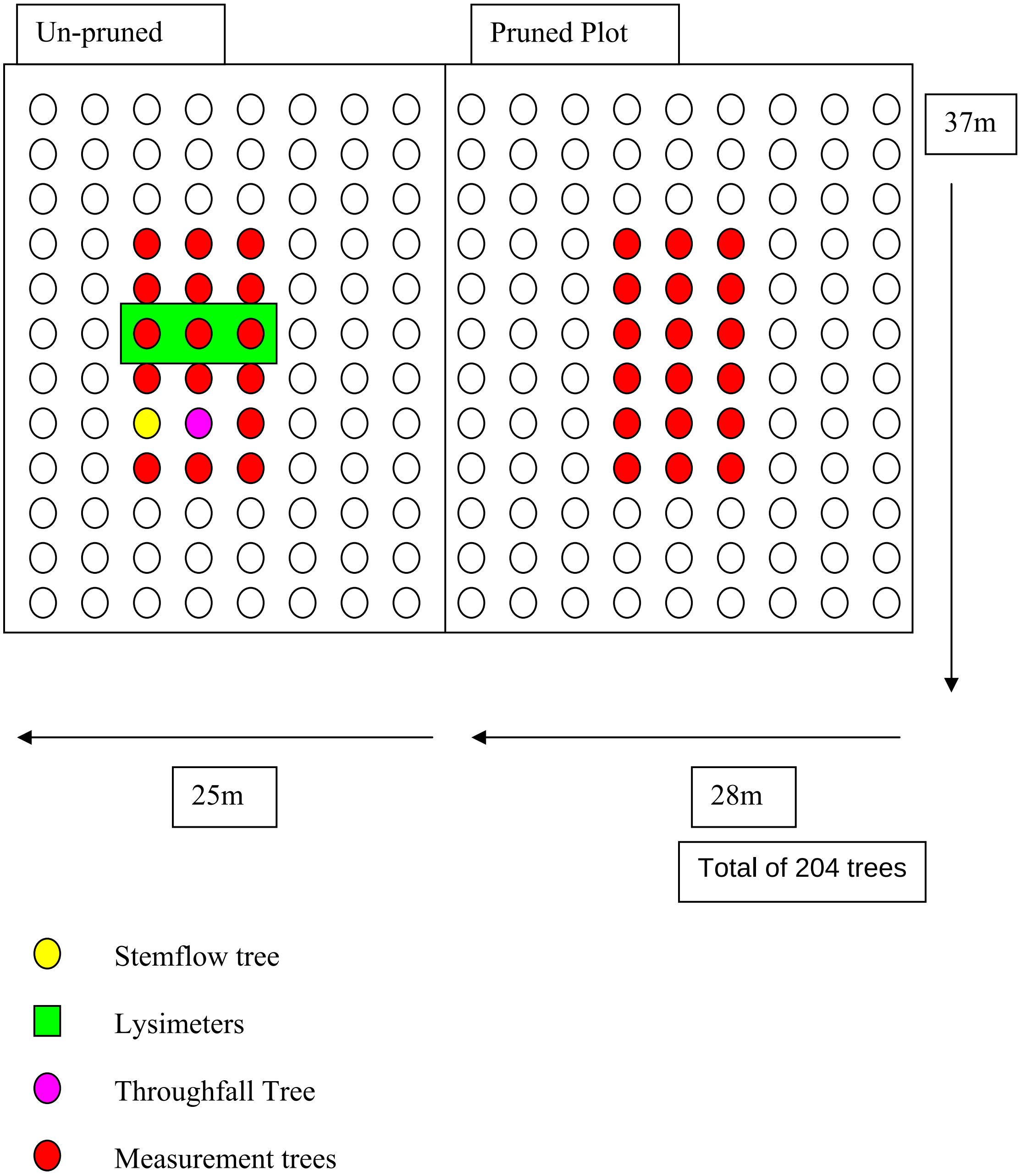

Figure A.4. Individual plot design for plots in OHPA plantation.

Appendix B

Supplementary Data for Soil Properties Measured at the HPA, HPP and OHPA Plantations in Meadow Lake, SK.

Table B.1. Soil exchangeable nutrients from 0-60 (10 cm increments) and 60-120 (20 cm increments) for the HPA, HPP, and OHPA plantations from soil collected in 2004.

Site	Depth	NO_3	NH_4	P	Ca	Mg	K	Na
		---kg ha^{-1}---						
4-y.o. Alfalfa	0-10cm	69.4	5.5	44.6	961	85	280	221
	10-20cm	31.8	3.4	18.1	1237	119	134	240
	20-30cm	28.9	3.8	8.9	2476	358	184	268
	30-40cm	25.4	5.0	8.3	2670	507	197	256
	40-50cm	20.3	4.0	6.1	2312	490	158	2323
	50-60cm	15.3	3.8	6.8	2273	510	155	228
	60-80cm	26.7	6.5	14.7	5222	1062	304	481
	80-100cm	20.5	7.8	14.9	2729	1075	280	487
	100-120cm	17.6	7.0	11.9	2602	1023	269	481
4-y.o. Pasture	0-10cm	25.8	3.9	17.8	1464	198	202	207
	10-20cm	21.5	3.0	5.6	1132	191	102	211
	20-30cm	25.6	4.9	5.9	1250	405	128	255
	30-40cm	24.2	6.6	4.9	2025	836	184	350
	40-50cm	21.7	5.1	5.2	2175	1043	198	405
	50-60cm	16.8	5.0	10.5	2127	1128	186	454
	60-80cm	27.0	8.3	7.7	4802	2534	388	1004
	80-100cm	21.8	8.8	9.6	2662	2382	350	858
	100-120cm	17.6	9.2	27.7	2798	2179	330	815
7-y.o. Alfalfa	0-10 cm	4.3	5.5	38.1	1019	121	236	199
	10-20 cm	4.4	4.2	25.3	1535	283	185	194
	20-30 cm	4.2	4.5	13.1	2887	799	258	309
	30-40 cm	4.7	6.1	9.9	2563	917	230	298
	40-50 cm	4.6	8.9	12.2	2506	885	248	334
	50-60 cm	4.9	8.4	12.1	2780	1105	223	307
	60-80 cm	9.8	16.4	25.8	6631	1938	436	541
	80-100 cm	7.8	13.9	18.4	3368	1950	429	643
	100-120 cm	8.6	11.9	18.7	2903	1493	350	550

Appendix C

Supplementary Data for Plant Tissue Nutrient Concentrations at the HPA, HPP and OHPA Plantations in Meadow Lake, SK.

Table C.1. Mean nutrient concentrations of tree components (± Standard Deviation) for N, P, Ca, Mg and K at the HPA and HPP sites in both fertilized and unfertilized treatments.

Component	Element	Alfalfa		Pasture	
		Fertilized	Unfertilized	Fertilized	Unfertilized
		---------------------------10^3 µg g	---------------------------		
Bark					
	N	12.2±3.2	14.2±3.7	10.9±2.8	10.2±2.7
	P	1.2±0.5	1.4±0.7	1.1±0.5	1.2±0.4
	Ca	5.2±0.8	5.1±1.0	4.6±0.8	4.7±0.6
	Mg	1.6±0.3	1.8±0.5	1.7±0.3	1.6±0.2
	K	11.7±2.6	11.5±3.6	9.8±2.7	10.6±3.1
Bole					
	N	3.9±3.1	5.0±4.4	2.6±1.9	2.4±1.2
	P	0.6±0.5	0.9±1.0	0.5±0.3	0.5±0.3
	Ca	1.0±0.3	0.9±0.3	0.9±0.2	1.0±0.3
	Mg	0.8±0.1	1.0±0.4	0.8±0.1	0.7±0.1
	K	7.1±3.6	7.5±4.2	5.2±1.6	5.3±1.6
Branches					
	N	9.4±2.3	10.2±2.5	9.5±2.5	9.0±3.5
	P	1.5±0.5	1.7±0.5	1.7±0.5	1.5±0.6
	Ca	3.8±1.0	3.7±1.1	3.3±1.2	3.2±0.9
	Mg	1.5±0.1	1.5±0.2	1.8±0.2	1.6±0.2
	K	13.9±3.2	14.1±3.9	13.2±2.8	11.6±2.7
Leaves					
	N	34.2±2.3	35.1±2.6	28.5±2.9	30.4±2.7
	P	2.2±0.5	2.4±0.7	2.2±0.5	2.3±0.4
	Ca	4.0±1.0	4.1±1.3	4.2±1.1	4.3±1.1
	Mg	1.6±0.2	1.8±0.4	2.1±0.4	2.1±0.4
	K	23.0±2.6	20.4±4.0	18.4±3.0	17.8±3.3
Roots					
	N	12.1±0.3	14.5±0.7	12.3±1.4	11.0±2.2
	P	1.9±0.6	1.6±0.2	1.7±0.3	1.8±0.6
	Ca	3.6±0.3	3.8±0.1	3.1±0.4	3.5±0.2
	Mg	1.3±0.1	1.3±0.1	1.2±0.1	1.2±0.2
	K	14.7±2.5	12.5±2.3	12.5±4.6	10.8±3.9

Appendix D

Supplementary Data and Setup Pictures for Atmospheric Deposition, Throughfall and Stemflow at the HPA, HPP and OHPA Plantations in Meadow Lake, SK.

Figure D.1. Throughfall collector mounted on 1 m high fencepost under a four-year-old tree at the Pasture site in May, 2004 (left) and underneath a seven-year-old tree at the Alfalfa site in June, 2004 (right).

Figure D.2. Stemflow collection installation on the bole of a seven-year-old tree in the Alfalfa plantation. The tubing was nailed and stapled to the tree (top left and right) and then caulked so no gap existed between the tree and the tubing (bottom left) and then attached to a 10 L plastic container to collect the stemflow solution (bottom right).

Table D.1. Mean atmospheric deposition nutrient concentrations (± standard deviation) which includes bulk deposition (BDep), throughfall (TF) and stemflow (SF) for 2004 and 2005 for HPA and HPP plantations.

Element	Atmos. Dep.	HPA	HPP	HPA	HPP
		-----------2004-----------		------------2005-----------	
		---------------------------mg L^{-1}	---------------------------		
NO_3	BDep	0.95 ± 0.82	1.00 ± 1.33	0.73 ± 0.98	0.54 ± 0.46
	TF	0.89 ± 0.84	0.63 ± 1.20	0.35 ± 0.19	0.69 ± 1.25
	SF	0.40 ± 1.15	0.40 ± 1.15	0.12 ± 0.11	0.12 ± 0.11
NH_4	BDep	2.64 ± 5.04	4.63 ± 6.56	2.13 ± 3.28	4.00 ± 9.16
	TF	1.60 ± 2.48	1.47 ± 4.47	1.05 ± 1.94	0.87 ± 1.48
	SF	0.44 ± 1.16	0.44 ± 1.16	0.10 ± 0.16	0.10 ± 0.16
P	BDep	0.45 ± 0.87	1.30 ± 2.20	0.41 ± 0.84	0.77 ± 2.33
	TF	0.35 ± 0.63	0.25 ± 0.62	0.21 ± 0.38	0.28 ± 0.60
	SF	0.47 ± 0.54	0.47 ± 0.54	0.11 ± 0.11	0.11 ± 0.11
Ca	BDep	1.71 ± 0.76	1.63 ± 0.61	0.62 ± 0.49	0.53 ± 0.35
	TF	3.02 ± 2.82	2.61 ± 2.45	1.24 ± 1.06	1.61 ± 2.73
	SF	13.5 ± 10.4	13.5 ± 10.4	7.65 ± 5.86	7.65 ± 5.86
Mg	BDep	0.24 ± 0.22	0.47 ± 0.58	0.21 ± 0.16	0.27 ± 0.32
	TF	0.40 ± 0.41	0.53 ± 0.95	0.33 ± 0.24	0.45 ± 0.59
	SF	3.97 ± 3.09	3.97 ± 3.09	2.11 ± 1.61	2.11 ± 1.61
K	BDep	1.60 ± 2.07	2.87 ± 2.98	1.49 ± 1.74	1.68 ± 3.49
	TF	5.89 ± 7.51	10.8 ± 34.4	4.76 ± 5.09	4.16 ± 6.06
	SF	38.4 ± 41.4	38.4 ± 41.4	21.3 ± 21.0	21.3 ± 21.0
Na	BDep	3.54 ± 1.20	3.47 ± 1.47	3.04 ± 0.83	2.83 ± 0.79
	TF	4.17 ± 1.54	3.83 ± 1.40	3.07 ± 1.25	2.96 ± 1.18
	SF	3.92 ± 0.98	3.92 ± 0.98	2.77 ± 1.04	2.77 ± 1.04

Appendix E

Supplementary Data for 2004 Temperature and Rainfall at the HPA, HPP and OHPA Plantations at Meadow Lake, SK.

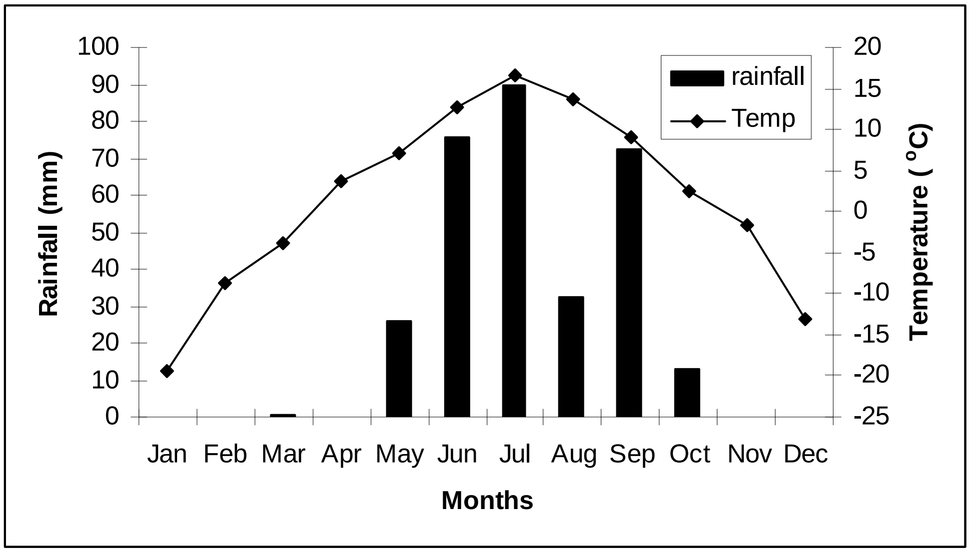

Figure E.1. Monthly rainfall (mm) and average air temperature (°C) at the HPA Plantation in 2004

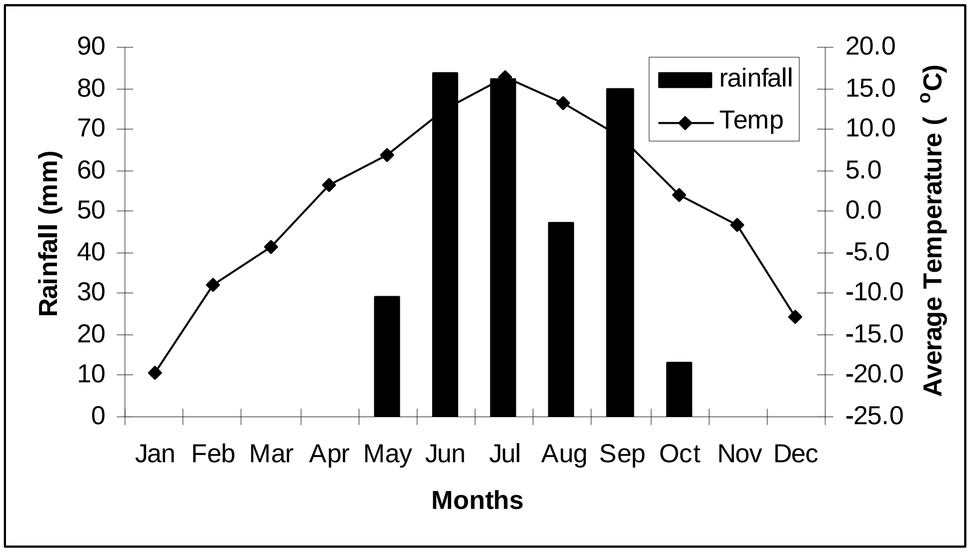

Figure E.2. Monthly rainfall (mm) and average air temperature (°C) at the HPP Plantation in 2004

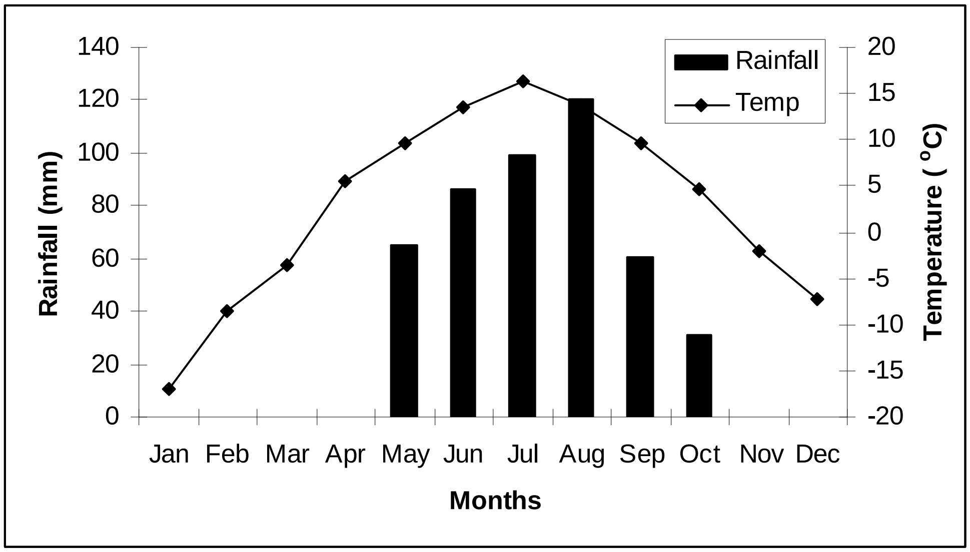

Figure E.3. Monthly rainfall (mm) and average air temperature (^{o}C) at the HPA Plantation in 2005

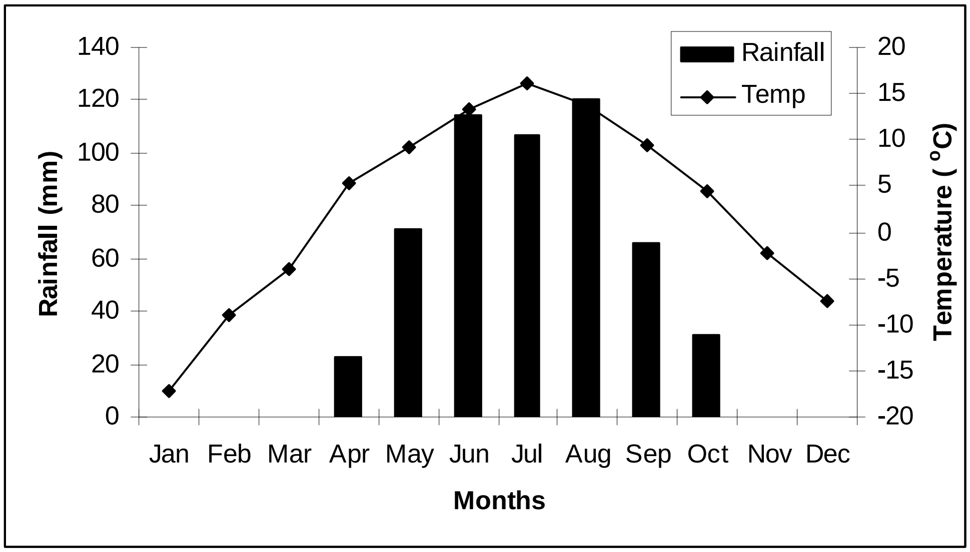

Figure E.4. Monthly rainfall (mm) and average air temperature (^{o}C) at the HPP Plantation in 2005

Appendix F

Supplementary Data for Soil Leachate Concentrations at 20cm at both the HPA, HPP and OHPA Plantations

Table F.1. Mean soil solution concentrations from soil solution lysimeters (± Standard Deviation) for NO_3, NH_4, P, Ca, Mg and K at a 20 cm depth for 2004 and 2005 for the HPA, HPP and OHPA sites in both fertilized and unfertilized treatments.

Year	Element	Alfalfa		Pasture		OHPA
		Fertilized	Unfertilized	Fertilized	Unfertilized	
		--------------------------------------µg ml^{-1}------------------------------------				
2004	NO_3	498.1±247.9	271.9±91.7	29.7±55.4	37.0±0.0	1.3±0.0
	NH_4	1.5±1.3	0.4±0.2	0.1±0.1	0.0±0.0	0.3±0.4
	P	0.3±0.3	0.0±0.0	0.0±0.0	1.25±0.0	0.1±0.0
	Ca	761.2±343.7	265.8±124.5	130.25±92.1	31.2±0.0	22.8±0.7
	Mg	98.0±35.3	56.9±52.0	33.9±20.0	11.7±0.0	4.66±0.3
	K	17.4±19.9	8.0±8.2	1.7±1.0	71.3±0.0	16.3±3.5
2005	NO_3	21.1±26.5	28.3±23.4	2.4±3.4	7.1±7.5	~
	NH_4	0.5±0.6	0.2±0.2	0.1±0.0	0.1±0.0	~
	P	0.2±0.2	0.0±0.0	0.0±0.0	0.0±0.0	~
	Ca	46.8±42.6	58.6±37.4	21.8±8.9	16.7±6.6	~
	Mg	9.4±7.2	13.1±10.0	5.1±1.9	4.1±1.9	~
	K	7.2±14.7	1.7±1.1	1.7±0.9	8.6±16.5	~

Appendix G

Supplementary Data Showing Water Balance Model Used For Calculation of Water Volume Leached at both the HPA and HPP Plantations at Meadow Lake, SK.

Table G.1. Soil water balance model used to determine amount of water leachate that passed through the soil at the HPA Plantation in 2004.

Row	Parameter	Reference	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
A	**Avg. Mo. Temp**	Input data	-19.4	-8.60	-3.74	3.70	7.08	12.7	16.5	13.6	9.01	2.53	-1.64	-13.1	
B	**Mo. Heat Index**		0.00	0.00	0.00	0.63	1.69	4.09	6.11	4.56	2.44	0.36	0.00	0.00	19.9
C	**Unadj. Daily PET**		0.00	0.00	0.00	0.91	1.61	2.69	3.39	2.86	1.99	0.66	0.00	0.00	
D	**Mo. Sunlight**	Input Data	20.7	22.9	30.6	35.1	41.3	42.7	42.9	38.4	31.9	27.	21.5	19.3	
E	**PET (mm)**		0.00	0.00	0.00	32.0	66.6	115	145	110	63.5	17.9	0.00	0.00	550
F	**Precip. (mm)**	Input data	31.4	4.20	23.8	136	35.0	81.8	98.8	46.4	77.0	35.5	7.00	54.0	631
G	**Runoff Coeff.**	0.10	0.25	0.25	0.25	0.25	0.10	0.10	0.10	0.10	0.10	0.10	0.25	0.25	
H	**Runoff (mm)**		7.85	1.05	5.95	33.9	3.50	8.18	9.88	4.64	7.70	3.55	1.75	13.5	
I	**Infiltration (mm)**		0.00	0.00	0.00	102	31.5	73.6	88.9	41.8	69.3	32.0	0.00	0.00	
J	**IN - PET (mm)**		0.00	0.00	0.00	69.7	-35.1	-41.0	-56.5	-68.1	5.80	14.1	0.00	0.00	
K	**Acc. H_2O loss**		0.00	0.00	0.00	0.00	-35.1	-76.1	-132.6	-201	-201	-201	-201	-201	
L	**H_2O stored (mm)**		196	196	196	196	162	124.6	77.5	30.9	36.7	50.8	196	196	
M	**Chg H_2O storage**		0.00	0.00	0.00	0.00	-33.5	-37.7	-47.1	-46.7	5.80	14.1	0.00	0.00	
N	**AET**		0.00	0.00	0.00	32.0	65.0	111	136	88.4	63.5	17.9	0.00	0.00	514
O	**Percolation (mm)**		0.00	0.00	0.00	69.7	-1.57	-3.25	-9.37	-21.4	0.00	0.00		0.00	34.0
P	**Check (mm)**		7.85	1.05	5.95	136	33.4	78.6	89.4	24.9	77.0	35.5	1.75	13.5	

Table G.2. Soil water balance model used to determine amount of water leachate that passed through the soil at the HPA Plantation in 2005.

Row	Parameter	Reference	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
A	**Avg. Mo. Temp**	Input data	-16.9	-8.48	-3.49	5.61	9.69	13.6	16.4	13.7	9.62	4.32	-3.10	-8.94	
B	**Mo. Heat Index**		0.00	0.00	0.00	1.19	2.72	4.55	6.04	4.61	2.69	0.80	0.00	0.00	22.6
C	**Unadj. Daily PET**		0.00	0.00	0.00	1.32	2.12	2.86	3.37	2.88	2.11	1.05	0.00	0.00	
D	**Mo. Sunlight**	Input Data	20.7	22.9	30.5	35.1	41.3	42.7	42.9	38.4	31.9	27.3	21.5	19.3	
E	**PET (mm)**		0.00	0.00	0.00	46.2	87.6	122	144	111	67.3	28.6	0.00	0.00	607
F	**Precip. (mm)**	Input data	14.4	3.40	18.0	94.2	65.2	86.4	99.0	120	60.3	35.5	7.20	6.00	610
G	**Runoff Coeff.**	0.10	0.00	0.00	0.00	0.25	0.10	0.10	0.10	0.10	0.10	0.10	0.00	0.00	
H	**Runoff (mm)**		0.00	0.00	0.00	23.6	6.52	8.64	9.90	12.0	6.03	3.55	0.00	0.00	
I	**Infiltration (mm)**		0.00	0.00	0.00	70.7	58.7	77.8	89.1	108	54.3	32.0	0.00	0.00	
J	**IN - PET (mm)**		0.00	0.00	0.00	24.5	-29.0	-44.3	-55.3	-2.40	-13.0	3.40	0.00	0.00	
K	**Acc. H_2O loss**		0.00	0.00	0.00	0.00	-29.0	-73.2	-129	-131	-131	-131	-131	-131	
L	**H_2O stored (mm)**		165	165	165	165	137	98.0	54.2	51.8	38.8	42.2	165	165	
M	**Chg H_2O storage**		0.00	0.00	0.00	0.00	-27.7	-39.4	-43.7	-2.46	-13.0	3.40	0.00	0.00	
N	**AET**		0.00	0.00	0.00	46.2	86.4	117	133	111	67.3	28.5	0.00	0.00	589
O	**Percolation (mm)**		0.00	0.00	0.00	24.5	-1.24	-4.91	-11.6	0.06	0.00	0.00	0.00	0.00	6.84
P	**Check (mm)**		0.00	0.00	0.00	94.2	64.0	81.5	87.4	120	60.3	35.5	0.00	0.00	

Table G.3. Soil water balance model used to determine amount of water leachate that passed through the soil at the HPP Plantation in 2004.

Row	Parameter	Reference	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
A	**Avg. Mo. Temp**	Input data	-19.5	-8.85	-4.33	3.32	6.75	12.4	16.4	13.2	8.98	2.04	-1.77	-12.9	
B	**Mo. Heat Index**		0.00	0.00	0.00	0.54	1.58	3.95	6.03	4.37	2.43	0.26	0.00	0.00	19.2
C	**Unadj. Daily PET**		0.00	0.00	0.00	0.86	1.60	2.72	3.48	2.89	2.05	0.56	0.00	0.00	
D	**Mo. Sunlight**	Input Data	20.7	22.9	30.6	35.1	41.3	42.7	42.9	38.4	31.9	27.3	21.5	19.3	
E	**PET (mm)**		0.00	0.00	0.00	30.1	66.0	116	149	111	65.5	15.3	0.00	0.00	553
F	**Precip. (mm)**	Input data	31.4	4.20	23.8	136	29.1	83.5	82.2	47.4	79.7	12.9	7.00	54.0	591
G	**Runoff Coeff.**	0.10	0.00	0.00	0.00	0.25	0.10	0.10	0.10	0.10	0.10	0.10	0.00	0.00	
H	**Runoff (mm)**		0.00	0.00	0.00	33.9	2.91	8.35	8.22	4.74	7.97	1.29	0.00	0.00	67.4
I	**Infiltration (mm)**		0.00	0.00	0.00	102	26.2	75.1	73.4	42.7	71.7	11.6	0.00	0.00	403
J	**IN - PET (mm)**		0.00	0.00	0.00	71.6	-39.8	-41.0	-75.1	-68.1	6.27	-3.69	0.00	0.00	
K	**Acc. H_2O loss**		0.00	0.00	0.00	0.00	-39.8	-80.8	-156	-224	-223	-223	-223	-223	
L	**H_2O stored (mm)**		239	239	239	239	201	162	100	48.9	55.2	51.5	239	239	
M	**Chg H_2O storage**		0.00	0.00	0.00	0.00	-38.3	-38.7	-62.4	-51.0	6.27	-3.69	0.00	0.00	
N	**AET**		0.00	0.00	0.00	30.1	64.5	114	136	93.7	65.5	15.3	0.00	0.00	519
O	**Percolation (mm)**		0.00	0.00	0.00	71.6	-1.54	-2.33	-12.8	-17.1	0.00	0.00	0.00	0.00	37.9
P	**Check (mm)**		0.00	0.00	0.00	136	27.6	81.2	69.4	30.3	79.7	12.9	0.00	0.00	437

Table G.4. Soil water balance model used to determine amount of water leachate that passed through the soil at the HPP Plantation in 2005.

Row	Parameter	Reference	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
A	**Avg. Mo. Temp**	Input data	-17.2	-9.06	-3.91	5.30	9.29	13.4	16.2	13.7	9.40	4.28	-3.10	-8.94	
B	**Mo. Heat Index**		0.00	0.00	0.00	1.09	2.55	4.44	5.92	4.57	2.60	0.79	0.00	0.00	22.0
C	**Unadj. Daily PET**		0.00	0.00	0.00	1.25	2.05	2.82	3.33	2.87	2.07	1.04	0.00	0.00	
D	**Mo. Sunlight**	Input Data	20.7	22.9	30.6	35.1	41.3	42.7	42.9	38.4	31.9	27.3	21.5	19.3	
E	**PET (mm)**		0.00	0.00	0.00	43.9	84.0	120	143	111	66.0	28.3	0.00	0.00	596
F	**Precip. (mm)**	Input data	14.4	3.40	18.0	71.6	71.1	114	107	120	65.7	25.9	7.20	6.00	625
G	**Runoff Coeff.**	0.10	0.00	0.00	0.00	0.25	0.10	0.10	0.10	0.10	0.10	0.10	0.00	0.00	
H	**Runoff (mm)**		0.00	0.00	0.00	17.9	7.11	11.4	10.7	12.0	6.57	2.59	0.00	0.00	
I	**Infiltration (mm)**		0.00	0.00	0.00	53.7	64.0	103	96.1	108	59.1	23.3	0.00	0.00	
J	**IN - PET (mm)**		0.00	0.00	0.00	9.82	-20.4	-17.4	-46.6	-1.82	-6.82	-4.99	0.00	0.00	
K	**Acc. H_2O loss**		0.00	0.00	0.00	0.00	-20.4	-37.9	-84.5	-86.3	-86.3	-86.3	-86.3	-86.3	
L	**H_2O stored (mm)**		281	281	281	281	261	243	197	197	190	185	281.2	281.2	
M	**Chg H_2O storage**		0.00	0.00	0.00	0.00	-20.6	-17.7	-44.2	-1.90	-6.82	-4.99	0.00	0.00	
N	**AET**		0.00	0.00	0.00	43.9	84.6	120	140	110	66.0	28.3	0.00	0.00	594
O	**Percolation (mm)**		0.00	0.00	0.00	9.82	0.18	0.21	-2.37	0.08	0.00	0.00	0.00	0.00	7.91
P	**Check (mm)**		0.00	0.00	0.00	71.6	71.3	114	104	120	65.7	25.9	0.00	0.00	

Appendix H

Supplementary Data for Extreme Budget Calculations for HPA and HPP Plantations based on Flux Means ± Standard Deviations

Table H.1. Range of values of budgets totals at the end of 20 years, based on calculations using flux means +/- standard deviations

Scenario	Range†	N	P	Ca	Mg	K
		--	--	kg ha^{-1}	--	--
Alfalfa, unfertilized	Inputs +, Outputs +	(475.4)‡	(72.1)	(258.5)	(129.0)	(355.2)
WTH	Inputs -, Outputs -	(376.2)	(56.6)	71.5	(9.9)	(316.4)
Alfalfa, fertilized	Inputs +, Outputs –	(463.0)	(72.1)	(359.3)	(123.1)	(357.6)
WTH	Inputs -, Outputs +	(288.4)	(56.3)	55.3	(6.5)	(318.6)
Alfalfa, unfertilized	Inputs +, Outputs –	(234.6)	(52.2)	(190.2)	(107.7)	(150.6)
SOH	Inputs -, Outputs +	(234.9)	(44.6)	113.2	1.5	(199.7)
Alfalfa, fertilized	Inputs +, Outputs –	(222.2)	(52.1)	(290.9)	(101.8)	(153.0)
SOH	Inputs -, Outputs +	(147.0)	(44.4)	97.1	4.9	(201.9)
Pasture, unfertilized	Inputs +, Outputs –	(174.3)	(35.3)	183.5	(19.0)	(241.3)
WTH	Inputs -, Outputs +	(199.8)	(45.4)	207.6	34.1	(243.8)
Pasture, fertilized	Inputs +, Outputs –	(195.2)	(35.3)	90.8	(29.1)	(242.3)
WTH	Inputs -, Outputs +	(120.4)	(45.4)	198.8	19.9	(243.9)
Pasture, unfertilized	Inputs +, Outputs –	(54.3)	(2.4)	159.1	(7.8)	(37.7)
SOH	Inputs -, Outputs +	(79.0)	(33.5)	240.6	31.2	(127.2)
Pasture, fertilized	Inputs +, Outputs –	166.5	(15.4)	251.9	2.3	(36.7))
SOH	Inputs -, Outputs +	41.5	(33.5)	249.4	45.5	(127.1)

† Range is the values around the mean calculated by adding and subtracting s.d.

‡ ( ) indicates negative values