NITROGEN FERTILIZATION OF HYBRID POPLAR PLANTATIONS IN SASKATCHEWAN, CANADA

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ABSTRACT

The increasing input costs for traditional agriculture has led land owners and producers in search of alternative opportunities to increase on-farm income. Replacing agricultural crops with short rotation woody species such as hybrid poplar trees is a form of agroforestry. The objectives of this project were to evaluate: 1) a suitable planting stock for hybrid poplar, 2) the effect of nitrogen (N) fertilizer application and pruning on hybrid poplar growth and, 3) the response of four hybrid poplar clones to fertilizer application and their suitability in the boreal transition ecoregion of Saskatchewan.

Two trials were established near Meadow Lake, Saskatchewan where three stock types (cuttings, root cuttings and rooted plugs) of Walker poplar were planted into former alfalfa and pasture fields. Trees were pruned each spring to remove multiple leaders and fertilized in year 2 with 100 kg N ha^{-1}. The presence of roots on rooted cutting and plug stock types was beneficial in terms of hybrid poplar growth and survival. Trees grown from planting stock without roots had survival rates between 32-37% whereas, the survival of trees with roots at the time of planting ranged from 62-81% after two years of growth. Trees that were planted as a rooted stock were 3.5 to 4.2 times greater in height and 4.0 to 5.6 times greater in root collar diameter than trees planted as an un-rooted stock type. The application of fertilizer N decreased tree volumes by 31% at the Alfalfa site and had no effect on tree growth at the Pasture site. The total amount of fertilizer N recovered by the hybrid poplar trees ranged from 1-3% at the Alfalfa site and 3-5% at the Pasture site.

The second study involved planting four clones of hybrid poplar (Hill, Katepwa, Walker and WP-69) at the same two sites and applying fertilizer at rates of 0, 150 and 300 kg N ha^{-1} the first two years. Following the second growing season, Katepwa and WP-69 clones had the highest tree volumes of 750 and 1147 cm^3 of the four clones evaluated. The Walker clone had the poorest survival rates (52-56%) compared to the other three clones (> 90% survival). Foliar N levels were not correlated with tree height at the Alfalfa (p=0.1326) or the Pasture (p=0.1063) sites. The relationship between foliar P concentration and tree height was more pronounced during July at the Alfalfa site with an r^2 value of 0.7102. The N:P ratios for foliar tissue decreased with increasing fertilizer

N application during August at the Alfalfa site. Foliar N:P ratios were the same among fertilizer and clone treatments at the Pasture site in August.

Results from this study suggest that rooted stock types increase the successful establishment of hybrid poplar plantations. However, application of N fertilizer may not increase growth of trees if soil N is adequate. Other soil nutrients need to be measured prior to fertilization to determine what nutrients may be limiting plant growth.

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As with most soil science Master's thesis, much of the work was completed in the field. This required many long days and overnight trips to Meadow Lake. Doug Jackson has seen this project through from the beginning to the end and I really appreciated his efforts. It took a lot of dedicated hard working people to complete this field work. I would like to thank all of those who helped out in the field - Amanda Kalyn, Ashley Anholt, Heidi Lazorko, Rick Block, Mike Steckler, Bachitter Singh, Lee Kalcits and Ryan Hangs. I would like to thank Janet Foley, Myles Stocki, Renato de Freitas, Cory Fatteicher and Barry Goetz for allowing me to work with them in their labs and gain valuable experience running a variety of lab equipment. Thanks go to my fellow grad students and Elaine Farkas for putting up with me when I have locked myself out of my office.

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1. INTRODUCTION

The application of fertilizer on agricultural lands has been used with great success, both from a production standpoint and an economic standpoint. In Saskatchewan, the majority of fertilizer is applied to annual dryland agricultural crops and, to a lesser extent, perennial forages and pasture land. Recent advances in soil testing and soil test interpretation have helped farmers manage their fertilizer inputs with greater efficiency. Research into the development and production of fertilizer application equipment has enabled farmers to place fertilizer where it will be the most effective. Although technology has helped increase the efficiency of modern grain farming, on-farm profitability is decreasing. Decreasing profit margins for Saskatchewan farmers are the result of larger increases in operating expenses compared to increases in on-farm revenues (Sobool, 2004). The increase in operating expenses and inadequate subsidy programs has lead farmers to evaluate other marketable crops. Growing hybrid poplar trees as a crop may be an economically viable option for Saskatchewan producers (van Oosten, 2006). The production of trees (hardwood or softwood tree species) on agricultural land is referred to as tree farming and is one of the practices associated with agroforestry. Throughout this thesis I will use the word agroforestry as the utilization of fast-growing hybrid poplar clones on agricultural lands for the purpose of generating marketable wood products.

Agroforestry is a relatively new concept in Saskatchewan and there are currently no large-scale plantations in production. Agroforestry systems differ from conventional agricultural systems during planting, crop establishment and harvesting. For tree planting there are a number of stock types available to plant in a hybrid poplar plantation including unrooted cuttings (15-25 cm pieces of shoot material), and a variety of rooted cuttings (rooted material grown outdoors in nursery beds or rooted plugs grown in greenhouses). In conventional agriculture systems, plants are grown directly from seed and applied fertilizer is intended for use in the year of application. In hybrid poplar plantations the different stock types may respond differently to fertilizer application and could result in separate fertilizer regimes designed specifically for the stock type or hybrid poplar clone variety.

There has been little advancement of planting and fertilizer application equipment for agroforestry. There is also little information available to determine how much fertilizer to apply and at what time during the rotation. A soil test can be taken and analyzed but there is no generally accepted interpretation of the test. There are no yield response curves and therefore fertilizer recommendations are based on research undertaken in areas other than Saskatchewan. The lack of specialized fertilizer application equipment results in the majority of fertilizer being applied as a surface broadcast application. A surface applied application of nitrogen (N) fertilizer in a forestry system can have as low as 7.5% of the applied fertilizer recovered in the plant (Choi et al., 2005). In cereal grain production, N use efficiency averages 33% across the world (Raun et al., 2002). This reduced uptake efficiency presents many challenges in agroforestry systems and, as a result, fertilizer rates tend to be very high to reflect the inefficiency of application methods. These high rates are applied to overcome N losses through volatilization, leaching, denitrification and uptake from competing vegetation. Fertilizer that is utilized by competing vegetation may become available to the hybrid poplar trees in subsequent years (Welham et al., 2007). The goal of fertilization is to overcome nutrient losses and to match nutrient demand with soil nutrient supply for fast growing hybrid poplar clones. It is unclear whether each clone will have the same nutrient demand and response to fertilizer application.

Agroforestry has followed a similar trend as conventional agriculture. Breeding programs in traditional agriculture focus on creating hybrid varieties of crops with desirable characteristics. The new hybrids are made to have higher resistance to pests and diseases, increased yield, increased vigor and as a result increased demand for fertilizers. The Agroforestry Division within Agriculture and Agri-Food Canada has similar goals to that of traditional agriculture research focused towards hybrid poplar development. It is important to evaluate the strengths and weaknesses of hybrid poplar clones as it may take a crop 15 to 25 years to fully mature. Hybrid poplar clones will be susceptible to similar disease and pest infestations as agricultural crops, and possibly greater stress as the hybrid poplar crop will be in production for a much longer duration.

In the time it will take a hybrid poplar crop to mature it will have gone through a range of fertility, pest, disease and climatic conditions. The desirable characteristics of a clone today may not be desirable for a clone grown in the future.

To successfully establish a profitable hybrid poplar plantation, the growth rates and fertility requirements for each clone and planting stock need to be evaluated. The main objective of this study, therefore, was to identify and quantify the best management practices to successfully establish a hybrid poplar plantation. The specific objectives were to: 1) identify hybrid poplar stock types and clones suited for the boreal transition ecoregion of Saskatchewan; 2) evaluate the response of Walker, Hill, Katepwa and WP 69 hybrid poplar clones to N fertilizer application; and 3) evaluate the effect of pruning on Walker hybrid poplar. The goal of this study is to provide practical information for growers that can be used for the successful establishment and production of hybrid poplar plantations on agricultural land in Saskatchewan.

This thesis is divided into five chapters wherein the research objectives will be addressed at two hybrid poplar research plantations located near Meadow Lake, Saskatchewan. Chapter 2 is a literature review of the cultural practices for the establishment and management of hybrid poplar plantations. Topics focus on the agronomic challenges facing agroforestry in Saskatchewan including: a background on poplar trees, agronomics, management, maintenance and nutritional information. Chapter 3 describes a research study evaluating the treatment effects of pruning, fertilization and stock type on N uptake from dual labeled ^{15}N ammonium nitrate fertilizer and N distribution in Walker hybrid poplar. Chapter 4 discusses a research study comparing the growth characteristics of four hybrid poplar clones and their response to three rates of N fertilizer application. Finally, Chapter 5 discusses the results from the two research studies along with general recommendations for agroforestry management and future research needs.

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2. LITERATURE REVIEW

2.1 The Genus *Populus*

Poplars, belonging to the genus *Populus,* are believed to have originated in China and Japan (Khosla and Khurana, 1982). They are wide-spread across Canada and the genus includes the following species: trembling aspen (*P. tremuloides*), largetooth aspen, (*P. grandidentata*), balsam poplar, (*P. balsamifera*) and the cottonwoods, eastern cotton wood (*P. deltoides*) and black cottonwood (*P. trichocarpa*) (Morley and Balatinecz, 1993). These species are deciduous, fast growing, moisture loving and generally intolerant of shade (Morley and Balatinecz, 1993) and have large variations in morphological and physiological characteristics among clones within the same species (Palmer, 1991). The large variation between species and the ease of interspecific breeding has lead to a high degree of genetic diversity within the *Populus* species and hybrids creating a wide tolerance for site conditions.

Testing of hybrid poplars was initiated at the Forest Nursery Station in Indian Head, Saskatchewan in 1942 to provide fast growing trees for shelterbelts in the Canadian prairies (Palmer, 1991). In 1976, the first hybrid poplar was released as P. x 'Walker' (Lindquist et al., 1997) with the female parent being *Populus deltoides* and it is suggested that the male parent is P. x *petrowskyana*; however, this is not confirmed (Walker and Schroeder, 2001). 'Walker' proved to be an outstanding clone resulting in a widespread distribution throughout the prairies for shelterbelts and is the reason it was chosen for further study as a short rotation woody crop.

2.2 Short Rotation Forestry

The definition of short rotation forestry depends on the rotation length and size of the trees at the time of harvest (Palmer, 1991). In this study, the term short-rotation forestry refers to the management of even-aged, fast growing hybrid poplar trees established in a grid arrangement that are subject to weed control and varying levels of fertilizer application. Short rotation woody crops, such as 'Walker' poplar produce large amounts of biomass in less time and on smaller land bases than native stands (Zabek and Prescott, 2001). A short-rotation hybrid poplar plantation may be harvested as early as 15 to 20 years compared to over 40 years for other hardwood and softwood trees (Sobool, 2004; van Kooten et al., 1999). However, the yield is difficult to determine as productivity is dependent on many factors such as site, planting methods, planting stock, spacing, cultural treatments, fertilization, length of rotation and environmental conditions (Steinbeck et al., 1972).

2.3 Site Selection

Similar to arable agriculture in Saskatchewan, the main limitation to growth of hybrid poplar stands is the availability of water. Walker poplars have high rates of evapotranspiration and require at least 400 mm of precipitation throughout the year (van Oosten, 2006). When precipitation is less than 400 mm, roots must have access to groundwater reserves or irrigation water (van Oosten, 2006). Similar to agricultural crops, certain soil characteristics are favorable for increased hybrid poplar growth. The Saskatchewan Forestry Centre (SFC, 2003) suggests that hybrid poplars be grown on loamy, nitrogen rich soils with a pH of 5.5-7.5. Soils with high nitrate supply power will encourage root proliferation and uptake of N as opposed to soils with high ammonium supply (Woolfolk and Friend, 2003; DesRochers et al., 2006). Furthermore, soils should not be saline or subject to flooding to achieve the best growth results.

2.4 Site Preparation

Site preparation for hybrid poplars is similar to that for conventional agriculture for the purpose of reducing competing vegetation and providing a seedbed favorable to seedling establishment. There are a number of site-preparation methods that may be used alone or in combination with each other including: i) plowing and disking, ii) summer fallowing (repeated tillage for one season before planting), and iii) herbicide application (Palmer, 1991). Site preparation can be expensive but will result in higher survival of seedlings and more rapid growth (Hansen et al., 1983).

2.5 Planting

Similar to agricultural crops, mechanical tilling using a chisel plow or a tandem disk provides an adequate seedbed for establishing a hybrid poplar plantation. Incorporating soil residues will increase aeration as well as soil temperatures and make planting easier. Repeated tillage prior to planting can reduce soil moisture to a point where newly planted seedlings may be adversely affected. Moisture is one of the most important requirements for poplar root development (Puri and Thompson, 2003).

Large numbers of hybrid poplars can be successfully established from dormant hardwood stem cuttings (Farmer, 1973; Fege, 1983). The advantage of this auto-vegetation propagation of hybrid poplars is a convenient and relatively inexpensive means of establishing hybrid poplar plantations (Palmer, 1991). Cuttings are usually taken from one year-old shoots; however, lower branches and second stems of older trees can be used as a source of the cuttings (Heilman et al., 1995).

The success of a hybrid poplar plantation is dependent on a number of factors that affect seedling growth and development including: light (Shapiro, 1958), soil moisture (Allen and McComb, 1956; Bloomberg, 1963), cutting diameter (Bowersox, 1970; Smith and Wareing, 1974; Dickman et al., 1980), cutting length (Allen and McComb, 1956; McKnight, 1970; Anon, 1979), soil temperature (Hansen, 1986a), planting orientation (Bloomberg, 1963), planting depth (McKnight, 1970; Fege, 1983; Hansen et al., 1983), weed competition (Armson et al., 1980; Hansen et al., 1983; Danfield et al., 1983; Hansen et al., 1984; Heilman et al., 1995), and the moisture content of the cutting (McKnight, 1970; Phipps, 1978; Hansen and Phipps, 1983; Phipps et al., 1983; Hansen, 1986a).

Survival and early growth of hybrid poplar cuttings increases with increasing soil moisture (Bergez et al., 1989; Shock et al., 2002). In addition, warming and soaking the cuttings prior to planting to the point of imminent root emergence accelerated early shoot growth (Hansen and Phipps, 1983). Fege (1983) recommended that cuttings be soaked in 15^{o}C water for 7-10 days before planting, whereas Heilman et al. (1995) suggested submerging the lower fourth of the cuttings into cold water for 2-4 days prior to planting until root primordia appear. Cuttings should not soak beyond the point of initial root emergence as these initial roots may be damaged during planting resulting in decreased shoot and root growth (Palmer, 1991). Soil temperatures of 10^{o}C are optimal for planting hybrid poplar cuttings (Hansen et al., 1986a).

The diameter and length of cuttings influence survival and growth of hybrid poplar trees (Palmer, 1991). Survival and growth of cuttings generally increased with increasing diameter (Dickman et al., 1980). Height and diameter growth of cuttings were correlated with the diameter of the initial cutting during the first two years after planting, but was no longer correlated after three years of growth (Bowersox, 1970).

Cuttings should be planted vertically, with an undamaged bud pointing upwards, into soft moist soil that is packed firmly around the cutting to ensure good rooting (Heilman et al., 1995). Bloomberg (1963) found that hybrid poplars produced more roots when they were planted vertically instead of horizontally or upside down. Cuttings should be planted with 1-2 cm of the cutting above the ground (Fege, 1983; Heilman et al., 1995).

2.6 Tree Spacing

No set tree spacing is best for the establishment of an intensively managed hybrid poplar plantation, however; spacing will influence the physical characteristics of the trees as well as the time and cost to produce them (Palmer, 1991). The end product of the trees should be determined prior to planting, as smaller spacings are used for shorter rotations (pulp products), whereas longer rotations require wider spacing to produce saw timber (Krinard and Johnson, 1975). Some advantages of wider spacings include faster diameter growth and lower planting costs. Some disadvantages include inefficient utilization of growth space until canopy closure, poor stem form and heavy branching (von Althen, 1990). Stem form and heavy branching can be controlled by pruning the trees to encourage one dominant leader. Pruning of lower branches and co-dominant leaders will encourage straighter growth desired for high value saw logs. The delay in canopy closure in wider tree spacing may require weed control into years five and six or longer, compared to smaller tree spacing where canopy closure may occur in three or four years (Buhler et al., 1998).

2.7 Weed Control

Weed control is essential for the establishment of a successful hybrid poplar plantation and should be continued until canopy closure occurs to reduce competition between trees and weeds (Buhler et al., 1998). If weeds are not controlled, hybrid poplar growth will slow and trees as old as four years old may die (Heilman et al., 1995). Competition for resources below-ground can sometimes be greater than competition for resources above-ground (Casper and Jackson, 1997). Chemical and mechanical weed control along with a cover crop has been used successfully, separately or in combination, to control competing vegetation in hybrid poplar plantations (Palmer, 1991). Tillage is important in cool northerly climates, such as the Canadian prairies, for increasing soil temperatures to improve hybrid poplar growth (Crosson, 1981). In these areas no-till is not recommended (Lester, 1995). Hansen et al. (1984) used legumes as a cover crop, which resulted in good first year growth and survival of the hybrid poplar followed by poor growth in the second year when the legume crop was more established and was a better competitor for soil resources.

If weed control is not implemented prior to planting, hybrid poplar trees have to compete with other vegetation which may reduce the growth rate and decrease the survival of the trees (Heilman et al., 1995). Once the hybrid poplar trees have outgrown the competing vegetation and have established a canopy, hybrid poplar trees are better able to compete for soil resources and sunlight. Soil applied herbicides can help in decreasing the time to canopy closure by controlling weeds in subsequent years. Difficulties in controlling weeds arise in site preparation as there are currently very few herbicides registered for use in hybrid poplar plantations in Saskatchewan.

Linuron is safe to use in hybrid polar plantations as it is applied prior to planting and prevents weed seed germination for four to six weeks (Palmer, 1991). Glyphosate is very difficult to apply after planting because actively growing hybrid poplars (less than 1 year old) are easily damaged by even small amounts of glyphosate spray drift (von Althen, 1981; Akinyemiju et al., 1982).

Buhler et al. (1998) showed that weeds should be controlled for the entire growing season as 50% of the total season growth in the first year of a hybrid polar plantation occurs late in the growing season. These authors also developed recommendations for weed control in hybrid poplar plantations as follows: a combination of tillage and herbicides should be used to control first year weeds along with a pre-emergent herbicide such as linuron and, if necessary, the use of grassy and broadleaf herbicides to control other weeds. However, there are only a few herbicides registered for use in hybrid poplar plantations (van Oosten, 2006) (Appendix A).

2.8 Pruning

In order to achieve high value solid wood products, hybrid poplar trees may need to be pruned to create strong boles that are straight and free of knots and other flaws (Balandier, 1997). Pruning lower branches will encourage upward growth of the hybrid poplar. The dominant leader is considered to be the main shoot contributing to plant growth and will eventually make up the bole of the tree. This dominant leader is untouched during pruning whereas co-dominant leaders are reduced to 2/3rd of their size. Pruning may start as early as year one or two in plantations to achieve well-formed trees for lumber or plywood production (Heilman et al., 1995). Pruning should take place during the late spring or early summer where pruning wounds can heal quickly and reduce the incidence of disease infection (van Oosten, 2006).

2.9 Disease and Insects

The utilization of a single hybrid poplar clone creates a monoculture environment that may leave plantations vulnerable to pest and disease outbreaks. One of the most destructive insects to invade hybrid poplar stands is the gray willow leaf beetle (*Tricholochmaia decora*) (Reynard, 2001). A list of other insects that may decrease the production and health of the hybrid poplar trees in Saskatchewan are listed in Table 2.1. Disease infestation in hybrid poplar plantations can also devastate stand productivity and health. Septoria canker (*Septoria musiva*), is a serious plant disease that could potentially destroy hybrid poplar plantations in mid–rotation (Schroeder et al., 2006). Melamspora rust (*Melamspora medusae*) and septoria leaf spot (*Septoria musiva*) are other potentially damaging diseases (Schroeder et al., 2006). Sheperd's crook *(Venturia populina)* is a fungus that causes leaf and shoot blight with varying degrees of infection amongst hybrid poplar clones (Newcombe and van Oosten, 1997). Pest and disease infestations are a threat to plantation productivity throughout the entire length of the rotation. During the winter months low temperatures and strong frosts can help manage pest and disease problems (Weih, 2004). Avoiding a monoculture by including a variety of clones within a plantation can decrease disease and insect pressures. Breeding programs provide clones with different levels of disease and insect resistance along with cold hardiness, wood quality and drought resistance.

Table 2.1 Potentially destructive insects feeding on hybrid poplar plantations in Saskatchewan. (Source: Reynard (2001)).

Common Name	Latin Name
Alder dagger moth	*Acronicta dactylina*
American hornet moth	*Sesia tibialis*
Aspen serpentine leafminer	*Phllocnistis populiella*
Black willow aphid	*Pterocomma smithiae*
Canadian tiger swallowtail	*Pterourus glaucus canadensis*
Cottonwood leaf beetle	*Chrysomela scripta*
Cottonwood leafmining beetle	*Zeugophora scutellaris*
Flea beetle	*Phyllotreta and Crepidodera sp*
Forest tent caterpillar	*Malacosoma disstria*
Grasshopper	Various species
Gray willow leaf beetle	*Tricholochmaia decora*
Green aspen leafroller	*Apotomis removana*
Leaf folding sawfly	*Phyllocolpa agama*
Leafminer	*Messa leucostoma*
Leafminer	*Phllonorycter salicifoliella*
Lined black aspen caterpillar	*Xylomyges dolosa*
Oblique banded leafroller	*Choristoneura rosaceana*
Poplar and willow borer	*Cryptorhynchus lapathi*
Poplar and willow leaf weevil	*Lepyrus canadensis*
Rustylined leaftier	*Clostera albosigma*
Rusty tussock moth	*Orgyia antique*
Spotted poplar aphid	*Aphis maculatae*
Spotted tussock moth	*Lophocampa maculata*
Tarnish plant bug	*Lygus lineolaris*
Willow sawfly	*Nematus ventralis*
White admiral	*Basilarchia arthemis*

2.10 Fertilization

It is essential to manage soil fertility to maintain a high level of productivity in a short-rotation hybrid poplar plantation (Ericsson et al., 1992). To successfully manage plant nutrition it is important to understand the relationship between plant nutrient requirements and maximum growth rate (Kelly and Ericsson, 2003). In soils with adequate moisture, N availability in the rooting zone has the major influence on plantation productivity (Liu and Dickman, 1996).

Fertilization of short-rotation forestry can increase hybrid poplar growth (Brown and van den Driessche, 2002), as well as reduce or have no effect on hybrid poplar height and diameter (DesRochers et al., 2006). Fertilization is usually delayed for one or two years after planting to minimize leaching losses or uptake by competing vegetation (Hansen et al., 1988; Hansen, 1994; Heilman et al., 1995). van den Driessche (1999) showed that placement of readily soluble forms of N and phosphorus (P) placed in dribble holes next to cuttings at the time of planting increased growth considerably compared to banding the fertilizer.

2.10.1 Nitrogen competition

The application of N can encourage the growth of non-target vegetation before crown closure occurs resulting in increased competition for nutrients and other resources between the tree and non-target vegetation (Chang et al., 1996; Staples et al., 1999). Once crown closure has occurred, decomposing litter from the non-target vegetation may release enough N for maximum uptake by the tree, reducing or possibly eliminating the need to fertilize (McLaughlin et al., 1985). Therefore, this non-target vegetation may be viewed as a pool of immobilized, long-term, potentially available N until canopy closure occurs (Preston and Mead, 1994). Welham et al. (2007) found fast growing grass species played an important role in conserving nutrients. These herbaceous species act both as a nutrient sink to minimize N leaching as well as an N source to maintain long-term tree productivity (Welham et al., 2007).

2.10.2 Fertilizer placement

Broadcast applications of fertilizer are common in young plantations because an established plantation poses challenges for equipment maneuverability. Another reason for broadcast fertilizer is because tree roots present an obstacle when banding or incorporating fertilizer in years after plantation establishment. On the other hand, broadcast applications of fertilizer tend to stimulate non-target vegetation and result in poor fertilizer use-efficiencies. Placement of fertilizer near cuttings was about twice as effective as banding fertilizer in the attempt to increase tree growth (van den Driessche, 1999). The greater fertilizer use-efficiency is the result of the fertilizer being closer to the seedling roots and the absence of weed competition.

2.10.3 Nitrogen leaching

Studies of agricultural systems typically report that nitrate leaching after mid-season is significantly decreased when crop demand for soil water prevents the movement of nitrate out of the rooting zone (Gerwing et al., 1979; Hubbard et al., 1984;

Saffigna and Keeney, 1977). In a study conducted by McLaughlin et al. (1985), soil solution nitrate in fertilized plots was consistently higher than in unfertilized plots at 15 cm and 120 cm in the first growing season. In the first and second growing seasons, soil solution nitrate concentrations were over 150 mg N L^{-1} in bare soil treatments that received 112 kg ha^{-1} per year with 50% of the fertilizer applied in June and 50% of the fertilizer applied in July. In the third growing season, the concentration of soil nitrate in solution did not increase after fertilization and declined to less than 50 mg N L^{-1} in bare soil treatments. Nitrate concentrations in the unfertilized plots were less than 100 mg N L^{-1} in the second growing season and declined to less than 25 mg N L^{-1} in the third growing season.

2.11 Nutrient Deficiency

Fertilization responses for hybrid poplar vary widely in the literature as plantations are being grown over a wide variety of environmental and site conditions. There is generally a response to N fertilizer in plantations that do not receive irrigation and less frequently a response to P and potassium (van Oosten et al., 2001). Matching fertility levels of soil and added nutrients to specific clones may be necessary to achieve maximum productivity, as hybrid poplar clones differ in their responses to added fertilizer (van den Driessche, 1999).

2.12 Nitrogen

Nitrogen is generally the most deficient soil nutrient for poplars (Hansen, 1986b). N fertilization each year increased hybrid poplar growth by 50-400% in the first five growing seasons depending on site and level of N applied (Hansen and Tolsted, 1981). N deficient trees have smaller leaves than trees with sufficient N and the leaves are light green and may even turn yellow, with the lower leaves on the tree being the first indicators of nutrient stress (Heilman et al., 1995). van den Driessche (1999) suggested that the optimum value for leaf N concentrations is 23-25 mg g^{-1}, and is in general agreement with values reported for several other poplar species and hybrids (van den Burg, 1985).

2.13 Phosphorus and Sulfur

Phosphorus and sulfur (s) are two nutrients that may be limiting in poplar plantations. Stem height and diameter growth strongly correlated with foliar P and S concentrations (Brown and van den Driessche, 2002). Although stem growth increased with increasing N rate, foliar P and S concentrations decreased with increasing N rate for some fertilizer sources. The average foliar concentrations of P did not exceed 1.8 g kg^{-1}, which is lower than the 2.5 g kg^{-1} level considered sufficient and slightly greater than the 1.6 g kg^{-1} considered critical indicating an insufficient level of P (van den Driessche, 2000). Critical levels for foliar S concentrations are not widely published for hybrid poplars. Hybrid poplar trees may benefit from the addition of S when applied with N (Brown and van den Driessche, 2002)

The application of P can increase the growth response of hybrid poplar up to 50%, with responses reduced under dry soil conditions (van den Driessche, 1996). Menetrier (1979) found P to be the most important nutrient for hybrid poplar growth as the application of P alone was better than the application of N alone in the first growing season. Foliar levels of P were also better indicators of height and diameter growth than N in the first year of growth.

2.14 Utilization of Hybrid Poplar

Hybrid poplar differs from natural wood fiber, as it is both juvenile and rapidly growing, which influences the wood product quality (Palmer, 1991). Recent advances in processing technology has lead to a corporate exploration of hybrid poplar uses such as, oriented strand board, medium-density fiber boards, parallel lamination, veneers and finishing products (Puckette et al., 1999). The vast majority of the 30,000 hectares of hybrid poplar plantations in the Pacific Northwest of the United States and Southwestern British Columbia is managed by corporations utilizing the wood for a variety of end uses from pulp to solid wood (van Oosten et al., 2001). Sawmill tests have shown that lumber from hybrid poplar has advantages over black cottonwood, including: i) easier debarking of less fibrous bark, ii) lighter colored heartwood, an advantage in both lumber and paper manufacturing, and iii) fewer defects in wood quality that have straighter boles with less tension wood, a feature resulting in better lumber quality and end use (Heilman et al., 1995). A higher value end product is more desirable as it provides more income as well as more marketing opportunities. Beginning a plantation with an end product in mind will help a producer make informed decisions on plantation establishment and management.

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3. STOCK TYPE, PRUNING AND N FERTILIZER UPTAKE IN A WALKER HYBRID POPLAR PLANTATION

3.1 Introduction

The recent and increasing interest in agroforestry has stimulated many research projects in Saskatchewan that address concerns such as: fertility, survival, planting stock, clone, disease, nutrient cycling, pruning and tree spacing. The increased activity in agroforestry research is supported by the previous government's vision to convert 10% of the arable land in Saskatchewan to agroforestry, giving Saskatchewan the opportunity to become Canada's agroforestry leader (Calvert, 2006). In order to successfully achieve this goal there is a need for research to determine suitable management practices that are appropriate for Saskatchewan landowners. Agroforestry also has the potential to reduce the use of fossil fuels and become an important supplier of energy as the market for biofuels is expected to grow strongly in the future (Weih, 2004).

A major obstacle in the development of agroforestry in Saskatchewan is evidence that transforming agricultural land into a hybrid poplar plantation is economically viable. In addition to providing a detailed economic analysis on agroforestry we must also solve some key agronomic questions. These questions will need to address how hybrid poplar will grow in an agricultural system, what land will be available for agroforestry, what will be the limitations of this land for agroforestry systems, how will the plantations be designed as to shape and arrangement, how will the trees be planted, what stock types are available, what are the nutritional requirements for clones, how will competeing vegetation and disease affect tree growth? Due to the nature of hybrid poplar trees maturing over a period of 15-25 years, research on these topics will need to be long-term and carried out for more than one rotation. Three topics selected in this research study are focused on determining a suitable type of planting stock, effect of pruning and quantifying the response and partitioning of a one-time application of N fertilizer in the second year of a hybrid poplar plantation. The specific objectives were to: 1) identify one or more hybrid poplar stock types in terms of growth potential and seedling survival; 2) evaluate the response of Walker poplar to N fertilizer; and 3) evaluate the effect of pruning on Walker poplar.

3.2 Materials and Methods

3.2.1 Site description

The two hybrid poplar plantations used for this study are located approximately 25 km southwest of Meadow Lake, Saskatchewan, Canada (Figure 3.1). Both sites are located in the boreal transition ecoregion of Saskatchewan. Although both sites are within close proximity, the soil properties are different (Table 3.1). The first site was previously managed as an alfalfa field and will be referred to as the Alfalfa site. The second site was managed as a pasture and will be referred to as the Pasture site. The Alfalfa site (UTM 12U E0646897 N5988954) is located on predominantly sandy-loam to loamy Orthic Gray Luvisol soils developed from weakly to moderately calcareous glacial till (Loon River Association), with occasional Gleyed Gray Luvisols from similar parent material in low lying areas (SCSR, 1995). In the top 10 cm the cation exchange capacity is 7.8 cmol kg^{-1} and 1.6% organic carbon content. The landscape of the Alfalfa site is very gently undulating to dissected, with slopes < 2% and a moderate stone class (SCSR, 1995).

The Pasture site (UTM 12U E0642250 N5981507) occurs on soils that are mapped as predominantly a mixture of Brunisolic Gray Luvisols and Orthic Gray Luvisols developed from loam to clay-loam glacial till material overlain by sandy glaciofluvial material (Bittern Lake Association) with significant inclusions of sandy Orthic Regosols and Eluviated Eutric Brunisols (Pine Association) (SCSR, 1995). In the top 10 cm the cation exchange capacity is 8.9 cmol kg^{-1} and 1.3% organic carbon content. The landscape is very gently undulating with slopes <3% and stoniness classed as slight to moderate (SCSR, 1995).

3.2.2 Experimental design

The three different cultural treatments included stock type, pruning and fertilizer application. The treatments are planted in a 3 X 2 X 2 randomized complete block design and are replicated three times at both the Alfalfa (Figure 3.2) and Pasture (Figure 3.3)

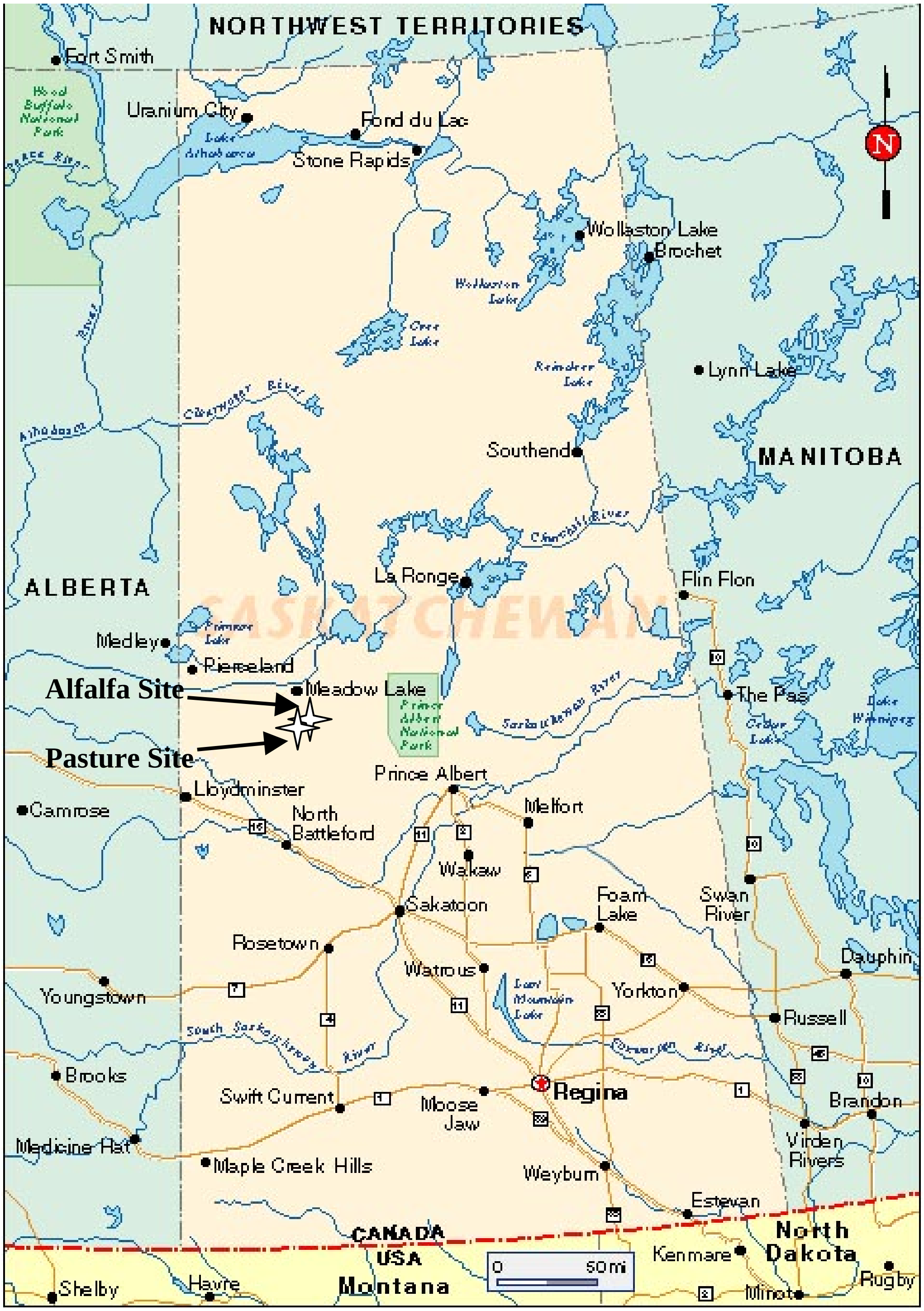

Figure 3.1 Location of the Alfalfa and Pasture hybrid poplar study sites in Saskatchewan, Canada. (Source: Canada Maps, 2007)

sites. Each treatment was numbered from 1 to 12 to minimize confusion among treatments. There are 12 treatments in each block with each treatment consisting of one

Table 3.1 Soil properties for the individual blocks at the Alfalfa and Pasture hybrid poplar plantations.

Site	Soil Horizon	% Sand	% Silt	% Clay	Soil Texture
Alfalfa Block 1	Ap	54	38	8	SL
	Bt	53	20	27	SCL
	C	56	22	23	SCL
Alfalfa Block 2	Ap	56	37	7	SL
	Ae 1	66	28	6	SL
	Ae 2	60	31	9	SL
	AB	61	28	11	SL
	Bt 1	53	22	25	SCL
	Bt 2	45	28	27	CL
	C	58	21	22	CL
Alfalfa Block 3	Ap	57	34	9	SL
	Ae	58	28	13	SL
	Bt	52	25	23	SCL
	C	58	21	22	SCL
Pasture Block 1	Ap	72	22	6	SL
	Ae	64	28	8	SL
	Bt	49	20	31	SCL
	C	69	15	16	SL
Pasture Block 2	Ap	65	29	6	SL
	Bt	50	18	31	SCL
	C	57	15	28	SCL
Pasture Block 3	Ap	75	20	5	SL-LS
	Ae	83	14	4	LS
	Bt	56	19	25	SCL
	Ck	46	23	31	CL

plot of 176 trees spaced 2.4 m apart within each of the 16 rows and 3.2 m between each of the rows. Each plot is separated by a 10 m buffer area and blocks are separated by 4 m pathways. Buffer areas are planted with Walker hybrid poplar. Fertilizer treatment plots received fertilizer in year 2 of the study (2003). Within each plot of 176 trees there are 20 measurement trees.

Environmental data at each site was monitored in treatment 7 in each of the three blocks using Campbell Scientific (Edmonton, AB) soil monitoring equipment. Soil temperature probes were placed at 5, 10, 20, 30, 40, 50 and 70 cm depths. Volumetric soil moisture was measured at 10 cm increments up to 70 cm using time domain reflectrometry (TDR) probes. A data logger recorded temperature every five minutes and soil moisture every hour to calculate daily averages. A weather station was set up at each site to measure air temperature and precipitation.

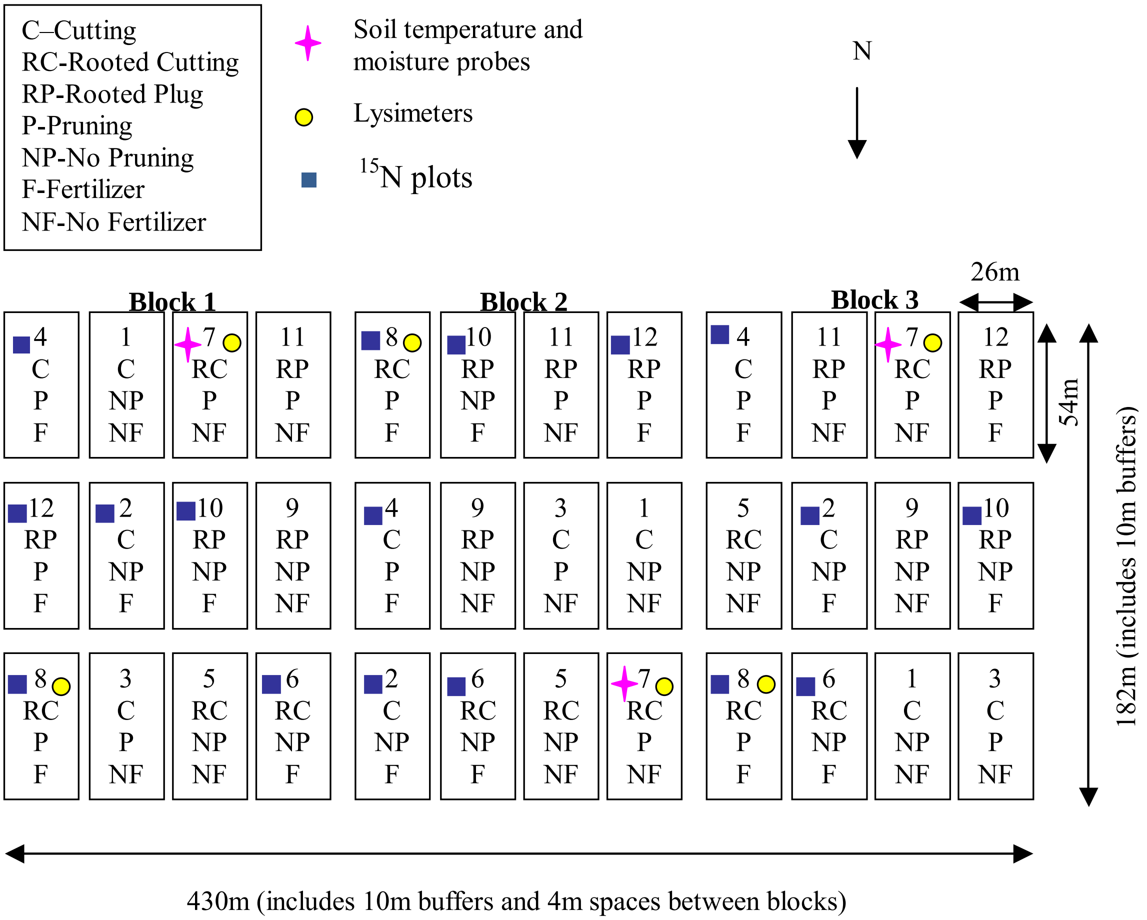

Figure 3.2 Randomized complete block design for the Alfalfa site.

3.2.3 Site preparation

Prior to planting, both sites underwent a mechanical plowing with a tandem disc followed by tillage with a chisel plow. In addition to mechanical tillage, applications of glyphosate were used to control unwanted vegetation and an application of Liunuron was used for residual weed control. Linuron was applied October 22nd and 23rd, 2002 at a rate of 4 kg ha^{-1} within the rows. Glyphosate was applied between the rows at a rate of 2.5 L ha^{-1}. In June 2002, 6336 Walker hybrid poplar seedlings were planted at each 8 ha site.

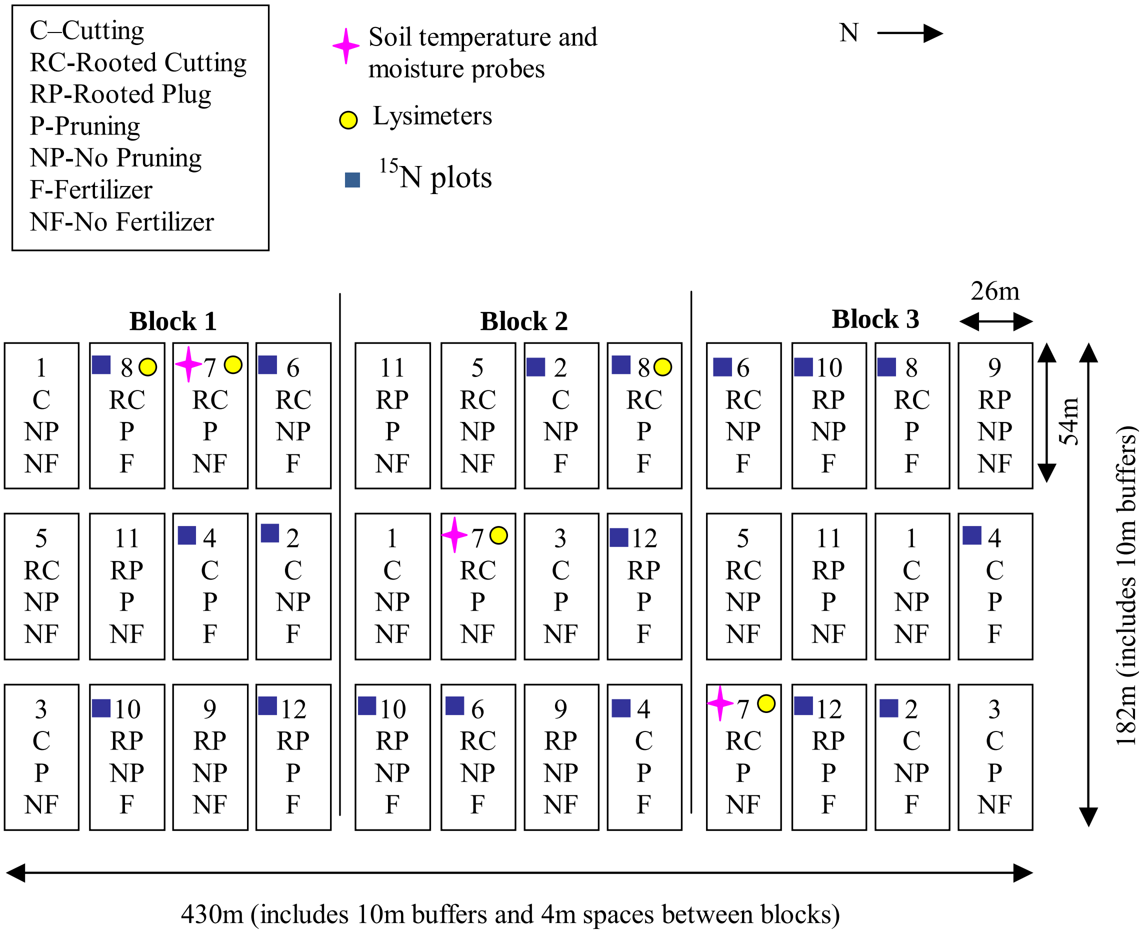

Figure 3.3 Randomized complete block design for the Pasture study site.

3.2.4 Cultural treatments

Three rooting stocks were assessed: cuttings (C), rooted cuttings (RC), and rooted plugs (RP) (Figure 3.4). The cutting and rooted cutting stocks were supplied by the Prairie Farm Rehabilitation Administration (PFRA) Shelterbelt Centre in Indian Head, Saskatchewan. The rooted cuttings were grown in a nursery bed for one year prior to planting. The rooted plugs (cuttings grown in a greenhouse) were supplied by Pacific Regeneration Technologies (PRT) in Prince Albert, Saskatchewan.

Figure 3.4 Three hybrid poplar stock types used in this study. The stock type on the left is a rooted cutting (RC), the center stock type is a rooted plug (RP), and the stock type on the right is a cutting (C).

A pruning treatment was included in this study to determine the effects on seedling growth. Pruning was completed in the spring of the second growing season and each year at the beginning of the growing season for the duration of the study. Pruning was completed by hand with pruning shears prior to bud break. Co-dominant shoots were reduced to one-third of their original length or completely removed in order to encourage the growth of one dominant leading shoot (Figure 3.5).

3.2.5 Fertilizer application

A broadcast application of ammonium nitrate was uniformly applied at a rate of 100 kg N ha^{-1} in June of 2003 (year 2). The ammonium nitrate fertilizer was broadcast using hand-held spreaders and was incorporated to a depth of 7-10 cm with a tandem disk.

The application of dual ^{15}N-labeled ammonium nitrate fertilizer was done similarly to that described by Staples et al. (1999). The trees selected for labeled N fertilization included all three stock types both pruned and un-pruned in each of the three blocks. One tree located outside of the measurement tree plot was randomly selected in

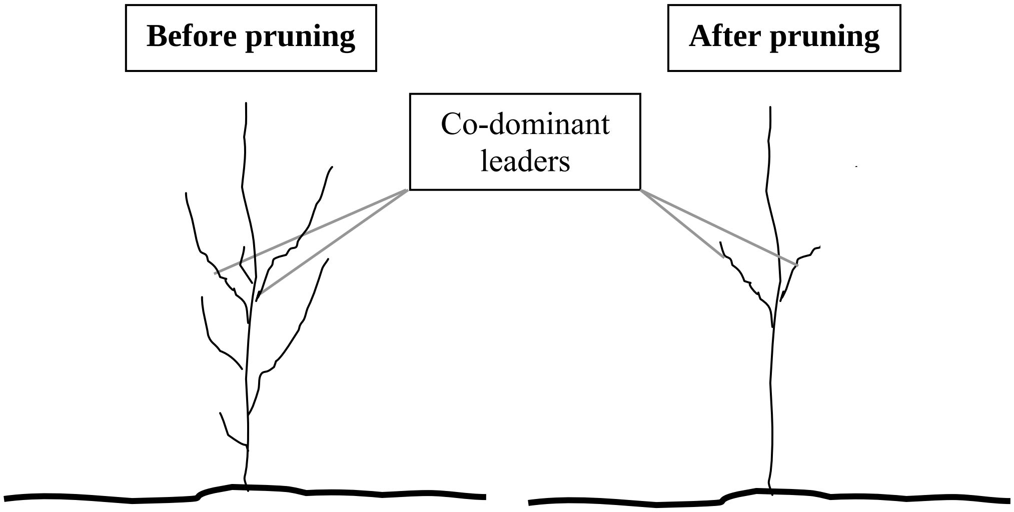

Figure 3.5 Schematic representing a hybrid poplar tree before and after pruning.

each of the fertilizer treatments and received dual-labeled ^{15}N fertilizer on June 3rd, 2003 (year 2). A stock solution of 389 g $L^{-1}$of the 10.4 atom% enriched ammonium nitrate fertilizer was prepared for each site. 18 mL of this solution was diluted into approximately 2 L of water and applied with a watering can to a 1 m^2 area around each tree. Another 2 L of water was applied over the 1 m^2 area and the hybrid poplar tree. Water was applied to the foliage of the hybrid poplar to reduce any foliar uptake of fertilizer. The second application of water also helped wash the N into the soil where it would be less susceptible to volatilization losses. The 1 m^2 area was kept free of weeds until the trees were excavated.

The following day granular ammonium nitrate fertilizer was applied to the same 1 m^2 area to bring the total fertilization rate up to 100 kg N ha^{-1} (25% from 10.4% enriched ammonium nitrate and 75% from non-labeled ammonium nitrate). Applying 75% of the N fertilizer in a granular form to the trees receiving ^{15}N fertilizer was an attempt to keep fertilizer applications as similar as possible. The granular fertilizer was hand-broadcast and incorporated to a depth of 7 to 10 cm using shovels. The fertilizer was applied in this manner because of the high cost of the dual-labeled ammonium nitrate fertilizer. The remaining fertilizer treatments in the study were fertilized with granular ammonium nitrate fertilizer at a rate of 100 kg N ha^{-1}.

3.2.6 Destructive tree sampling

In the second year of the study, 18 trees from each site were destructively sampled on August 26th and 27th, 2003. Trees that received ^{15}N-labeled fertilizer in June of 2003 were harvested. Each tree was excavated to a depth of 40 cm and separated into roots, shoots, and leaves. Roots, shoots and leaves were kept cool using ice packs and insulated coolers until they were brought back to the lab. Root samples were washed free of soil and weighed to determine fresh weight prior to drying. The roots, shoots and leaves were oven-dried at 40^{o}C in a controlled environment for five weeks and weighed.

Roots, shoots and leaves were ground separately in a Wiley mill (0.4mm mesh) and reground in a rotating ball-bearing mill. The samples were analyzed for total % N along with atom % ^{15}N excess using pea grain as the reference (0.36726 atom % ^{15}N). This was done using a TracerMass mass spectrometer interfaced with a RoboPrep sample converter (Europa Scientific, Crewe, U.K.).

3.2.7 Soil sampling

A JMC Backsaver^{TM} probe with a 2 cm diameter aluminum tip was used to take all soil samples. Soil samples were taken from the ^{15}N treatment plots at 0-5, 5-10, 10-15, 15-20, and 20-30 cm depths and oven-dried at 60 ^{o}C for 72 hours. Soil samples were ground in a rotating ball-bearing mill and analyzed for total % N and atom % ^{15}N excess. The results for the atom % ^{15}N were expressed using an atom % ^{15}N of 0.3663 for air as the standard and pea grain as the reference (0.36726 atom % ^{15}N). Additional soil samples were taken from the fertilized and non-fertilized plots. Soils from 0-5, 5-10, 10-15, 15-20, 20-30 cm depths were sampled during the last week in August in 2003 and 2004. Soil samples in the fall of 2003 were only taken to a 20 cm depth as sampling beyond this point was too difficult. Soil samples were only taken from the rooted cutting and rooted plug plots because of the poor survival of the cutting stock. The soil samples were air-dried, ground and passed through a 2mm sieve. Nitrate and exchangeable ammonium N was determined by a 2*M* KCL extraction (Maynard and Kalra, 1993). Extracts were analyzed on a Technicon^{TM} Autoanalyzer^{TM} II colorimeter (Technicon Instrument Corporation, 1972).

3.2.8 Plant tissue sampling (non ^{15}N plots)

Twenty leaves were randomly selected from the top one-third of the trees in the measurement plots for each of the 12 treatments. Leaf samples were collected during the last week in August in 2003 and 2004. Leaf samples were air-dried in a controlled environment for 5 weeks at 40 ^{o}C. The leaf samples were digested using a H_2SO_4-H_2O_2 ashing method (Thomas et al., 1967). N and P concentrations of leaf samples were analyzed using a Technicon^{TM} AutoAnalyzer^{TM} II colorimeter (Technicon Instrument Corporation, 1973).

3.2.9 Tree measurements

Twenty trees in each of the measurement plots were measured at the end of each growing season. Height, height increment and root collar diameter was measured for each treatment. A digital caliper was used to measure root collar diameter and a meter stick was used to measure tree height. Tree volume was calculated using the equation $v=1/3\pi r^2h$.

3.2.10 Statistical analysis

Each site was treated separately with the plot representing the experimental unit in the statistical analyses. All statistical models were tested for homogeneity of variance using Levene's test. If required, a log transformation was used to transform the data for non-homogeneity of variance. Plant recovery of applied ^{15}N fertilizer needed to be ln transformed in order to meet ANOVA assumptions. All data were tested for normality using the Kolmogorov-Smirnov test and the Shapiro-Wilk test. Analysis of variance was used to test for the significance of block effects. No block effects were significant for any treatment. Data were tested using a three-way ANOVA with stock type, fertilizer and pruning being the nominal variables. Post-hoc tests were used to compare treatment means using least significant difference (LSD) at a significance level of $p < 0.05$.

3.3 Results

3.3.1 Tree productivity

At both the Alfalfa and Pasture sites there was no difference between above-ground biomass of shoot material for either the stock or the pruning treatments (Table 3.2). The largest difference in hybrid poplar production occurred at the Alfalfa site where the cutting stock produced only 28% of the root biomass than the rooted cutting and rooted plug stock types. A similar pattern was seen for leaf biomass where trees from the rooted stock type produced only two and a half times more than the cutting stock. This pattern was not seen at the Pasture site where above- and below-ground growth did not differ within stock type or pruning treatments for the root, shoot and leaf measurements. Trees from the rooted cutting and rooted plug stock partitioned biomass in a similar manner at the Alfalfa site. Of the total plant biomass, trees from the cutting stock partitioned 53, 22 and 25% into the shoots, roots and leaves, respectively, while those from rooted stocks partitioned 38, 34 and 28%. The Pasture site had a slightly different allocation of plant biomass with 32, 34 and 33% partitioned between the shoots, roots and leaves for trees in the rooted stock treatment, respectively. For pruned trees, biomass production was allocated to 41, 32 and 27% between the shoots, roots and leaves, respectively, at the Alfalfa site. There was a slight difference in biomass allocation between trees from the pruning treatments at the Pasture site with 35, 33 and 32% for the pruned treatment, and 29, 36 and 34% for those from the non-pruned treatment between shoots, roots and leaves, respectively.

Table 3.2 Above and below-ground biomass of 2-year-old Walker hybrid poplar trees at the Alfalfa and Pasture sites.

Treatment	Tree biomass		
	Shoot (g)	Root (g)	Leaf (g)
		Alfalfa	
Cutting	81.8	33.2b†	37.7b
Rooted cutting	128.8	115.1a	90.2a
Rooted plug	133.8	120.5a	99.7a
Prune	102.0	75.2a	66.4a
No Prune	127.7	103.9a	85.2a
		Pasture	
Cutting	81.7	81.3	83.2
Rooted cutting	109.5	120.5	109.8
Rooted plug	84.7	95.8	91.2
Prune	98.3	92.7	89.9
No Prune	85.5	105.8	99.6

†At each site, treatment means within a column followed by the same letter are not significantly different ($p<0.05$) using least significant differences (LSD), columns with no letters have no significant differences.

3.3.2 Soil N availability

There were no differences in extractable soil N among soil depth, fertilizer treatment and stock type in 2003; however, the extractable soil N at the Alfalfa site was twice that of the Pasture site (Table 3.3). In the year following fertilizer application (2004) there were no significant differences in residual soil N among the soil samples taken from the stock type, pruning and fertilizer treatments (Appendix B). Soil available N (NO_3^- and NH_4^+) in the 0-10 cm depth at the end of the 2004 growing season was 178% greater at the Alfalfa site than the Pasture site. Soil N levels decreased by 42% from the 0-10 cm depth to the 10-20 cm depth but did not differ between the 10-20 cm and 20-40 cm depths at the Alfalfa site in 2004. The Pasture site showed a different pattern for soil N with a decrease of 30% from the 0-10 to the 10-20 cm depth, followed by an increase of 26% at the 20-40 cm depth. Total soil N at the Alfalfa site was 2.9 and 2.3 times greater in 2004 than in 2003 for the Alfalfa and Pasture sites, respectively. Additional soil data is available in Appendix C.

Table 3.3 Total extractable soil N (NO_3 and NH_4) taken during the fall of 2003 and 2004 at the Alfalfa and Pasture hybrid poplar plantations.

Depth	Total Extractable Soil N			
	Alfalfa	Pasture	Alfalfa	Pasture
	2003		2004	
(cm)	(mg g^{-1})			
0-10	35	16	103a‡	37a
10-20	38	17	60b	26b
20-40	nd†	nd	54b	35a

† nd=not determined

‡Means in each column followed by the same letter are not significantly different (p<0.05) using least significant differences (LSD), columns with no letters have no significant differences.

3.3.3 Growth parameters

At each of the two sites, trees from the un-rooted cutting stock were less productive in terms of tree growth than the trees from rooted stock (Table 3.4). Trees in the rooted stock treatment ranged from 3.5 to 4.2 times greater in height and 4.0 to 5.6 times greater in root collar diameter than the trees in the cuttings stock treatment. Furthermore, the survival of hybrid poplar grown from cuttings was 32 and 38% at the

Alfalfa and Pasture sites, respectively, compared to 73 and 69% survival from rooted cuttings and 81 and 62% from rooted plugs. Trees from the rooted plugs were taller and had larger volumes than trees from the rooted cuttings at the Alfalfa site while the opposite was true at the Pasture site. For the Alfalfa site, trees from the rooted plugs were 18% greater in volume, which can be attributed to an 8% increase in tree height as there was no difference between root collar diameters when compared to the rooted cutting trees. At the Pasture site, the rooted cutting trees were 13 and 27% greater in height and root collar diameter than rooted plug trees. The increased height and root collar diameter of trees grown from a rooted cutting, doubled tree volume compared to trees grown from rooted plugs at the Pasture site. Tree volumes at the Alfalfa and Pasture sites were 842 and 993 cm^3 and 551 and 276 cm^3 for the rooted cutting and rooted plug trees, respectively.

Table 3.4 3-year-old growth and survival of Walker hybrid poplar planting stock grown at two sites (Alfalfa and Pasture).

Treatment	Height	RCD†	Volume	Survival
	(cm)	(mm)	(cm^3)	(%)
		Alfalfa		
Cutting	55c‡	8b	29c	38
Rooted cutting	194b	32a	842b	73
Rooted plug	210a	35a	993a	81
		Pasture		
Cutting	40a	5c	6c	32
Rooted cutting	169b	28a	551a	69
Rooted plug	150b	22b	276a	62

†RCD=Root collar diameter

‡For each site, means within a column followed by the same letter are not significantly different (*p*<0.05) using least significant differences (LSD), columns with no letters have no significant differences.

The application of fertilizer N decreased tree volume by 31% at the Alfalfa site compared to non-fertilized trees. After two growing seasons there was a 13% reduction in tree height and a 16% reduction in root collar diameter for fertilized trees at the Alfalfa site when compared to unfertilized trees (Table 3.5). Fertilization had no effect on tree height, root collar diameter or volume at the Pasture site. Survival of fertilized trees was 4 to 5% lower than trees that did not receive any fertilizer at both of the sites (Table 3.5).

Table 3.5 Growth and survival of N-fertilized and non-fertilized hybrid poplar trees grown at two sites (Alfalfa and Pasture), two growing seasons following fertilizer application.

Treatment	Height	RCD†	Volume	Survival
	(cm)	(mm)	(cm^3)	(%)
		Alfalfa		
Fertilizer	162b‡	27b	606b	62
No fertilizer	186a	32a	883a	66
		Pasture		
Fertilizer	118	18	288	52
No fertilizer	121	19	266	57

†RCD=Root collar diameter

‡For each site, means within a column followed by the same letter are not significantly different ($p<0.05$) using least significant differences (LSD), columns with no letters have no significant differences.

Two pruning treatments in the spring of 2003 and 2004 caused a 35% decrease in tree volume at the Alfalfa site compared to trees that were not pruned (Table 3.6). Following two years of successive pruning treatments, there was an 11% decrease in tree height and a 32% decrease in root collar diameter for pruned trees at the Alfalfa site when compared to trees that were not pruned. Annual pruning also decreased tree height and root collar diameter at the Alfalfa site while there were no differences for growth parameters at the Pasture site. Survival of the non-pruned trees was 2% lower at the Alfalfa site and 9% lower at the Pasture site compared to pruned trees.

Table 3.6 Growth and survival of pruned and non-pruned hybrid poplar trees grown at the Alfalfa and Pasture sites following the 2004 growing season.

Treatment	Height	RCD†	Volume	Survival
	(cm)	(mm)	(cm^3)	(%)
		Alfalfa		
Pruned	166b‡	25b	596b	65
Non-pruned	184a	33a	916a	63
		Pasture		
Pruned	122	18	283	59
Non-pruned	116	18	271	50

†RCD=Root collar diameter

‡For each site, means within a column followed by the same letter are not significantly different ($p<0.05$) using least significant differences (LSD), columns with no letters have no significant differences.

3.3.4 Foliar nutrient concentrations

Fertilizer was applied in the spring of 2003. There were no statistical differences between foliar N levels in the fall of 2003 or 2004 for any of the treatments at either site (Appendix B). Foliar N concentration ranged from 20.9 to 22.0 mg g^{-1} at the Alfalfa site in 2003 and increased to 33.9 to 34.1 mg g^{-1} in 2004 (Table 3.7). In 2003 foliar leaf N was 18% higher at the Pasture site than the Alfalfa site. In 2004 values were comparable at both sites. Similar to foliar N levels, there was no difference between foliar phosphorus (P) levels in the fall of 2003 for any of the treatments at either site. Foliar P showed an inverse relationship to that of foliar N at the Alfalfa site between 2003 and 2004. In 2003 foliar P levels ranged from 2.7 to 2.8 mg g^{-1} and decreased to 1.6 to 1.8 mg g^{-1} in 2004 at the Alfalfa site. Foliar P levels were 15% greater at the Alfalfa site than the Pasture site in 2003. In 2004 foliar P levels were 32% greater at the Pasture site. The only measurable difference between treatments occurred at the Alfalfa site during the fall of 2004. At this site trees that received fertilizer had foliar P levels that were 0.2 mg g^{-1} less than those from trees that did not receive fertilizer. There was no effect of fertilizer, pruning or stock type on foliar nutrient concentration for the trees at the pasture site in either 2003 or 2004.

3.3.5 Nitrogen and P ratios

At the Alfalfa site there were no differences in foliar N:P ratios between treatments in either 2003 or 2004 (Table 3.8). Foliar N:P ratios of the hybrid poplar leaves ranged from 7.7 to 8.1 in 2003 and more than doubled in 2004 to 18.9 to 20.9 at the Alfalfa site. Foliar N:P ratios of the trees grown on the Pasture site were 33% greater than those grown at the Alfalfa site in 2003. This relationship was reversed in 2004, where the N:P foliar ratios at the Alfalfa site were 37% greater than those at the Pasture site.

Similar to the Alfalfa site, stock type and pruning treatments had no effect on the foliar N:P ratios in 2003 or in 2004 at the Pasture site. In contrast to the Alfalfa site, N fertilized trees had higher foliar N:P ratios than the unfertilized trees in both years at the Pasture site. For the fertilized trees grown at the Pasture site in 2003 and 2004, foliar N:P ratios increased by 8 and 13% respectively, over the trees that were not fertilized.

Table 3.7 Foliar N and P concentrations for all treatments in the Walker hybrid poplar trees prior to leaf senescence.

Treatment	Foliar N and P concentration			
	2003		2004	
	N (mg g^{-1})	P (mg g^{-1})	N (mg g^{-1})	P (mg g^{-1})
	Alfalfa			
Rooted cutting	21.6	2.7	33.9	1.7
Rooted plug	21.4	2.8	34.1	1.8
Fertilizer	20.9	2.7	33.9	1.6b†
No fertilizer	22.0	2.8	34.1	1.8
Prune	21.4	2.7	34.0	1.7
No prune	21.6	2.8	34.0	1.8
	Pasture			
Rooted cutting	25.7	2.5	33.0	2.2
Rooted plug	25.0	2.3	32.2	2.3
Fertilizer	25.7	2.4	33.0	2.2
No fertilizer	25.0	2.5	32.2	2.3
Prune	25.6	2.5	33.1	2.3
No prune	25.1	2.4	32.1	2.2

†For each treatment and site, means within a column followed by the same letter are not significantly different (p<0.05) using least significant differences (LSD), columns with no letters have no significant differences.

Table 3.8 Foliar N:P ratios for all treatments in the Walker hybrid poplar trees prior to leaf senescence at the Alfalfa and Pasture sites.

Treatment	Alfalfa		Pasture	
	2003	2004	2003	2004
Rooted cutting	8.1†	20.6	10.3	15.2
Rooted plug	7.8	19.2	10.7	13.8
Fertilizer	7.9	20.9	10.9a‡	15.4a
No fertilizer	8.0	18.9	10.1b	13.6b
Prune	8.1	20.4	10.3	14.5
No prune	7.7	19.3	10.7	14.6

† mg g^{-1}/mg g^{-1}

‡ For each treatment, N:P ratio means within a column followed by the same letter are not significantly different (p<0.05) using least significant differences (LSD), columns with no letters have no significant differences.

3.3.6 Recovery of applied fertilizer

Recovery of applied labeled N fertilizer from the soil after one growing season did not exceed 25% for the Pasture or Alfalfa sites (Figure 3.6). Fertilizer recovery showed a similar pattern between both of the sites with the greatest amount of fertilizer recovered in the depths closest to the surface. The trees grown from the cutting and rooted cutting stock type showed a similar pattern of N recovery at the two sites (Figure 3.7). Trees grown from rooted plug stock recovered 45% less total fertilizer N from the top 30 cm at the Alfalfa site than from the Pasture site.

Higher amounts of N derived from fertilizer were present in the leaves than in the shoots and roots at both the Alfalfa and Pasture sites. At the Alfalfa site, fertilizer N recovered in the leaves ranged from 0.8 to 1.9%. At the Alfalfa site there was 55 and 74% less fertilizer N recovered in the plant roots and shoots than in the leaves, respectively. Fertilizer N recovered in the leaves ranged from 2.1 to 2.5% at the Pasture site. The N fertilizer recovered within the roots and shoots was 4.1 and 4.4 times less than N fertilizer recovered in the leaves at the Pasture site, respectively. A similar amount of N fertilizer was recovered in the roots and shoots at the Pasture site. At the Alfalfa site, there was 41% less fertilizer N recovered in the shoots compared to the roots. The total amount of N fertilizer recovered by the trees ranged from 1-3% at the Alfalfa site and 3-5% at the Pasture site.

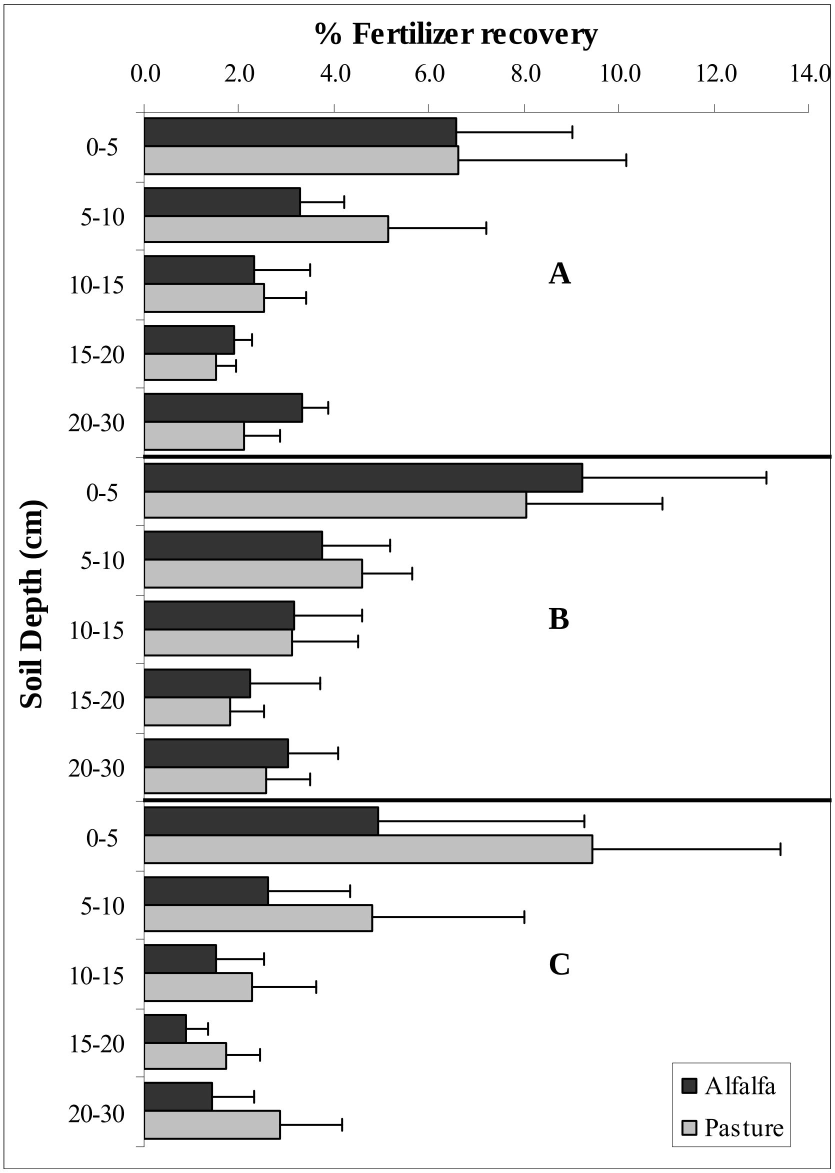

Figure 3.6 Percentage of applied fertilizer N recovered from the soil for the cutting (A) rooted cutting (B) and rooted plug (C) treatments at the Alfalfa and Pasture sites. (error bars represent one standard deviation)

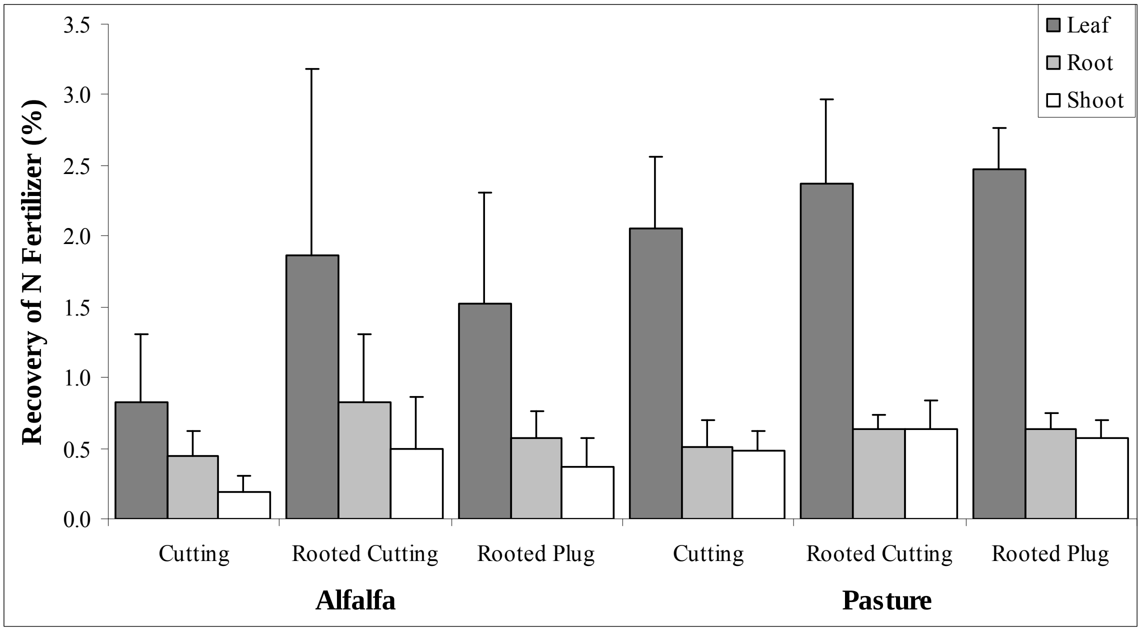

Figure 3.7 Percentage of applied fertilizer N recovered within 2-year-old Walker hybrid poplar trees one growing season following fertilizer application. (error bars represent one standard deviation)

3.4 Discussion

The growth of hybrid poplar is highly dependent on the supply of nutrients that will satisfy the nutrient demand of the hybrid poplar trees. The 100 kg N ha^{-1} of ammonium nitrate that was applied in 2003 was intended to increase soil nutrient supply and hybrid poplar growth. Two years following the application of fertilizer there were no detectable differences in soil nutrient supply between fertilized and unfertilized treatment plots (Appendix B). Soil N supply was different between the two sites and between both years. The soils at the Alfalfa site had at least double the amount of extractable soil N than at the Pasture site. Plant available N ranged from 107 to 211 kg N ha^{-1} in soils following the termination of an alfalfa crop, at four sites in Manitoba (Mohr et al., 1999). In this study, soil N at both sites increased in subsequent years following site establishment. Entz et al. (2001) reported that N concentration in the soil was higher following a continuous alfalfa rotation than a pasture system. Higher soil N values in 2004 compared to 2003 may also be a result of climate in our study (Appendix D). Soil N reserves following a growing season of below average rainfall are underutilized, resulting in large amounts of residual soil N in subsequent years (Kirkegaard, 2001). In this study, 1-5% of the applied fertilizer was recovered in the trees and 11-21% remained in the top 30 cm of the soil. The remainder of the fertilizer N was unaccounted for or lost. Some common losses of N from an agricultural system include: leaching, denitrification, volatilization and uptake by non-target species (Mosier et al., 1998). Uptake from non-target species may not be a system loss, instead N accumulated by competing vegetation can be viewed as long-term storage of N that can be recycled and utilized in subsequent years of the rotation (Staples et al., 1999; Preston and Mead, 1994).

The amount of fertilizer N recovered in the trees at the Pasture site was 2% greater than at the Alfalfa site. The fertilizer recovered in the trees was greater than that found in conifer species by Staples et al. (1999) but less than fertilizer recovered in a study conducted by Choi et al. (2005) where aspen recovered 7.5 to 40.6%. In this study, the majority of the recovered fertilizer N was present in the leaves for both of the sites. Kruse et al. (2003) found when soil N supplies were deficient, the allocation of fertilizer N to younger actively growing leaves was more pronounced than when N supplies were sufficient. Choi et al. (2005) found that over half of the fertilizer N that was taken up by hybrid and trembling aspen accumulated in the tree leaves. In this study there was a slightly different pattern between the two sites with allocation of fertilizer N between the shoots and roots. At the Pasture site, the roots and shoots recovered similar amounts of fertilizer N. At the Alfalfa site, the shoots recovered 41% less fertilizer N than the roots. A deficient soil N supply causes a reallocation of N to promote root growth (Kruse et al., 2003).

The trees grown from rooted stock types partitioned biomass similarly between the roots, shoots and leaves at both sites. At the Alfalfa site trees grown from the cutting stock partitioned 50% of total biomass in the shoots. Among the three stock types the rooted stock trees were superior to the un-rooted stock trees in terms of growth and survival. The advantage of roots at the time of planting was more pronounced at the Pasture site for both tree height and survival. In the boreal region of Alberta heavy grass competition decreased the survival and growth of hybrid poplar trees grown from cuttings (DesRochers et al., 2004). They suggested that cuttings should be planted deeply to avoid the development of too many leaf buds prior to planting. One of the most important factors during root development is the availability of water (Puri and

Thompson, 2003). In this study, the combination of weed competition and low rainfall during the establishment and replanting of the cutting stock contributed to the poor survival and growth of the trees. Other climatic factors such as spring or fall frosts can reduce the productivity of the trees if frost happens prior to bud set. During the fall of 2002 and the spring of 2003 periods of frost resulted in the dieback of the majority of shoot material (Appendix D). Many trees began to re-grow from the base of the tree, essentially losing all of the above-ground growth from 2002. Trees recovered quickly as roots established in the first year were still there to provide the trees with an early start. In field studies, the timing of bud set is influenced by a multiplicity of factors and their interactions including day length, soil moisture, and soil nutrients (Howe et al., 2000).

Fertilizer and pruning treatments had no effect on plant growth at the Pasture site. The addition of fertilizer and tree pruning decreased height, root collar diameter and volume of trees at the Alfalfa site. Decreases in plant growth from pruning can be expected as plant material is removed, possibly leading to an increase in disease susceptibility. The decreased plant growth with the addition of fertilizer was an unexpected result. Positive and negative responses to fertilizer have been seen in agroforestry systems (DesRochers et al., 2006). Lower than average rainfall, weed competition and unbalanced fertility contributed to the decrease in tree height for this study.

Foliar levels of N and P measured at the end of the 2003 and 2004 growing seasons were not influenced by treatment. Differences in foliar nutrient levels were more noticeable between years and sites rather than treatments. In 2003, trees from the Alfalfa site had foliar N levels below the suggested sufficiency level of 25 mg g^{-1} (Heilman and Xie, 1993; van den Driessche, 1999). The foliar N levels for the trees at the Pasture site during this time were at or above sufficient levels. This contradicts the extractable soil N level where the Alfalfa site had higher rates of N supply. Foliar P levels in the hybrid poplar trees were near or above a recommended sufficiency level of 2.5 mg g^{-1} at both sites in 2003 (Heilman and Xie, 1993; van den Driessche, 1999). In 2003, the foliar concentrations of N and P indicate the trees at the Alfalfa site will be more responsive to N fertilizer than the trees at the Pasture site.

Foliar N levels increased above 30 mg g^{-1} for the trees at both the Alfalfa and Pasture sites in 2004 regardless of treatment. Foliar levels increased even though fertilizer was not applied in 2004. Soil N increased at both sites from 2003 to 2004 and is likely the reason foliar levels of N increased. The increase in soil N regardless of fertilizer application suggests this was a result of increased mineralization or residual soil N that was not utilized in 2003. Brown and van den Driessche (2005) found significant responses to both N and P fertilizers among hybrid poplars with similar foliar N concentrations to those at the Alfalfa site. Foliar P levels decreased by 1.0 mg g^{-1} for the trees at the Alfalfa site and to a lesser extent at the Pasture site. Foliar P levels were below sufficiency levels at both sites in 2004. Low P fertility as well as an increased P demand in 2004 may be the cause of the low foliar P levels in the trees. Foliar P levels were the lowest at the Alfalfa site and approached concentrations of 1.5 mg g^{-1} which is considered to be the critical level (van den Burg, 1985).

To better understand the relationship between foliar N and P levels, concentrations can be looked at in more detail as a ratio. Preliminary research conducted by Zabek (2001) has suggested that a foliar N:P ratio of 9.5 corresponds with differences in tree growth responses to applied N and P fertilizers. A N:P ratio below 9.5 indicates a N deficiency while an N:P ratio above 9.5 indicates a P deficiency. Low N:P ratios from the trees at the Alfalfa site in 2003 are consistent with the low foliar N ratios and suggest that the trees at this site were limited by N. In 2004, the opposite trend was seen with a higher soil N supply, higher foliar N concentration and higher N:P ratios. The high N:P ratios of the tree leaves and low foliar P concentrations suggest that the nutrient dynamics changed in 2004. Foliar N and P measurements indicate that both sites should respond to fertilizer application, specifically P fertilizers. Trees at the Alfalfa site should benefit more from the addition of P fertilizer as trees at the Pasture site are more in balance. The difference in P uptake by the hybrid poplar trees between the two sites may be explained by site history. Alfalfa has been used in P contaminated soils to deplete high levels of soil P. This practice is successful if the Alfalfa is properly managed and above ground biomass is permanently removed from the field (Gaston et al., 2003). The amount of nutrients that are taken up by pasture grass species are similar to the nutrients released by the animals grazing the pasture (Pederson et al., 2002). These previous statements relate to the management histories of the two sites. The difference between the two sites would be the net exports of P from the Alfalfa site as hay, leading to lower levels of soil P. There would be more P returned to the soil and less P removed at the Pasture site. Soil P samples need to be taken to confirm low supply rates.

3.5 Conclusion

Trees planted as cuttings are at a greater risk of dying compared to those planted as rooted cuttings or rooted plugs. This is most evident in the survival rates of trees from the different stocks where less than 40% of the trees planted as cuttings survived in each year they were planted. High mortality for cuttings required extensive replanting operations by hand and on a large scale application, the cost of replanting this stock can be substantial. Replanting has to be done by hand as mechanical equipment cannot maneuver within plantations that already have two or three year old trees. The main difference between the cutting and rooted cutting stocks was the presence of live roots at the time of planting. Research using growth promoting hormones and high quality cutting stock may increase the viability of planting un-rooted stock types. Pruning reduced tree height and root collar diameters at the Alfalfa site and had no effect on tree growth at the Pasture site. The addition of N fertilizer either decreased or had no effect on tree growth. The majority of the fertilizer N was partitioned within the leaves and was similar for all stock types. Low concentrations of N in the foliage indicated that the trees should have responded to N fertilizer in 2003. The resulting decrease or no response from fertilizer was likely due to climatic factors, competition from weeds and inadequate levels of soil P. In 2004, foliar nutrient analysis indicated that trees at both sites had sufficient levels of N. Foliar P levels decreased below sufficient levels in 2004 making P more limiting than N. The more severe deficiencies of P at the Alfalfa site suggest it could be more responsive to P fertilizer application than trees at the Pasture site.

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4. SOIL NUTRIENT SUPPLY AND FOLIAR NUTRIENT CONCENTRATIONS AMONG FOUR HYBRID POPLAR CLONES

4.1 Introduction

The idea of utilizing fast growing hybrid poplar plantations for the production of marketable wood products (agroforestry) has been gaining popularity in the last ten years. This interest has stemmed from the increasing global demand for timber products, low agricultural commodity prices and public pressure placed on the forestry industry to manage timber resources in a sustainable way. Agroforestry provides an alternate source of timber resources by utilizing short-rotation woody crops on agricultural land rather than timber from forests. This practice has the potential to alleviate the harvesting pressure on natural forests as well as provide an alternative source of income for agricultural producers. Plantations are managed similarly to conventional agriculture systems including such practices as weed control, tillage and fertilizing. There are no large-scale (> 20 ha) intensively managed plantations on agricultural land in Saskatchewan.

In the experiment described in Chapter 3, a one-time application of N fertilizer was added in the second year of plantation growth to evaluate fertilizer response. No positive growth response was recorded from the Walker hybrid poplar in that study. Desrochers et al. (2006) found that N fertilization reduced height and basal diameter rather than increasing early growth and plantation establishment. Coleman et al. (2006) achieved consistent positive responses to repeated fertilizer applications for three years in a four-year old hybrid poplar plantation. Because of the mixed results of early fertilization in forestry, seedling fertilization has not become a regular practice (Rose and Ketchum, 2002). Achieving positive results may depend on a variety of factors including fertilizer formulation, rate and placement of fertilizer, stock type, site characteristics and vegetation control (Brockley, 1988; Rose and Ketchum, 2002). Responses to fertilizer may be delayed until the third year following fertilizer application (DesRochers et al., 2006). Any treatments that increase early growth or establishment will ultimately be advantageous to hybrid poplar producers, by reducing the time to harvest, thereby increasing stand productivity. Ensuring that the nutritional requirements are met during the initial stages of plantation establishment will encourage successful development and early growth.

The objective of this study was to determine the effect of successive annual applications of N fertilizer on the growth of four hybrid poplar clones planted in northwestern Saskatchewan. The specific objectives were to: 1) identify one or more hybrid poplar clones suited for the boreal transition ecoregion of Saskatchewan; and 2) evaluate the response of four hybrid poplar clones to three rates of N fertilizer.

4.2 Materials and Methods

4.2.1 Site description

The two hybrid poplar plantations used for this study are situated adjacent to the larger scale plantations at the Alfalfa and Pasture sites described in Chapter 3. The site description can be found in section 3.2.1 in Chapter 3.

Both sites (1.7 ha at each site) were prepared in 2002 using a tandem disc followed by repeated tillage with a chisel plow. Prior to planting in June of 2003, a mixture of trifluralin and metribuzin soil-applied herbicide was applied to provide residual weed control at both sites. The trifluralin was applied at a rate of 5 L ha^{-1}, and the metribuzin was applied at a rate of 395 g ha^{-1}. Both herbicides where applied in the same application and incorporated to a depth of 5 cm using a chisel plow in two directions. Seedlings (900 per site) were planted on June 4th (2003) at the Alfalfa site and June 5th (2003) at the Pasture site. Planting material included clones Walker (*Populus deltoides* x *Populus petrowskyana)*, Hill *(Populus deltoides* x *Populus petrowskyana*), Katepwa (an open pollinated Walker seedling) and WP-69 *(Populus x* 'Walker' x *Populus petrowskyana).* WP-69 was officially named Okanese in 2007.

4.2.2 Experimental design

The experiment was designed to determine the relationship between three N rates on four poplar clones during the first two years following establishment. The three different fertilizer rates were 0, 150 and 300 kg N ha^{-1} applied each year of the study to all clones. The treatments were planted in a 3 X 4 randomized complete block design and replicated three times at both the Alfalfa (Figure 4.1) and the Pasture (Figure 4.2) sites. In each plot there were 25 trees that were spaced 2.5 m X 3.5m with nine measurement trees in the middle of each plot.

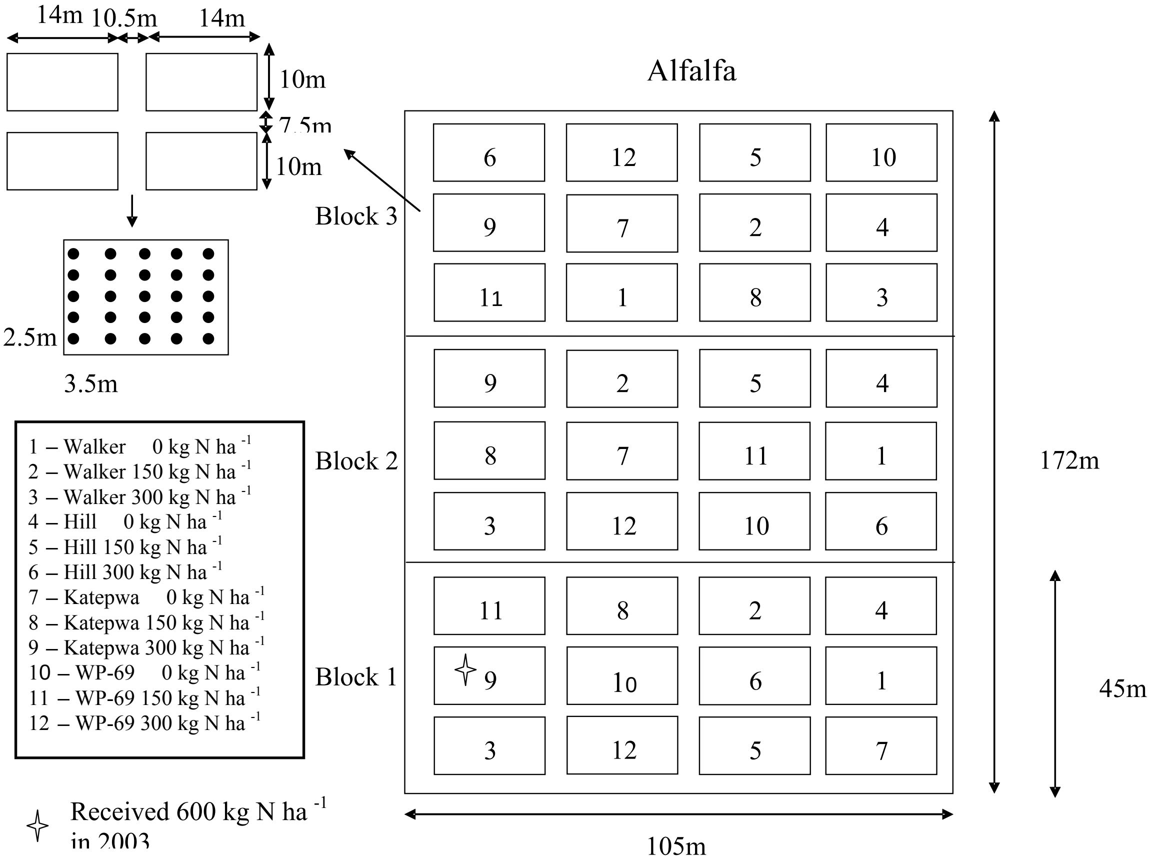


Figure 4.1 Randomized complete block design for the Alfalfa site.

4.2.3 Fertilizer application

Fertilizer was broadcast with the same equipment as the study in chapter 3 (section 3.2.5). The three different rates of ammonium nitrate (0, 150 and 300 kg N ha^{-1}) were applied July 21st (Alfalfa site) and July 22nd (Pasture site) 2003. The fertilizer was not incorporated into the soil. The fertilizer application was repeated in the same manner June 10th, 2004. The three rates were chosen to represent a control, sufficient and an excessive amount of N fertilizer (0, 150 and 300kg N ha^{-1}, respectively). In 2003, treatment 9 at the Alfalfa site inadvertently received an application of 600 kg N ha^{-1}.

During 2004, treatment 9 at the Alfalfa site was treated in the same manner as the other 300kg N ha^{-1} treatments.

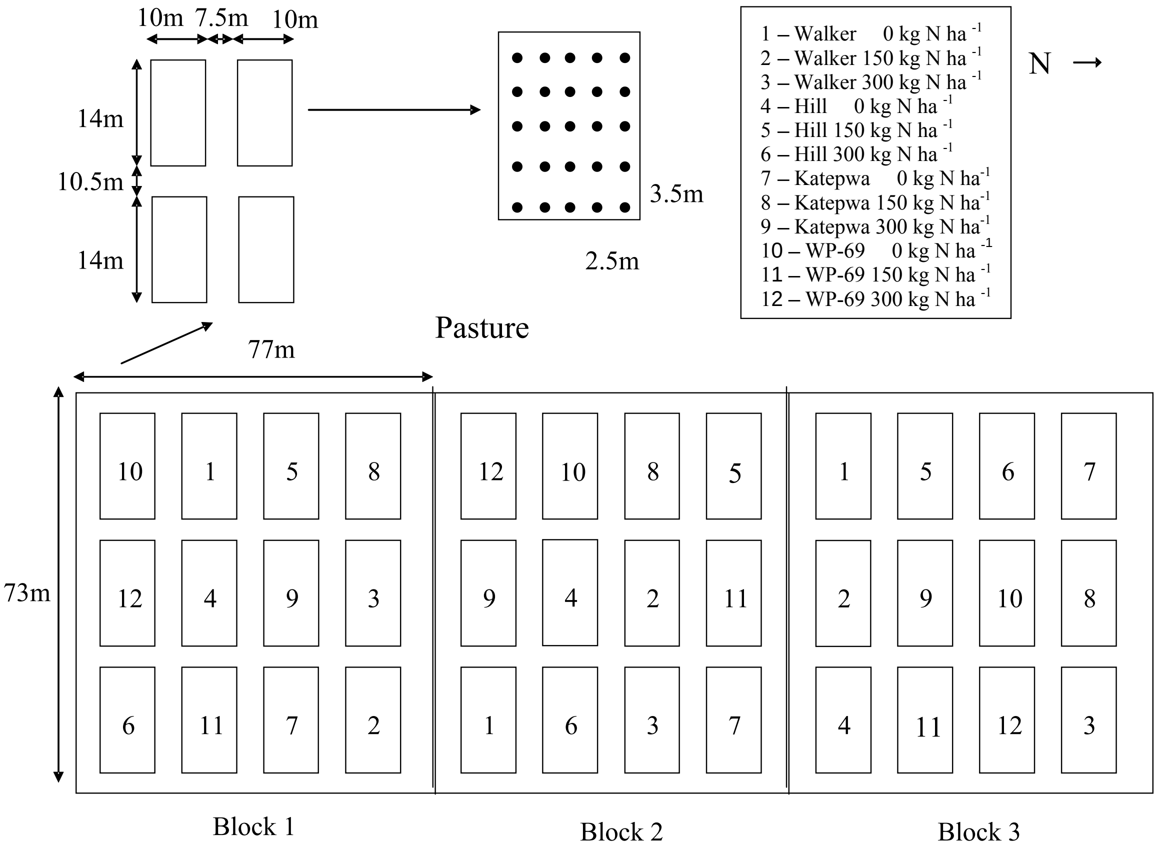


Figure 4.2 Randomized complete block design for the Pasture site.

4.2.4 Plant tissue

Twenty-five leaves were randomly selected from the top third of the nine measurement trees from all the plots during the fall of 2003. In 2004, the 25 leaf samples were collected at the end of every month between May and October. The leaves were air-dried in a controlled environment for 5 weeks at 40 ^{o}C and 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 N and P concentrations were determined on a Technicon^{TM} AutoAnalyzer^{TM} II colorimeter (Technicon Industrial Systems, 1973).

4.2.5 Resorption efficiency

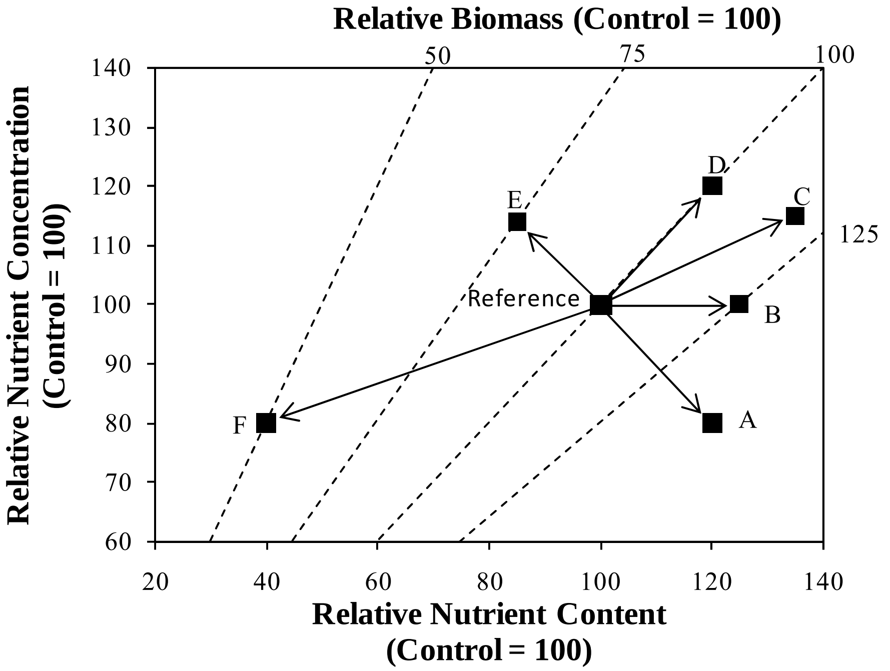
Resorption efficiency is defined as the amount of a nutrient resorbed during senescence and is expressed as a percentage of the total amount of nutrient present in the leaves prior to senescence (Aerts, 1996). Nutrients that are mobilized and moved into other plant tissues can be used in the future to support biosynthesis for growth or other plant functions (Chapin et al., 1990). Nutrient resorption efficiencies in this study are reported as a concentration per unit mass. Mass-based measurements may not account for the changes in specific leaf mass, however, the amount of leaf mass lost during leaf senescence is generally only 0 to 10% (Chapin et al., 1990). The error involved in calculating nutrient resorption on a mass-based estimate is relatively small (Aerts, 1996).

4.2.6 Vector analysis

Vector analysis allows for simultaneous comparison of plant growth, nutrient concentration and nutrient content in an integrated graphical format (Haase and Rose, 1995). In practice, vector analysis is independent of critical nutrient values and optimum ratios as seedlings are evaluated against a common reference (Timmer, 1991). For each treatment, leaf biomass, nutrient concentration and nutrient content from samples collected in July were compared at each site for foliar N and P. For each analysis, the data were normalized relative to the 0 kg N ha^{-1} fertilizer treatment within each hybrid poplar clone. The interpretation of the vector diagrams are based on the magnitude and direction of each vector (Haase and Rose, 1995). Vector movement along the nutrient content, nutrient concentration and biomass axes are observed as an increase (+), decrease (-), or no change (o) relative to the reference (Imo and Timmer, 1998). Diagonal isolines are drawn through selected data points, as well as the reference point, and correspond to the relative biomass. Arrow lines are also drawn into the vector nomograms to aid in the interpretation of treatment responses (Figure 4.3).

4.2.7 Soil sampling

A JMC Backsaver^{TM} probe with a 2 cm diameter aluminum tip was used to take soil samples. Soil samples were collected from 0-5, 5-10, 10-15, 15-20, 20-30, 40-50, and 50-60 cm depths from the measurement plots at both sites in 2004. A composite sample of six soil cores was taken from each treatment. Each treatment from each block and site were analyzed separately. A JMC Backsaver^{TM} probe was used to collect the soil



Shift	Biomass	Concentration	Content	Nutrient Status	Possible Diagnosis
A	+	-	+	Non-limiting	Dilution
B	+	o	+	Non-limiting	Sufficiency
C	+	+	+	Limiting	Deficiency
D	o	+	+	Non-limiting	Luxury consumption
E	-	++	+,-	Excess	Toxic accumulation
F	-	-	-	Limiting	Induced deficiency

Figure 4.3 Interpretation of directional vector shifts in relative biomass, nutrient concentration and nutrient content. The reference point represents the control treatment normalized to 100. Dashed lines represent relative biomass isolines. Directional arrows (A to F) indicate nutrient status based on the direction and magnitude of vector shift (modified from, Timmer 1991).

samples in the spring (2nd week of May), mid-season (after fertilizing in the 2nd week of June) and fall (last week in August). The soil samples were air-dried and ground to pass a 2 mm sieve. Nitrate and exchangeable ammonium N were determined by a 2*M* KCL extraction (Maynard and Kalra, 1993). Extracts were analyzed using a Technicon^{TM} AutoAnalyzer^{TM} II colorimeter (Technicon Industrial Systems, 1972).

In addition to the conventional 2*M* KCL extraction soil test, plant root simulator (PRS)^{TM} probes (Western Ag Innovations Inc., Saskatoon, SK) were used in 2004 to estimate soil nutrient supply rates. At each site, two pairs of PRS^{TM} probes (2 cation probes, 2 anion probes) were inserted into the soil in each of the measurement plots.

PRS^{TM} probes were buried for a period of four weeks before being replaced with new PRS^{TM} probes. PRS^{TM} probes were inserted into the original slot for all five burial periods beginning May 12th. The first set of probes were replaced on June 9th and fertilizer was applied June 10th. Following the burial period the PRS^{TM} probes were collected and sent to Western Ag Labs for determination of ammonium and nitrate. Laboratory results are expressed as µg of nutrient per 10 cm^2 over a period of 4 weeks.

4.2.8 Tree measurements

Nine trees (hereafter called measurement trees) in each of the plots were measured in October, 2003 and each month during the growing season (May to October 2004) for height, height increment, and root collar diameter. A digital caliper was used to measure root collar diameter and a meter stick was used to measure tree height. Tree volume was calculated using the equation $v=1/3\pi r^2 h$.

4.2.9 Statistical analysis

Each site was treated separately with the plot representing the experimental unit in statistical analyses. All statistical models were tested for homogeneity of variance using Levene's test. If required, a log transformation was used for data with non-homogeneity of variance. Analysis of variance was used to test for the significance of block effects. There were no significant block effects for any treatment. Data were tested using a two-way ANOVA with fertilizer rate and hybrid poplar clone being the nominal variables. Post-hoc tests were used to compare treatment means using least significant difference (LSD) at a significance level of $p < 0.05$.

4.3 Results

4.3.1 Nutrient supply rates

Total N supply (NO_3, NH_4) was not influenced by type of clone (Appendix E). Total N supply was influenced by fertilizer rate (Table 4.1). Throughout the growing season plots that received a spring application of fertilizer had higher rates of soil N supply than those that did not receive fertilizer for both of the sites. Soil N increased with increasing rate of fertilizer application for the first four burial periods (May through August determined by PRS probes) at the Alfalfa site. At the Pasture site, soil N supply rates were greater in the fertilizer treatment plots for the burial periods June through

September compared to the non-fertilized treatments. At the Alfalfa site the highest supply rates during the growing season occurred with the 300 kg N ha^{-1} treatment with a range of 1058-1759 μg/10cm^2/4weeks followed by the 150 kg N ha^{-1} treatment with a range of 579-1316 μg/10cm^2/4weeks and lastly the control with a range of 187-574 μg/10cm^2/4weeks. A similar trend was seen at the Pasture site; however, total soil N supply rates were 13, 36 and 7% greater for the 300, 150 and 0 kg N ha^{-1} treatments, respectively at the Alfalfa site. Soil N supply rates peaked following fertilization in June at both sites for the 150 and 300 kg N ha^{-1} treatments. The highest supply rate for the control treatment at the Alfalfa site occurred during September followed by May. At the Pasture site the highest soil N supply for the control treatment occurred during the first measurement in May and was more than three times higher than any of the following months. Soil N supply rates for the 150 and 300 kg N ha^{-1} treatments were at their lowest during July at the Alfalfa and Pasture sites. Soil N supply rates in July at the Alfalfa site were 48 and 60% of those measured during June for the 150 and 300 kg N ha^{-1} treatments, respectively. At the Pasture site soil N supply rates in July were 27 and 42% of those measured during the previous month for the 150 and 300 kg N ha^{-1} treatments.

Table 4.1 Available soil N supply rate (μg/10cm^2/4 weeks) (NO_3 and NH_4) in the hybrid poplar plantations during the 2004 growing season.

Treatment	Total N supply rate				
	May	June†	July	August	September
			Alfalfa		
0 kg N ha^{-1}	574c‡	331c	192c	187c	631b
150 kg N ha^{-1}	861b	1316b	579b	782b	1201a
300 kg N ha^{-1}	1124a	1759a	1058a	1203a	1382a
			Pasture		
0 kg N ha^{-1}	927b	271c	150c	171c	265c
150 kg N ha^{-1}	1037a	1170b	321b	544b	410b
300 kg N ha^{-1}	1352a	1606a	671a	1189a	949a

† Fertilizer was applied one day after June probes were placed in the soil.

‡ For each site, means within a column followed by the same letter are not significantly different (*p*<0.05) using least significant differences (LSD), columns with no letters have no significant differences.

4.3.2 Extractable soil N

Extractable soil N (NH_4, NO_3) values at the Alfalfa site were highest for all three sampling periods in the 0 to 5 cm depth for each of the three fertilizer treatment plots and decreased with soil depth (Figure 4.4). Soil N levels were highest at the Alfalfa site in the 300 kg N ha^{-1} treatment plots and ranged from 167 to 206 mg g^{-1} for the 0 to 5 cm depth in the spring, mid-season and fall soil samples. In the top 20 cm, soil N for the 0 kg N ha^{-1} and 150 kg N ha^{-1} averaged 71 and 41 % less than the 300 kg N ha^{-1} treatment plots at the Alfalfa site, respectively. During the spring and fall at the Alfalfa site 50, 62 and 67% of the total extractable soil N was available in the top 15 cm for the 0, 150 and 300 kg N ha^{-1} treatments, respectively. Levels of soil N below 40 cm were similar between the fertilizer treatments and ranged between 15 and 30 mg g^{-1}.

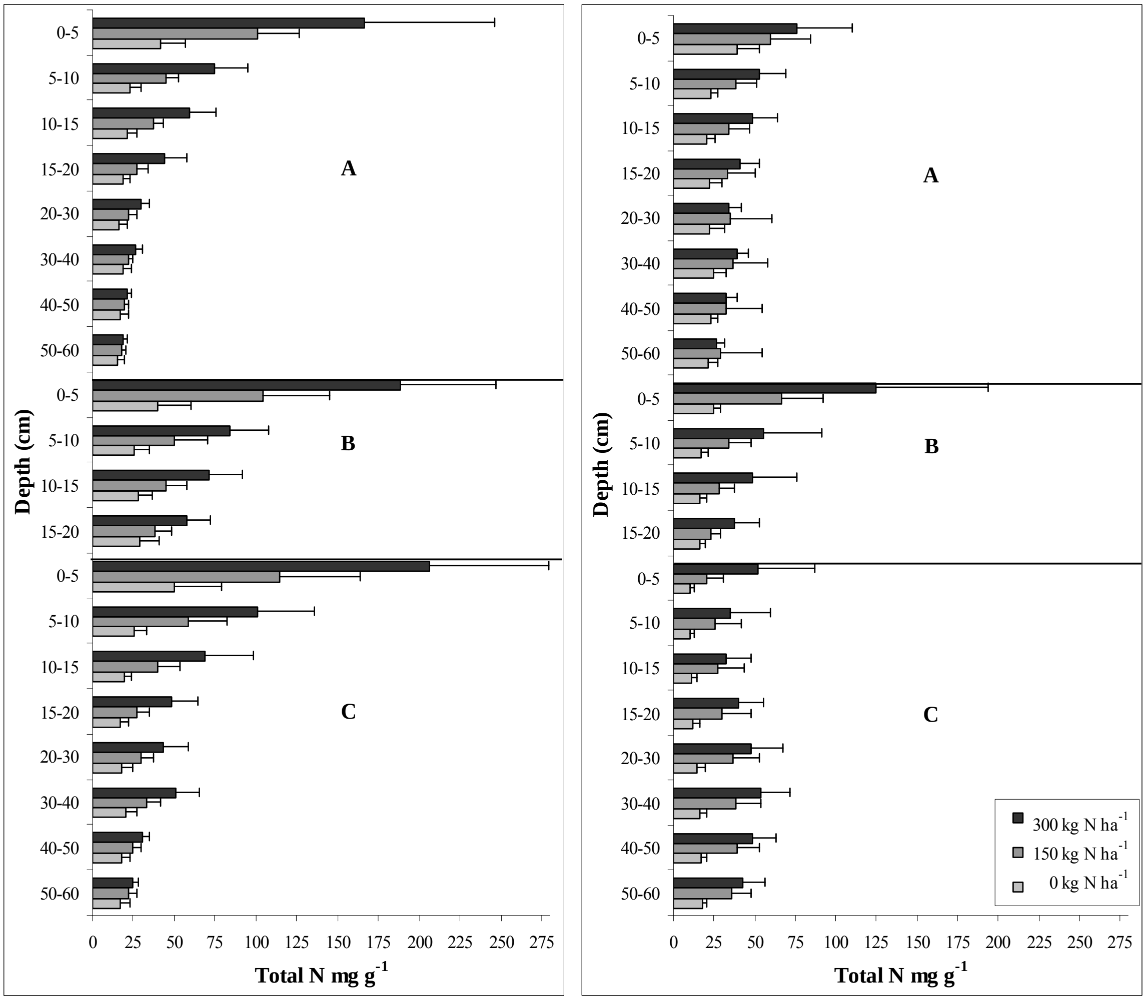


Figure 4.4 Mean extractable soil N (NO_3 and NH_4) for the Alfalfa (left) and Pasture (right) sites during the 2004 growing season in the spring (A), mid-season (B) and fall (C). (error bars represent one standard deviation)

Soil N values in the top 20 cm at the Pasture site were 34, 39 and 45% less than the soil N at the Alfalfa site for the 0 kg N ha^{-1}, 150 kg N ha^{-1} and 300 kg N ha^{-1}

treatment plots, respectively. Soil N at the Pastures site did not show the same relationship between depth or sample date as the Alfalfa site. Soil N levels at the Pasture site peaked during mid-season at 125 mg g^{-1} in the 0 to 5 cm depth for the 300 kg N ha^{-1} treatment. Within the top 20 cm, soil N was 65 and 35% lower for the 0 kg N ha^{-1} and 150 kg N ha^{-1} compared to the 300 kg N ha^{-1} treatment plots at the Pasture site. For the Pasture site 60, 62, and 65% of the total soil N measured was found in the top 30 cm for the 0 kg N ha^{-1}, 150 kg N ha^{-1} and 300 kg N ha^{-1} treatments, respectively. At the Pasture site there was an increase of 22 mg g^{-1} moving from the 10 to 15 cm depth to the 30 to 40 cm depth in the 300 kg N ha^{-1} treatment plot and a 18 mg g^{-1} increase from the 0 to 5 cm depth to the 30 to 40 cm depth in the 150 kg N ha^{-1} treatment.

4.3.3 Tree growth

Tree height at the end of the second growing season (2004) was highest for the Katepwa clone with a height of 176 cm at the Alfalfa site (Table 4.2). The WP-69, Hill and Walker clones were 5, 31 and 40% shorter than the Katepwa clone at the Alfalfa site. WP-69 had the largest root collar diameter of 33 mm, which was double that of the Walker clone. Both Katepwa and WP-69 clones were tall with large RCD's resulting in both clones having the largest seedling volumes of 417 and 546 cm^3, respectively. The Hill and Walker clones had 68 and 80% less volume than the WP-69 clone. Survival of the Hill, Katepwa and WP-69 clones were comparable and all above 90%, while only 52% of the Walker clones survived at the Alfalfa site.

Similar trends in height, root collar diameter and survival were observed in the Pasture site in 2004. The Katepwa and WP-69 clones both had similar heights at the Pasture site, growing over 200 cm. The Hill and Walker clones were 23 and 34% shorter than the Katepwa clone. The WP-69 clone also had the greatest root collar diameter at the Pasture site and was 1.8 times greater than the Walker clone. At the Pasture site tree volume of the WP-69 clone was 1147 cm^3; 1.5, 2.6 and 4.1 times greater than the Katepwa, Hill and Walker clones, respectively. Total tree volumes were 1.8 to 2.5 times greater at the Pasture site than at the Alfalfa site. Survival was comparable between both sites with over 90% of the Katepwa, Hill and WP-69 clones surviving. Survival of the Walker clone was 52 and 56% at the Alfalfa and Pasture sites, respectively.

Table 4.2 Growth and survival of hybrid poplar clones grown at the Alfalfa and Pasture sites after two years of growth.

Treatment	Height (cm)	RCD† (mm)	Volume (cm^3)	Survival (%)
		Alfalfa		
Hill	122c‡	22c	177b	93
Katepwa	176a	29b	417a	99
Walker	105d	17d	111c	52
WP-69	168b	33a	546a	98
		Pasture		
Hill	161b	31c	439c	96
Katepwa	208a	36b	750b	99
Walker	137c	25d	278d	56
WP-69	200a	45a	1147a	94

†RCD=Root collar diameter

‡For each site, means within a column followed by the same letter are not significantly different (*p*<0.05) using least significant differences (LSD) columns with no letters have no significant differences.

Trees were browsed by animals during the fall of 2003 into the spring of 2004 causing a reduction in tree height (Figure 4.5). Patterns of monthly height growth were similar among clones through the months of October 2003 to October 2004 at both of the study sites. At the Alfalfa site, clones WP-69 and Walker experienced 24 and 51% less damage from animal browsing than the Hill and Katepwa clones, respectively. Between August and September the height growth of the Katepwa clone increased three times more than the WP-69 clone and doubled the increase of the Walker and Hill clones at the Alfalfa site. The decrease in height growth during the winter of 2003/2004 at the Pasture site was similar to the Alfalfa site for the clones Katepwa, Walker and Hill. Browsing of WP-69 trees at the Pasture site was negligible. Variations in monthly growth increases among clones were less pronounced at the Pasture site than at the Alfalfa site. Additional tables for monthly growth, RCD and volume are included in Appendix F.

At the Alfalfa site the tallest trees, at 167 cm, were within the control treatment of 0 kg N ha^{-1} (Table 4.3). The trees in the 150 kg N ha^{-1} and the 300 kg N ha^{-1} treatments had equal heights at the Alfalfa site and were up to 18% shorter than trees in the control treatment. At the Pasture site the trees in the 300 kg N ha^{-1} treatment were 13% shorter than the average height of the trees in the 0 kg N ha^{-1} and the 150 kg N ha^{-1} treatments. Root collar diameter for the trees in the 150 kg N ha^{-1} and the 300 kg N ha^{-1} treatments were 20% less than the control treatment at the Alfalfa site.

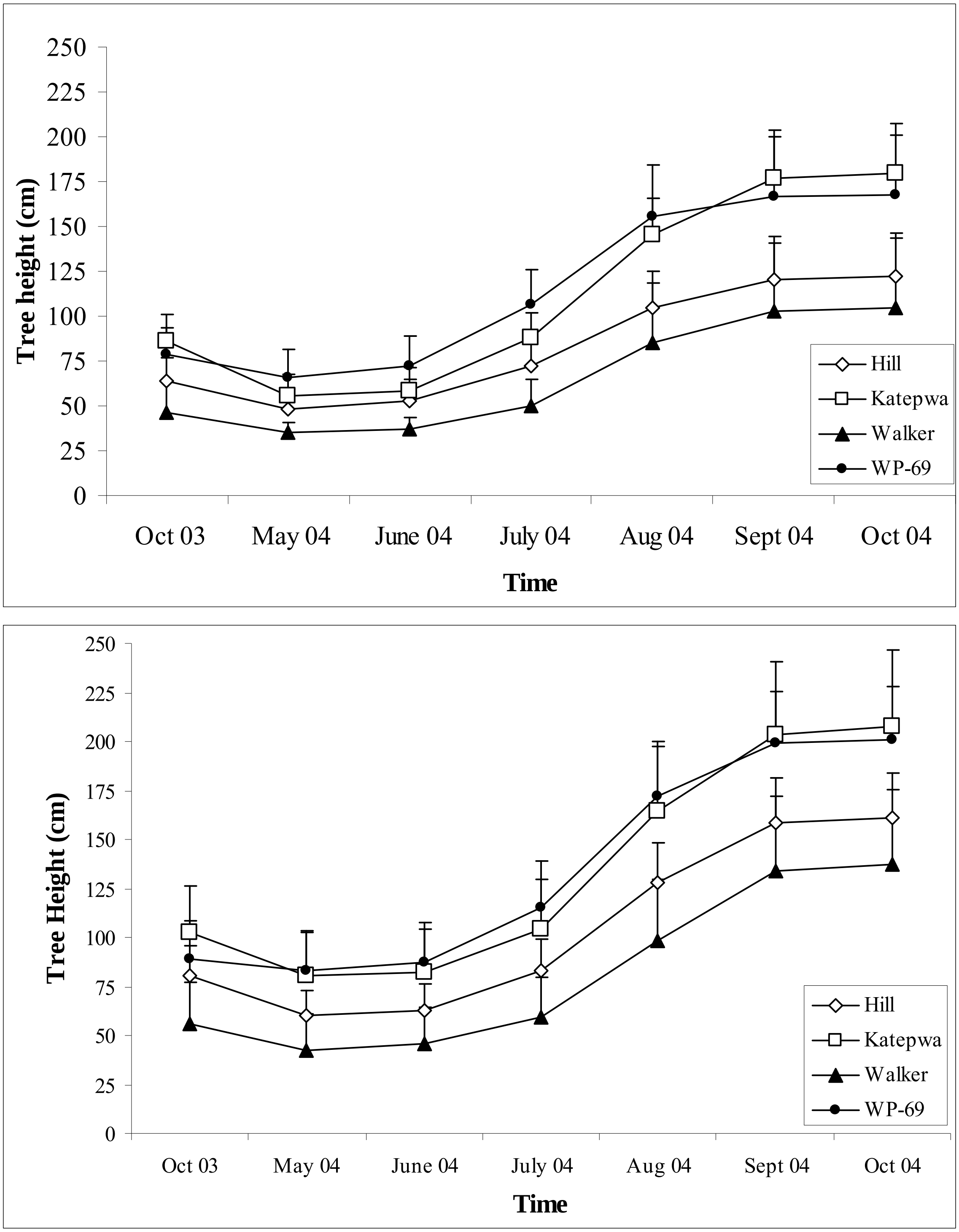


Figure 4.5 Monthly height growth for hybrid poplar clones in the 2004 growing season at the Alfalfa (top) and Pasture (bottom) plantations. (error bars represent one standard deviation)

Table 4.3 Growth of hybrid poplar trees influenced by annual fertilizer application following two years of growth at the Alfalfa and Pasture sites.

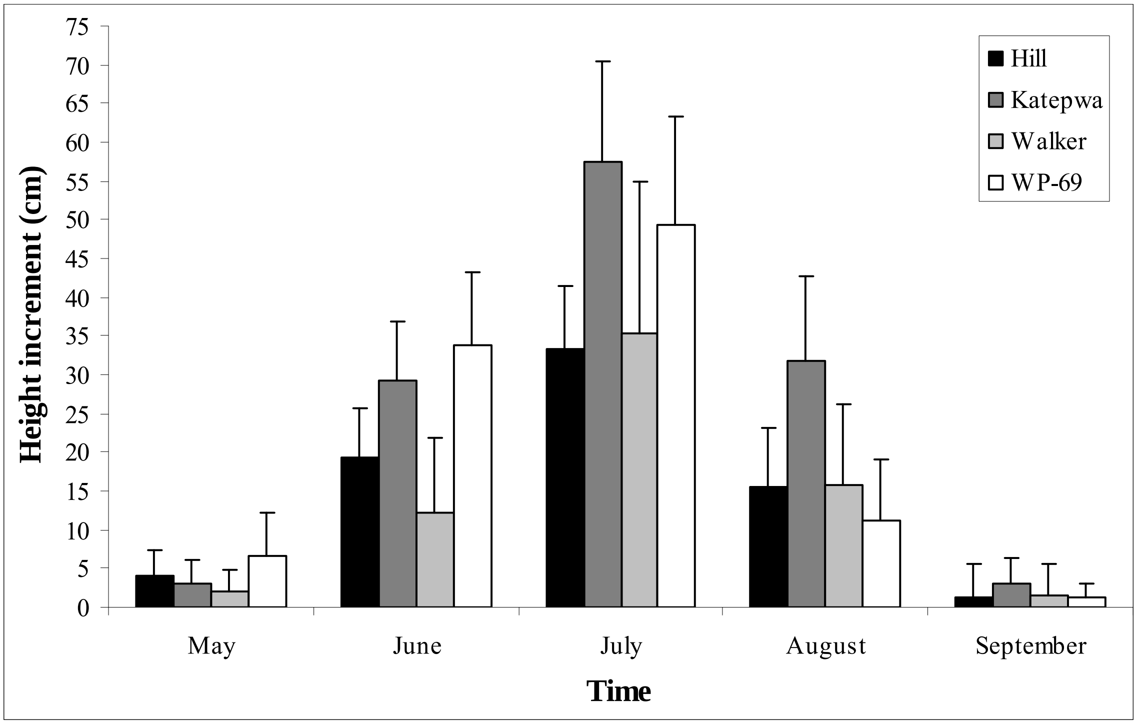
Treatment	Height	RCD†	Volume
	(cm)	(mm)	(cm^3)
		Alfalfa	
0 kg N ha^{-1}	167a‡	30a	492a
150 kg N ha^{-1}	141b	25b	294b
300 kg N ha^{-1}	137b	24b	251b
		Pasture	
0 kg N ha^{-1}	188a	37a	810a
150 kg N ha^{-1}	190a	36a	754a
300 kg N ha^{-1}	166b	32b	509b

†RCD=Root collar diameter

‡For each site, means within a column followed by the same letter are not significantly different ($p<0.05$) using least significant differences (LSD), columns with no letters have no significant differences.

Root collar diameters at the Pasture site for the trees in the 300 kg N ha^{-1} treatment was 14% lower than the 0 kg N ha^{-1} and the 150 kg N ha^{-1} treatments. Increased height and larger root collar diameter increased tree volume in the control treatment to almost two times those in the 300 kg N ha^{-1} treatment at the Alfalfa site. Trees in the 300 kg N ha^{-1} treatment at the Pasture site had 37% less volume than the trees in the control treatment. The tree volumes at the Pasture site were between 1.6 and 2.6 times greater than the trees at the Alfalfa site. Individual clone response to fertilizer addition is presented in Appendix F.

Growth rates throughout the growing season represent a bell shaped curve for both the Alfalfa and Pasture sites (Figure 4.6). All clones had the highest incremental growth during July at both study sites. At the Alfalfa site growth increment of the Katepwa clone was 16% greater than the WP-69 clone. Growth increment for the Katepwa and WP-69 clones were comparable at the Pasture site. Growth increment of the Walker hybrid poplar clone ranged between 28 and 39% less than the Katepwa and WP-69 clones for both of the sites. Growth increment of the Hill clone ranged between 21 and 25% less at the Pasture site and 32 to 42% less at the Alfalfa site compared to the Katepwa and WP-69 clones. The least growth occurred during May and September for both sites. Tree growth ranged from 2.0 to 6.6 cm in May and 0.8 to 3.1 cm in September at the Alfalfa site. At the Pasture site, tree growth was comparable between May and September and ranged from 1.8 to 4.9 cm.



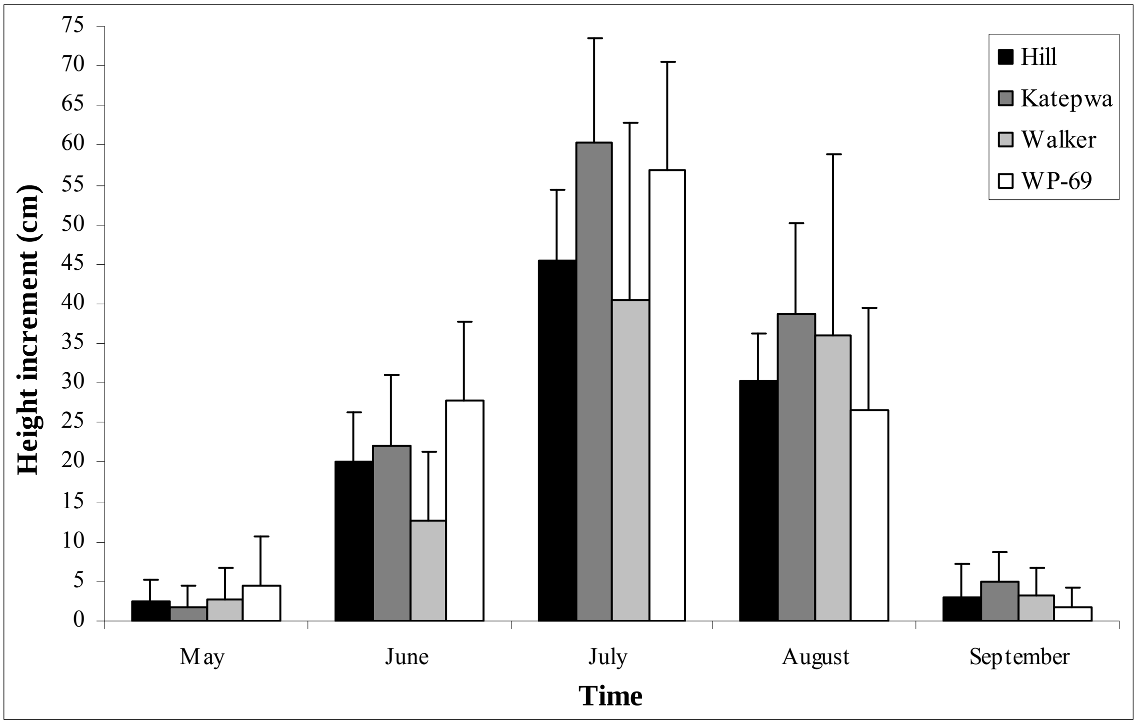


Figure 4.6 Height increment growth of hybrid poplar clones in the second growing season at the Alfalfa (top) and the Pasture (bottom) sites. (error bars represent one standard deviation)

4.3.4 Foliar N and P concentrations

Foliar N concentrations for the hybrid poplar clones were highest during May at both sites (Table 4.4). Foliar N at the Alfalfa site ranged from 31.0 to 34.5 mg g^{-1}, and 33.6 to 34.5 mg g^{-1} at the Pasture site. During the growing season, foliar N levels in the trees decreased between 25 and 40% at the Alfalfa site and 31 to 50% at the Pasture site. The WP-69 clone had the lowest foliar N level in May and the highest levels during July and August at the Alfalfa site. At the Pasture site, Katepwa had the highest value of leaf N during May whereas WP-69 had the lowest level during September and was among the lowest levels during May. Within the months of May, June, July and September foliar N levels did not vary by more than 16% among clones at the Alfalfa site. For the Pasture site, foliar N levels did not differ by more than 9% among clones during May through August. In September the foliar N content in the WP-69 trees were 21 to 28% less than the other three clones at the Pasture site.

Table 4.4 Foliar N concentration (mg g^{-1}) of four hybrid poplar clones during the second growing season at the Alfalfa and Pasture sites.

Treatment	Foliar N concentration				
	May	June†	July	August	September
			Alfalfa		
Hill	34.5a‡	30.8	24.5b	24.1b	23.1ab
Katepwa	34.3a	26.0	26.0b	25.2b	23.2a
Walker	33.4a	28.0	25.7b	21.8c	22.9ab
WP-69	31.0b	29.3	28.0a	27.6a	20.6b
			Pasture		
Hill	34.3ab	29.7	28.0	29.3	23.2a
Katepwa	34.5a	30.8	28.3	31.3	21.6a
Walker	33.8ab	28.6	28.7	27.5	23.7a
WP-69	33.6b	31.3	28.0	32.4	17.1b

† Fertilizer was applied one day after June probes were placed in the soil.
‡ For each site, means within a column followed by the same letter are not significantly different ($p<0.05$) using least significant differences (LSD), columns with no letters have no significant differences.

Trees within the fertilizer treatments had similar foliar N concentrations during May, June and July at the Alfalfa site and May through August at the Pasture site (Table 4.5). The highest foliar N levels at the Alfalfa site ranged from 33.0 to 33.8 mg g^{-1} and 34.0 to 34.1 mg g^{-1} at the Pasture site. The highest levels of foliar N occurred in May at both sites. Foliar N concentration in May were 33 to 66% greater than in September at the Alfalfa site and 41 to 77% greater than the trees at the Pasture site. In August, foliar N concentrations increased with increasing fertilizer rate at the Alfalfa site. Foliar N concentration was 9-29% greater for the trees in the 300 kg N ha^{-1} treatment than those in the 0 and 150 kg N ha^{-1} treatment plots for both sites.

Table 4.5 Foliar N concentration (mg g^{-1}) as affected by fertilizer N rate of hybrid poplar during the second growing season at the Alfalfa and Pasture sites.

Treatment	Foliar N concentration				
	May	June†	July	August	September
			Alfalfa		
0 kg N ha^{-1}	33.0	28.5	25.4	22.7c‡	20.4b
150 kg N ha^{-1}	33.2	28.6	25.9	24.8b	22.1b
300 kg N ha^{-1}	33.8	28.5	26.9	26.5a	24.9a
			Pasture		
0 kg N ha^{-1}	34.1	29.9	27.6	28.3	19.3b
150 kg N ha^{-1}	34.0	29.9	28.2	30.0	20.8b
300 kg N ha^{-1}	34.1	30.6	29.0	32.2	24.1a

† Fertilizer was applied one day after June probes were placed in the soil.

‡ For each site, means within a column followed by the same letter are not significantly different ($p<0.05$) using least significant differences (LSD), columns with no letters have no significant differences.

Foliar P levels showed a similar relationship as foliar N with the highest measurements during May ranging from 2.6 to 4.4 mg g^{-1} at the Alfalfa site and 2.3 to 4.3 mg g^{-1} at the Pasture site (Table 4.6). Foliar P levels were 3.2 to 6.3 times higher in May than in June at the Alfalfa site and 1.9 to 3.1 times higher at the Pasture site. At the Alfalfa site, foliar P levels in August increased from May values and ranged from 1.4 to 1.6 mg g^{-1}. At the Pasture site, foliar P levels ranged from 2.2 to 2.9 mg g^{-1} in August. In August the Katepwa trees had the highest levels of foliar P at the Pasture site. The Hill and Katepwa trees had the highest levels of foliar P at the Alfalfa site.

Foliar P concentrations in leaves were not different between fertilizer rate at the Alfalfa site in the months of May and September (Table 4.7). In June the foliar P levels of the trees in the 300 kg N ha^{-1} treatment were 25% less than the trees in the 0 and 150 kg N ha^{-1} treatments at the Alfalfa site. In July and August, foliar P levels in the trees for the 300 kg N ha^{-1} treatment were 24 and 22% lower those in the 0 kg N ha^{-1} treatment.

Table 4.6 Foliar P concentration (mg g^{-1}) of four hybrid poplar clones during the second growing season at the Alfalfa and Pasture sites.

Treatment	Foliar P concentration				
	May	June†	July	August	September
			Alfalfa		
Hill	4.4a‡	0.7	1.6c	1.6a	0.9ab
Katepwa	4.4a	0.7	1.9ab	1.8a	1.1a
Walker	3.2b	0.7	1.5bc	1.4b	0.9bc
WP-69	2.6c	0.8	2.0a	1.6ab	0.7c
			Pasture		
Hill	4.3a	1.4	2.6b	2.5ab	2.0
Katepwa	3.6b	1.3	3.0a	2.9a	2.0
Walker	3.3ab	1.2	2.6b	2.2b	1.9
WP-69	2.3c	1.2	2.4b	2.3b	1.2

† Fertilizer was applied one day after June probes were placed in the soil.
‡ For each site, means within a column followed by the same letter are not significantly different (p<0.05) using least significant differences (LSD), columns with no letters have no significant differences.

At the Pasture site there was no difference between foliar P concentrations among fertilizer treatments in May, June, July and August. Trees at the Pasture site in the 0 and 150 kg N ha^{-1} treatments had foliar P levels 30% less than the 300 kg N ha^{-1} treatment during the month of September.

Table 4.7 Foliar P concentration (mg g^{-1}) as affected by fertilizer N rate of hybrid poplar trees during the second growing season at the Alfalfa and Pasture sites.

Treatment	Foliar P concentration				
	May	June†	July	August	September
			Alfalfa		
0 kg N ha^{-1}	3.7	0.8a‡	2.1a	1.8a	1.0
150 kg N ha^{-1}	3.6	0.8a	1.7b	1.6b	0.9
300 kg N ha^{-1}	3.6	0.6b	1.6b	1.4c	0.8
			Pasture		
0 kg N ha^{-1}	3.3	1.3	2.7	2.6	1.5b
150 kg N ha^{-1}	3.4	1.2	2.6	2.3	1.6b
300 kg N ha^{-1}	3.4	1.3	2.6	2.5	2.2a

† Fertilizer was applied one day after June probes were placed in the soil.
‡ For each site, means within a column followed by the same letter are not significantly different (p<0.05) using least significant differences (LSD), columns with no letters have no significant differences.

A relationship between foliar P concentration and tree height was more pronounced at the Alfalfa site than the Pasture site in July, 2004 (Figure 4.7). The relationship between height and foliar P concentration was significant at the Alfalfa site with a *p* value of 0.001 and not significant at the Pasture site. A weaker relationship between height and P concentration existed when the two sites were analyzed together (*p*=0.011). Foliar N levels and tree heights were poorly correlated at the Alfalfa (*p*=0.234) and Pasture site (*p*=0.611). Foliar N was negatively correlated with tree height at the Pasture site.

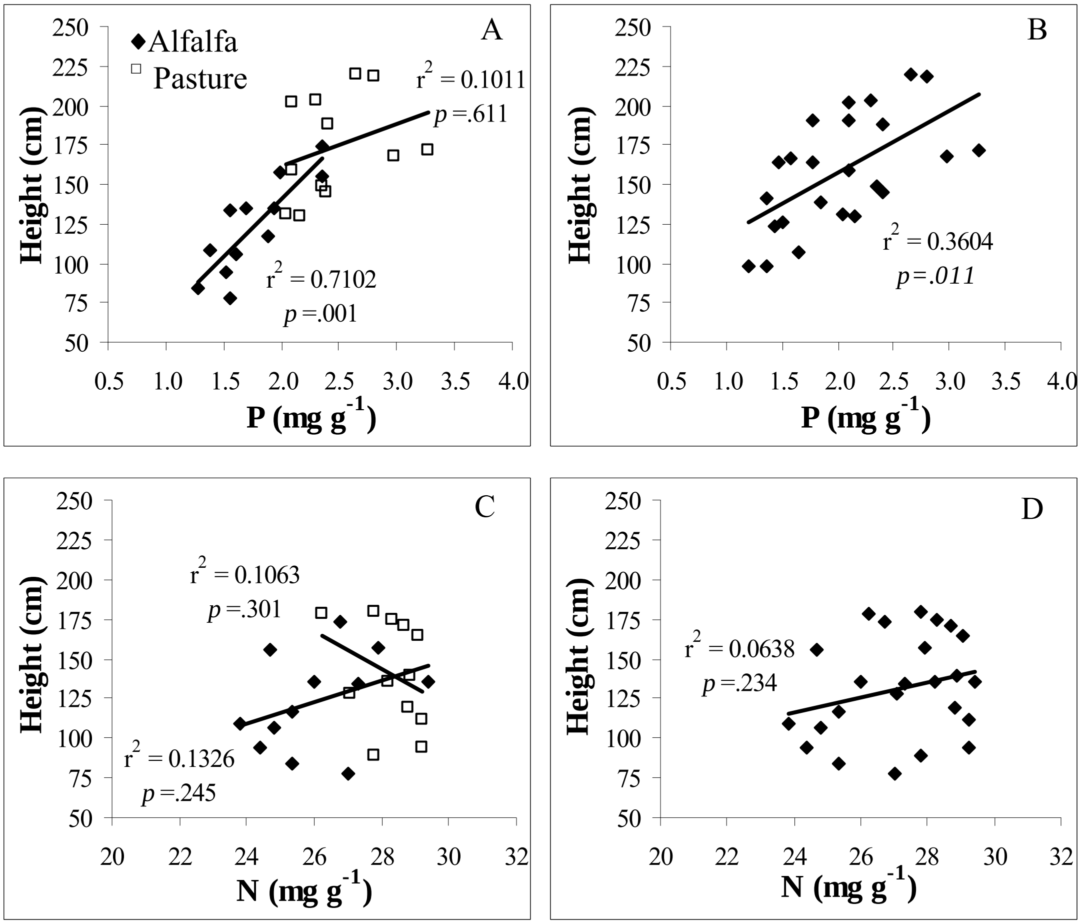
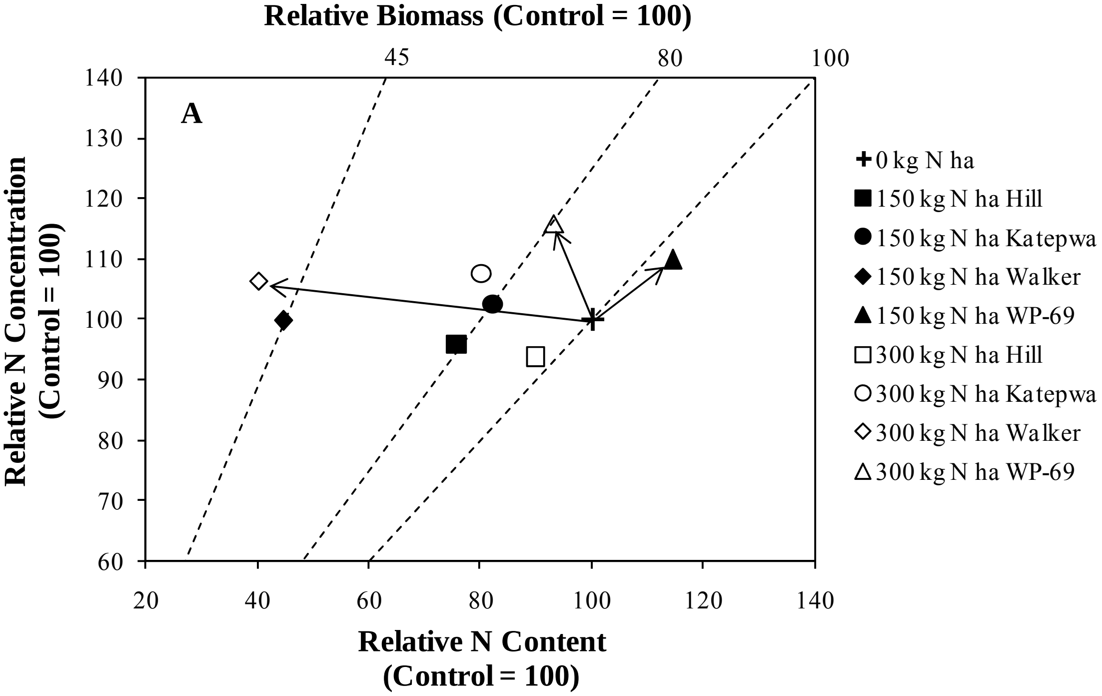


Figure 4.7 Foliar leaf concentrations in July of 2004 for P (top) and N (bottom) at the Alfalfa and Pasture sites (left) and combined sites (right). (Foliar P at the Alfalfa and Pasture sites (A). Foliar P combined between the Alfalfa and Pasture sites (B). Foliar N at the Alfalfa and Pasture sites (C). Foliar N combined between the Alfalfa and Pasture sites (D)).

4.3.5 Vector analysis

Vector analysis was used to determine a possible diagnosis for N and P from the fertilizer application at the Alfalfa and Pasture sites. The Walker poplar clone at both sites had the largest vector corresponding to a reduction in foliar biomass and N content suggesting a possible toxic accumulation of N (Figure 4.8). The Katepwa clone at both



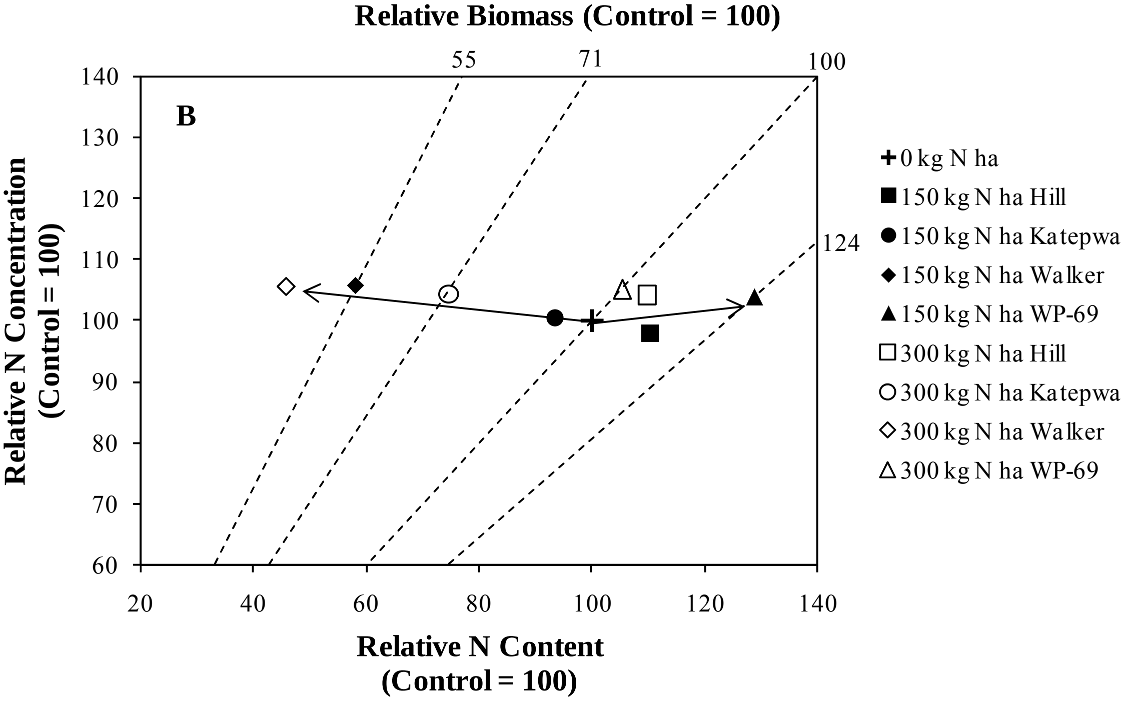


Figure 4.8 Vector nomograms of relative leaf biomass, N content and N concentration for 25 leaves collected in July 2004 from measurement plots at the Alfalfa (A) and Pasture (B) sites.

sites also responded in this direction, but not to the magnitude seen for the Walker clone. The 150 kg N ha^{-1} treatment for the WP-69 clone exhibited luxury consumption of N at the Alfalfa site; however, at 300 kg N ha^{-1} the vector showed a toxic accumulation of N.

At the Pasture site, WP-69 again showed luxury consumption at 150 kg N ha^{-1} but no change at 300 kg N ha^{-1}. The Hill clone showed no trends with fertilizer additions at either site. The addition of N fertilizer generally appeared to have induced a deficiency in P for all the clones at the Alfalfa site (Figure 4.9). At the Pasture site, the Walker clone showed some tendency to an induced deficiency for both fertilizer rates whereas the 300 kg N ha^{-1} for the Katepwa clone suggested foliar P levels were slightly in excess. The Katepwa and WP-69 clones did not show any strong trends for P with the N fertilizer at the Pasture site.

4.3.6 Foliar N:P ratio

Foliar N:P ratios of the four hybrid poplar clones ranged from 8 to 12 at the Alfalfa site and 8 to 16 at the Pasture site in May (Table 4.8). Within the months of June, July and September there was no difference in N:P ratios among clones at the

Alfalfa site. At the Alfalfa site, N:P ratios increased from May to June by 4.3 times before falling 61% during the months of July and August. The N:P ratios for the hybrid poplar trees ranged from 15 to 18 during the month of August. During the month of August, the Hill and Katepwa clones were 17% lower than the highest clone WP-69 at the Alfalfa site. There was no difference among clones in June, July, August and September at the Pasture site. The N:P ratios at the Pasture site ranged from 11 to 15 during August. From May to June a 2.3 times increase in the foliar N:P ratios at the Pasture site was comparable to differences at the Alfalfa site. Similar to the Alfalfa site N:P ratios decreased by 58% from June to July. End of season measurements in September were 27% greater than May and 44% less than the N:P ratios in June at the Pasture site.

Foliar N:P ratios in the fertilizer treatment trees were lowest for the Alfalfa site during May and ranged from 9 to 10 (Table 4.9). Foliar N:P ratios increased with increasing fertilizer application during August at the Alfalfa site. There was no difference between fertilizer treatment in May and July at the Alfalfa site. In September foliar N:P ratios from trees in the 0 kg N ha^{-1} treatment were 23% less those from the 300

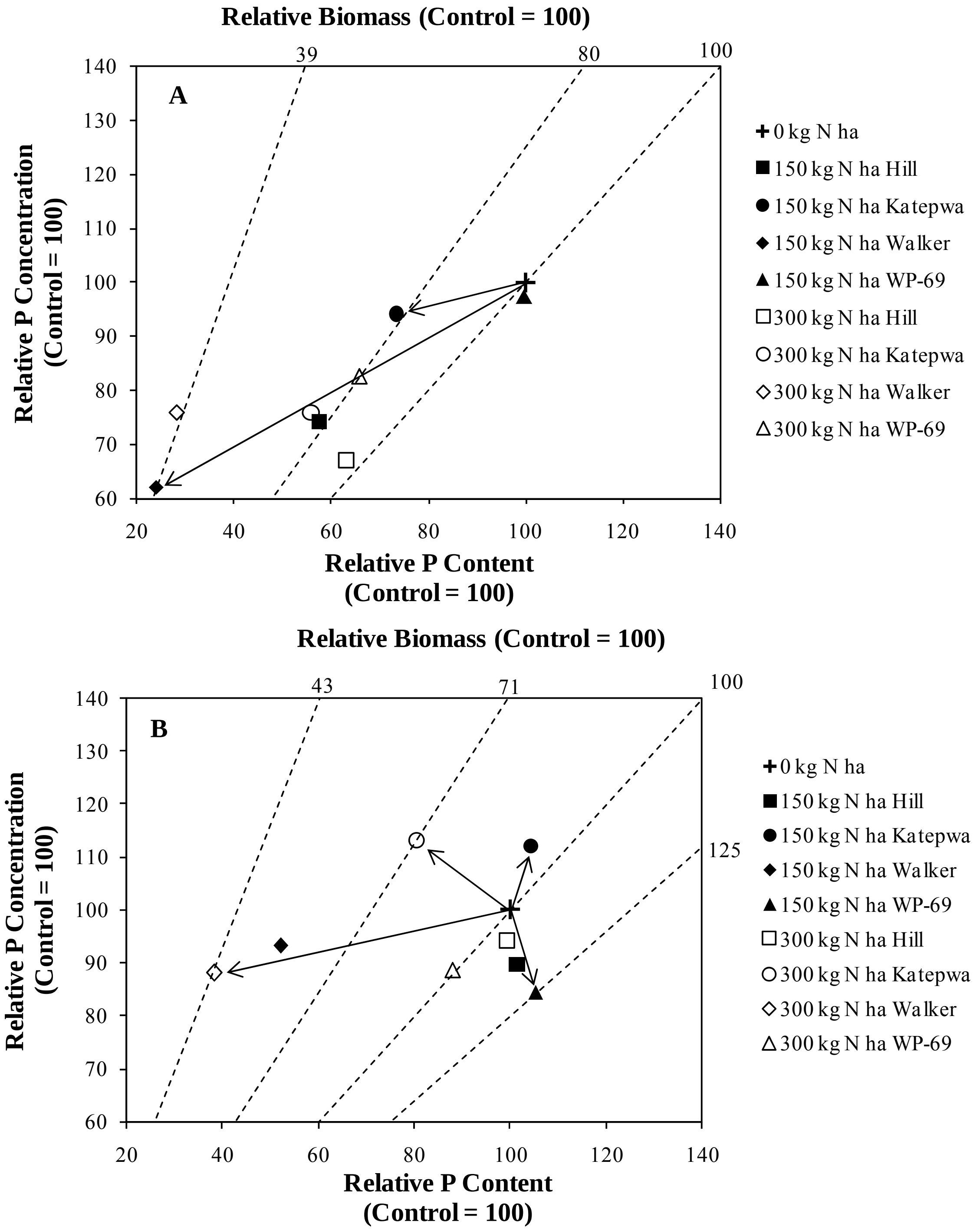


Figure 4.9 Vector nomograms of relative biomass, P content and P concentration for 25 leaves collected in July 2004 from measurement plots at the Alfalfa (A) and Pasture (B) sites.

Table 4.8 Foliar N:P ratios of hybrid poplar clones during the second growing season at the Alfalfa and Pasture sites grouped by clone.

Treatment	Foliar N:P ratio†				
	May	June‡	July	August	September
			Alfalfa		
Hill	8b§	44	16	15b	25
Katepwa	8b	44	14	15b	22
Walker	11ab	42	21	17ab	28
WP-69	12a	37	14	18a	35
			Pasture		
Hill	8b	21	11	12	13
Katepwa	10b	24	9	11	12
Walker	11b	30	11	13	14
WP-69	16a	27	12	15	18

† mg g^{-1}/mg g^{-1}

‡ Fertilizer was applied one day after June probes were placed in the soil.

§ For each site, means within a column followed by the same letter are not significantly different ($p<0.05$) using least significant differences (LSD), columns with no letters have no significant differences.

kg N ha^{-1}treatment plots. There was no difference in N:P ratios among fertilizer treatments during the 2004 growing season at the Pasture site. The N:P ratios did not differ by more than 10% during May, July and September at the Pasture site.

Table 4.9 Foliar N:P ratios of hybrid poplar clones within the fertilizer treatment during the second growing season at the Alfalfa and Pasture sites.

Treatment	Foliar N:P ratio				
	May	June†	July	August	September
			Alfalfa		
0 kg N ha^{-1}	9	40ab‡	14	13c	21a
150 kg N ha^{-1}	9	28b	17	16b	28ab
300 kg N ha^{-1}	10	48a	18	20a	34a
			Pasture		
0 kg N ha^{-1}	11	24	10	11	15
150 kg N ha^{-1}	11	30	11	13	14
300 kg N ha^{-1}	12	24	11	14	14

† Fertilizer was applied one day after June probes were placed in the soil.

‡ For each site, means within a column followed by the same letter are not significantly different ($p<0.05$) using least significant differences (LSD), columns with no letters have no significant differences.

4.3.7 Resorption efficiency

There was no difference in P resorption efficiencies among the clones at the Alfalfa site in 2004 (Table 4.10). P resorption efficiencies ranged from 36.5 to 53.6% and were higher than the N resorption efficiencies (-6.1 to 26.3%) at the Alfalfa site. N resorption efficiencies were 3.4 and 6.1 times higher for the WP-69 clone compared to the Katepwa and Hill clones, respectively. The Walker clone was the only clone to have a negative N resorption efficiency value at the Alfalfa site. P resorption efficiencies at the Pasture site ranged from 16.4 to 49.3%. The Walker clone had a P resorption efficiency that one third of the WP-69 clone. Similar to the Alfalfa site, N resorption efficiencies for the WP-69 clone was 1.5, 2.4 and 3.7 times greater than the Katepwa, Hill and Walker clones, respectively, at the Pasture site.

Table 4.10 Nitrogen and P resorption efficiencies (%) of four hybrid poplar clones after the second growing season (2004) for the Alfalfa and Pasture sites.

Clone	Alfalfa		Pasture	
	P	N	P	N
Hill	41.6	4.3b†	20.2ab	19.4bc
Katepwa	37.5	7.8b	34.4ab	30.4b
Walker	36.5	-6.1c	16.4b	13.2c
WP-69	53.6	26.3a	49.3a	47.0a

†Means within a column followed by the same letter are not significantly different ($P<0.05$) using least significant differences (LSD), columns with no letters have no significant differences.

When resorption efficiencies were grouped by fertilizer rate, there were no significant differences between treatments for P or N at the Alfalfa site (Table 4.11). P resorption efficiencies at the Pasture site were 30% less than the P resorption efficiencies at the Alfalfa site. Trees from the Pasture site in the 0 kg N ha^{-1} treatment had a P resorption efficiency that was 2.3 times greater than those from the 300 kg N ha^{-1} treatment. N resorption efficiencies at the Pasture sites did not differ between fertilizer treatments and were 3.5 times greater than the N resorption efficiencies at the Alfalfa site.

Table 4.11 Nitrogen and P resorption efficiencies (%) of four hybrid poplar clones grouped by fertilizer rate after the second growing season (2004) at the Alfalfa and Pasture sites.

Treatment	Alfalfa		Pasture	
	P	N	P	N
0 kg N ha^{-1}	43.0	5.7	41.1a†	24.5
150 kg N ha^{-1}	44.9	8.4	31.2ab	28.1
300 kg N ha^{-1}	38.9	9.8	17.8b	29.9

†Means within a column followed by the same letter are not significantly different ($P<0.05$) using least significant differences (LSD) columns with no letters have no significant differences.

4.4 Discussion

Hybrid poplars have rapid potential growth rates with a high demand for nutrients (Brown and van den Driessche, 2002) and therefore should benefit from the addition of fertilizers. At the Alfalfa and Pasture sites, trees that received 300 kg N ha^{-1} applied annually decreased growth compared to trees in the control treatment. Limitations to plant growth in boreal regions compared to warm-temperate regions is probably the indirect effect of a cool, short growing season on nutrient mineralization (Weih, 2004). This calls for the addition of fertilizers to make up for the deficiency in soil nutrient supply. Application of fertilizer to increase the soil supply of N is typically one of the least expensive treatments for increasing production in a hybrid poplar plantation (DesRochers et al., 2006). A greater precision is needed in the diagnosis of poplar fertilizer requirements as fertilizer amendments are not always successful (Coleman et al., 2006). Recent studies showed that N fertilization reduced both height and basal diameter in hybrid poplar (DesRochers et al., 2006) and had no effect on growth in aspen without irrigation (van den Driessche et al., 2003). Both of the previous studies also used fertilizer treatments with more than one nutrient that did not result in a positive growth response. The findings in this study were no different as there was no positive response to N fertilizer application. In a study conducted by Heilman and Xie (1993), three equal applications of 500 kg N ha^{-1} at the beginning of the second, third and fourth growing seasons did not increase hybrid poplar growth until the third growing season. DesRochers et al. (2006) suggested that a high soil pH (7.7-8.1) impeded the hybrid poplar's ability to take up nitrate based N fertilizer. However, this would not apply in this study as pH values were 5.4 and 6.5 for the Pasture and Alfalfa sites, respectively. It has generally been assumed that deciduous trees preferentially take up nitrate over ammonium (Choi et al., 2005). The main supply of plant available soil N at this site was in the form of nitrate (Appendix E).

Fertilizer application in 2003 showed higher levels of soil N in the spring of 2004 using both soil testing methodologies. The majority of the extractable N occurred near the soil surface. Soil samples taken in the fall of 2004 at 60 cm do not show significant amounts of N at depth for the Alfalfa site. Although application rates of N were 300 kg N ha^{-1} in both years of the study, N movement below 60 cm was negligible. PRS^{TM}

probes measured increased supply rates following fertilizer application in June of 2004 at both sites. A low or high supply of soil N did not have an effect on the growth of the four hybrid poplar clones. At the Alfalfa site increasing soil N increased foliar leaf N but this relationship was not seen at the Pasture site. The response to fertilizer at the Alfalfa site is more common as fertilizer treatments have been found to significantly increase the N concentration in the foliage (Heilman and Xie, 1993).

Foliar nutrient concentrations have been used to assess the nutrient requirements of hybrid poplars. Most studies place sufficient foliar nutrient levels for hybrid poplar at or near 25 mg g^{-1} for N and 2.5 mg g^{-1} for P (Heilman and Xie, 1993; van den Driessche, 1999). Coleman et al. (2006) documented consistent and significant growth responses despite high leaf N concentrations and suggested that relying on a single sufficiency level may be unsuccessful in describing nutrient requirements for maximum production. A downfall with using critical nutrient levels to diagnose nutrient requirements is that they assume that all other nutrients contributing to growth are sufficient and the nutrient in question is the only element inhibiting plant growth (Zabek, 2001).

Foliar N concentrations were greater than 25 mg g^{-1} at the Pasture site and at or near 25 mg g^{-1} at the Alfalfa site during the month of August in 2004. Trees that received spring applications of fertilizer had increased foliar N levels with increasing fertilizer rate at the Alfalfa site. This is similar to the Coleman et al. (2006) study where annual applications of N fertilizer maintained foliar N concentrations. Heilman and Xie (1993) reported that fertilization increased foliar N in the third growing season after two fertilizer applications. At the Pasture site, foliar levels of N were maintained above sufficient values from May through to the end of August. During this time, fertilizer applications did not have any influence on the foliar N level in the trees. DesRochers et al. (2006) also found that leaf concentrations did not vary with N fertilization levels. In our study productivity of the hybrid poplar clones did not increase with increasing foliar N concentration although there was a relationship with foliar P concentration.

Foliar P concentrations of the trees were highest for both sites during May. Once the leaves began to grow and expand foliar P concentrations declined below the suggested critical limit of 1.5 mg g^{-1} for *P. deltoides* and *P. trichocarpa* at both sites (van den Burg, 1985). At the end of the 2004 growing season the foliar P levels at the Alfalfa site were at or near the 1.5 mg g^{-1} critical limit and the P levels at the Pasture site were at or near the 2.5 mg g^{-1} sufficiency level. The lowest foliar P values occurred during the same month that the fertilizer N treatment was applied. Fertilizer N additions can decrease foliar P levels of the trees (Brown and van den Driessche, 2002, 2005). The results from trees in the Alfalfa site support this as levels of foliar P decreased with increasing fertilizer application. van den Driessche (1999) also reported a decrease in foliar P with increasing fertilizer application. Foliar nutrient concentrations can provide a good indication of nutrient deficiency if the measured nutrient is the main factor limiting plant growth. When more than one nutrient is suspected of being deficient examining a ratio between two or more nutrients may help to better define the factors limiting plant growth.

Current research suggests that a N:P ratio of 9.5 may be used as an effective diagnostic tool in determining responses to N and P fertilizers (Zabek, 2001). A leaf sample having a ratio below 9.5 indicates trees will respond to N fertilizer and ratios above 9.5 indicate trees will respond to P fertilizer. Similar to foliar P concentration, N:P ratios suggest that P is limiting tree growth at both sites in this study. The lower foliar P concentrations and higher N:P ratios at the Alfalfa site suggest that P was more available for plant growth at the Pasture site. The greater availability of P at the Pasture site resulted in higher growth rates of the trees compared to the Alfalfa site.

Vector analysis is a powerful tool for the simultaneous comparison of plant growth, nutrient concentration and nutrient content (Haase and Rose, 1995). Vector analysis at the Alfalfa site indicated that there was a tendancy towards a toxic accumulation of N in the Walker, Katepwa and WP-69 clones with N fertilization. Although this was not as evident for the Hill clone, tree growth was reduced by fertilization for all clones suggesting that N toxicity may have played a role in the reduced tree growth. Salifu and Timmer (2003) used vector analysis to show how the toxic accumulation of foliar N reduced tree growth of black spruce (*Picea mariana* (Mill.) BSP) resulting from the over application of fertilizer. Vector nomograms for foliar P at the Alfalfa site were striking in that they suggested that a P deficiency had been induced by the addition of N which corresponds to the N:P data. Thus N fertilization for hybrid poplar on previously managed alfalfa sites appeared to have caused a nutrient imbalance suggesting that these sites may require P fertilization as well in order to see a response. The induced P deficiency was also observed for some of the clones at the Pasture site as well. Brown and van den Dreissche (2002) observed decreasing foliar P levels with increasing fertilizer N in a hybrid poplar stand to a point where foliar N:P ratios exceeded values associated with N induced P deficiencies. The application of N fertilizer has also been shown to induce other nutrient deficiencies such as potassium using vector analysis (Weetman et al. 1972).

In this study, the growth of all four clones was unaffected by fertilizer application or rate. Similar results were reported for six hybrid poplar clones (Heilman and Xie, 1993). The largest difference between clones in our study was between height and survival. Hill, Katepwa and WP-69 all had survival rates above 90%. The clone Walker had the lowest survival rates of 52 and 56% at the Alfalfa and Pasture sites, respectively. The Walker clone is the most planted clone in Saskatchewan but it did not perform well in either of the two studies in this thesis. This was not expected and may have been influenced by poor quality stock. Clones WP-69 and Katepwa show great promise in becoming successful clones for this region of the province. The Katepwa clone had the highest rates of growth towards the end of the growing season. This positive late season growth may have implications for cold hardiness and risk of severe frost damage. Plants experience the highest risks of frost injury during the transition period between summer and winter (Weih, 2004; Verwijst et al., 1996). There is a concern with fast growing clones as there may be a biological trade-off between high frost resistance and rapid growth rate (Lenartsson and Ogren, 2002).

Resorption efficiency has many impacts on nutrient cycling. The resorption of nutrients from senescing leaves is a key process in the mineral nutrition of many perennial species (Aerts, 1997). Greater resorption of nutrients at senescence may increase long-term productivity of deciduous trees (Harvey and van den Driessche, 1999). The resorbed nutrients are available more quickly as they are stored in existing plant tissues and do not have to be obtained from the soil and transported through the plant. Nutrients that are not resorbed from the leaves must decompose and re-mineralize to become available for plant uptake, which could take years (Aerts, 1996). Approximately half of the N and P in senescing leaves can be re-used (Aerts, 1996). It is also well known that resorption efficiency values can be highly variable and biased by the measurement method that is used (van Heerwaarden et al., 2003). Sampling timing can affect results if resorption has not gone to completion. Measuring foliar nutrient levels throughout the growing season will make it easier to identify the maximum pool size needed for resorption efficiency calculations (Chapin and Van Cleve, 1994). Nutrient pool size should be close to maximal during August as leaf size is no longer increasing and autumnal nutrient retranslocation not yet started (Zabek, 2001). The foliar concentrations used to determine resorption efficiency for the four hybrid poplar clones in this study were sampled during the last week in August and September.

The N resorption values for this study were lower than those reported from a wide variety of studies on deciduous shrubs and trees conducted by Aerts (1996). At the Pasture site the WP-69 clone had the highest resorption rate at 47%. The higher percentage of re-translocation of N may make this clone more efficient at recycling nutrients. The lower N fertility of the Pasture site generally had higher N resorption efficiencies than the Alfalfa site. The application of fertilizer N did not affect the resorption rate of N at either of the two sites. In Aerts (1996) study, N resorption values for deciduous shrubs and trees were 54% with a standard deviation of 15.9.

P resorption values in this study ranged between 17-53% for foliar P. Aerts (1996) reported P resorption values of 50.4%. The relationship between P resorption efficiency and site was opposite that of the N resorption values. P resorption efficiencies were greater at the Alfalfa site than the Pasture site. There were no differences in P resorption among clones or fertilizer rates at the Alfalfa site. At the Pasture site clone WP-69 had higher P resorption efficiency than the Walker clone. P resorption efficiency was at its lowest when N supply rate was at its highest for the Pasture site. Some research suggests that increasing site fertility corresponds with decreasing resorption efficiency (Zabek, 2001; Aerts, 1996; van Heerwaarden et al., 2003). It should be cautioned that nutrient resorption is only weakly controlled by nutrient availability (Aerts, 1996).

4.5 Conclusion

In this study the application of N fertilizer in the first two years of plantation establishment was unsuccessful in increasing hybrid poplar production. In some cases the addition of fertilizer decreased hybrid poplar growth. No response or a decrease in plant growth with increasing N fertilization suggests another nutrient limiting plant growth. Low foliar P nutrient concentrations and high N:P ratios suggest that this nutrient was P. Further evidence that supports P deficiency was the higher N fertility at the Alfalfa site but higher growth at the Pasture site. Both the P concentration and the N:P ratios indicated that P was more severely limited at the Alfalfa site compared to the Pasture site. Foliar concentrations of other macro and micronutrients need to be analyzed to determine if P was the only nutrient limiting plant growth. Vector analysis is a useful tool in comparing a number of treatment effects on one graph. Vector analysis also concluded that the addition of fertilizer induced a P deficiency at the Alfalfa site. In addition, vector analysis indicated that P deficiencies were most limiting for the Walker clone at both the Alfalfa and Pasture sites. The hybrid poplar clones WP-69 and Katepwa had superior volume production and seedling survival over the Walker and Hill clones.

The results from this study suggest that the application of successive N fertilizer to hybrid poplar trees on land previously managed as an agricultural system may not increase tree production. Correlations with tree height and foliar P concentration indicate a need for P fertility research with hybrid poplar clones in Saskatchewan. The WP-69 and Katepwa clones would be great candidates for further research as their growth rates favor increased production over the Hill and Walker clones.

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5. GENERAL DISCUSSION

Narrowing profit margins in Saskatchewan has led landowners to search for other opportunities within the farming sector to increase on-farm profitability. Farm profitability is often increased by diversifying and specializing farming operations as well as off-farm income. In order to diversify a farming operation there must be a viable opportunity presented to the farming sector. One opportunity available to Saskatchewan producers is converting conventional agricultural land into hybrid poplar plantations. The idea of farming hybrid poplar trees in an agricultural system (agroforestry) has generated interest amongst farmers, government and research institutes. This interest has come from the proposed benefits of growing hybrid poplar trees. Global environmental problems related to climate change and societal pressures may force the development of agroforestry as an ecologically sustainable management practice that can reduce the use of fossil fuels (Weih 2004). A hybrid poplar plantation will sequester carbon, help to offset greenhouse gas emissions, reduce soil erosion and provide landowners with an alternative crop to market. These benefits have not been realized as there have been no large-scale plantations harvested in Saskatchewan. The benefits also assume that plantation establishment and hybrid poplar growth will be successful. During plantation establishment, costs are at their highest and management decisions are crucial. In order to prevent financial loss or possible plantation failure, hybrid poplar farmers must be informed of the most successful management strategies. The two studies undertaken in this thesis were intended to provide information towards making informed management decisions to facilitate the success of hybrid poplar plantations in Saskatchewan.

The first decision regarding the success of a hybrid poplar plantation is site selection. Growing hybrid poplar trees on nutrient rich, loamy soils with sufficient water and heat units are ideal. Knowledge of field history and inherent soil fertility will play a large role in the successful establishment and production of the plantation. It is important to understand that previous land management will influence cropping decisions. Issues such as salinity, soil texture and climate cannot be managed, whereas nutrients and water can be supplemented. Ecoregion and proximity to markets should also be considered during site selection as transportation costs increase with distance to processing facilities. Hybrid poplar clones have a variety of qualities that are suited to specific ecoregions. This multitude of factors will ultimately influence the ease of planting, stock survival and plantation production.

The first study in this thesis tested the suitability of three Walker poplar stock types. Of the three stock types used in the study, the cuttings were the least suitable stock type for the sites near Meadow Lake, Saskatchewan. The rooted cutting and rooted plug stocks were more suitable based on survival and growth production. Less than 40% of the cutting stock survived one year after planting. Weed competition may have affected survival of the cutting stock in the second and third years. Cutting stock planted during the second and third years of plantation establishment also had very poor survival rates. Replanting in years two and three increase the time to canopy closure as trees are of different age. In agricultural systems where weed pressures are expected to be high, a vigorous root system is beneficial. In agroforestry, root development of trees is much slower than in annual crops. The presence of roots at the time of planting allows faster development and advantages over non-rooted stock types. Advantages of pre-established roots includes faster uptake of soil nutrients and greater competition with weeds compared to non-rooted stock. Rooted stock types are slightly more difficult to plant because of the roots and are more expensive than non-rooted stock types. Research projects are needed to improve the successful establishment of cuttings before they are considered a viable option for hybrid poplar plantations in Saskatchewan.

Different hybrid poplar clones may be best suited for particular ecoregions and have different growth habits, tree morphology as well as wood product end use. The clones used in this thesis (Chapter 4) were compared based on tree height and diameter. All clones were planted as a rooted cutting stock type. There were significant differences among clones, with the Katepwa and WP-69 clones achieving the greatest height and diameter. The most widely planted Saskatchewan clone Walker, performed poorly compared to the top two clones. Walker has been a successful clone as it has proven to be widely adapted in Saskatchewan, mostly in shelter belts. Advancements in breeding and cloning technology can produce clones that are more suited to the boreal transition ecoregion. Although newly released clones are tested for 10-20 years before they are released, they may have a higher risk of failure as they have not been used as extensively as existing clones. Clones that seem suitable for a region now may have disadvantages that may not become apparent until well into the rotation. Breeders try to overcome these disadvantages by releasing a clone only after it has undergone a minimum of ten years of evaluation, ideally twenty (Walker and Schroeder, 2001).

In an agricultural system monoculture crops are protected by a variety of mechanical and chemical controls to prevent infestations from pests. In a hybrid poplar plantation it is more difficult to control disease and insect invasions as there are very few pesticides registered or in the process of being registered. Selecting a variety of hybrid poplar clones to be grown in a plantation may decrease the incidence of disease and insect damage. Selecting two new fast-growing hybrids along with a hybrid that has proven to be successful can increase plantation diversity. The fast-growing clones can be harvested out of the plantation earlier leaving room to establish other species. This will allow a producer to manage each clone for a specific end use. Some trees may be pruned for higher value wood products and other clones not pruned. In Chapter 3, pruning decreased tree volume at the Alfalfa site but had no effect on tree growth at the Pasture site. The branches that were pruned may have decreased the amount of photosynthesis the tree would have been able to perform. Also nutrients that were resorbed from the leaves into the branches the previous fall will have to be cycled through the soil before becoming available for plant uptake. A reduction in growth may be a trade off in order to achieve a higher value wood product at the end of the rotation.

There is little literature relating soil nutrient supply and hybrid poplar tree development. Both studies tried to relate soil N supply and tree growth. Fertilizer was applied to stimulate a growth response in the hybrid poplar clones. No positive fertilizer response was recorded throughout the study. Each of the stock types recovered and partitioned applied fertilizer N in a similar matter. The Walker hybrid poplar trees recovered 1-5% of the applied fertilizer with the highest amount of fertilizer N in the leaves. PRS$^{\underline{TM}}$ probes were able to track the seasonal variations in soil N supply. Neither the 2*M* KCL extract nor the PRS$^{\underline{TM}}$ probe method of determining soil N supply rates were related with growth response from fertilizer N. When fertilizer was applied on a yearly basis, soil N levels increased with application. Spring soil sample values at or above 950μg/10cm^2/4weeks, as found in this study; will result in no response to fertilizer N. Both studies showed that tree growth can be decreased by fertilization despite having higher soil N levels. Fertilizer N with ammonium based fertilizer generally decreases soil pH (Gahoonia et al., 1992). Iron and aluminum phosphates decrease in solubility with a decrease in pH (Hinsinger, 2001). In a follow up study, fertilizer decreased soil pH in the top 10 cm of soil at the Alfalfa and Pasture sites (Van Rees et al., 2006). It is possible that the application of fertilizer decreased soil pH and reduced the solubility of P in this study. It is unknown if the early application of fertilizer will have a lasting effect and increase hybrid poplar production in later years. Fertilizer application during the first 2-4 years of plantation establishment would be more favorable. Fertilizer application becomes more difficult as the hybrid poplar trees become larger and access to the plantation is reduced.

Literature relating fertilizer responses from foliar nutrient concentrations are more common than from soil nutrient supply rates. In an attempt to diagnose nutrient deficiencies, Zabek (2001) found interpreting foliar nutrient concentrations were better tools for deriving fertilizer prescriptions than soil nutrient supply rates. Critical foliar nutrient levels may vary between clones and between regions. Sampling methodology and timing may also influence foliar nutrient levels. Although the critical foliar nutrient levels may be subjective, seasonal variation and foliar nutrient concentration response to treatments can help determine nutrient deficiencies. Foliar nutrient levels are at their highest during spring and most representative of plant health during peak growth prior to leaf resorption. Coleman (2006) was unable to define an upper limit for foliar N concentration. Assessing nutrient deficiencies using foliar N concentrations may be misleading if N is not the main limiting nutrient. The foliar P levels from both studies in this thesis indicated that P was more limiting than N.

Approaches attempting to determine nutrient deficiencies based on critical foliar levels for agricultural land in Saskatchewan will be more successful if they evaluate more than one nutrient. Using a ratio-based approach or a nutrient-balance approach will provide more information on the balance of nutrients required for growth. An N and P ratio-approach was used in this thesis. This approach takes into account the changes in N foliar concentration with respect to changes in P nutrient concentration and vice versa. A N:P ratio of 9.5 may work better in diagnosing a fertilizer response for this study. In some instances the critical foliar nutrient value of N or P was at or slightly below sufficient foliar levels. Foliar nutrient concentrations near sufficient levels would not indicate a nutrient deficiency. An additional study would have to be conducted to test for a P deficiency.

Vector analysis is another emerging tool to aid in the diagnosis of plant nutrition. The advantage of vector analysis is that complicated relationships among biomass, nutrient concentration and nutrient content can be observed. Vector analysis may be most beneficial when analyzing a larger number of foliar nutrients or treatments as the vector nomograms allow a reader to visualize and interpret the results on one graph rather than a series of tables.

Vector analysis, nutrient critical limits and N:P ratios were only examined for two nutrients in this study and as such a total nutrient picture was not available for the hybrid poplar clones. N and P are two of the main nutrients limiting plant growth and are a good start point to determining nutrient deficiencies. The results for chapters three and four indicate that these hybrid poplar plantations will not respond to fertilizer until soil P deficiencies are corrected. P deficiencies at the Alfalfa site are more severe than at the Pasture site. This is due to the net removal of P on alfalfa managed-fields and the greater nutrient cycling on pasture-managed fields.

The findings in this study are of great importance to producers interested in establishing hybrid poplar plantations. Choosing to plant a non-rooted cutting instead of a rooted cutting will result in a much higher risk of plantation failure due to poor survival rates. In terms of tree height, root collar diameter and volume, clones Katepwa and WP-69 are best suited for the boreal transition ecoregion of Saskatchewan. The application of fertilizer N in early years may decrease the productivity of a hybrid poplar stand. Applying fertilizer may induce the deficiency of another nutrient that was not previously limiting. The over-application of N fertilizer is an inefficient use of money and causes environmental problems.

The findings of this study have also brought about more questions concerning planting stock, clone selection and fertilizer application. Non-rooted stock types will have an advantage in ease of planting and reduced cost of establishment compared to rooted stock if survival and productivity is improved. The two fast growing clones were successfully established but neither responded to fertilizer application. Will each of the clones respond alike to a balanced fertilizer application? It is unclear whether the hybrid poplars are limited by an unidentified nutrient or if they did not respond to fertilizer because they were limited by P? Will banding N fertilizer with P fertilizer increase the uptake and foliar P concentrations? There is also the possibility that the application of P will induce another nutrient deficiency. Using leaf chemical analysis, Teng and Timmer (1990) found P fertilization at high rates reduced hybrid poplar growth and caused P induced Zn and/or Cu deficiencies. A study looking at the full nutrient picture as well as fertilizer placement will help to understand the nutrient requirements of these hybrid poplars.

There is an abundance of information and assistance available to agricultural producers for growing cereal, oilseed and pulse crops in Saskatchewan. The amount of information available to agricultural producers is reflected by the number of research projects either funded or conducted by government, industry or university organizations. The forestry sector does not have this extensive support system. If the practice of agroforestry is to become a viable option for agricultural producers in Saskatchewan, research must be undertaken to assist in the adoption and successful utilization of short-rotation woody crops in agricultural systems.

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APPENDICES

Appendix A:

Hybrid poplar herbicide labels and safety data sheets (MSDS)

TableA.1 Registered herbicides for use in poplar crop maintenance. (source van Oosten, 2006)

Product name	Active ingredient	Company labels	Company MSDS
Lontrel 360	Clopyralid	http://www.dowagro.com/ca/prod/lontrel.htm	http://www.dowagro.com/ca/prod/lontrel.htm http
Casoron G-4 Granular herbicide	Dichlobenil	http://www.uap.ca/products/products.htm	http://www.uap.ca/products/products.htm
Venture L post-emergence herbicide	Fluazifop-P-butyl	http://www.syngenta.ca/en/labels/index.asp?nav=lbl	http://www.syngenta.ca/en/labels/index.asp?nav=msds
Vantage forestry herbicide solution	Glyphosate†	http://www.dowagro.com/ca/prod/vantage-forestry.htm	http://www.dowagro.com/ca/prod/vantage-forestry.htm
Vision max silviculture herbicide	Glyphosate	http://www.monsanto.ca/products/labelsmsds/index.shtml	http://www.monsanto.ca/products/labelsmsds/index.shtml
Vision silviculture herbicide B	Glyphosate	http://www.monsanto.ca/products/labelsmsds/index.shtml	http://www.monsanto.ca/products/labelsmsds/index.shtml

† This is not a complete listing of all glyphosate products, only those registered in a poplar crop.

Appendix B:

ANOVA tables

Table B.1 ANOVA table for % N recovered by Walker poplar at the Alfalfa site

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	25.756§	17	1.515	2.181	0.24
Intercept	22.349	1	22.349	32.171	.000
Tissue	18.926	2	9.463	13.622	.000
Stock	3.974	2	1.987	2.860	.070
Prune	.129	1	.129	.186	.669
Tissue*stock	.482	4	.121	.173	.951
Tissue*prune	.172	2	.086	.123	.884
Stock*prune	1.742	2	.871	1.254	.298
Tissue*stock*prune	.332	4	.083	.119	.975
Error	25.009	36	.695		
Total	73.115	54			
Corrected total	50.766	53			

†Degrees of freedom
‡F ratio
§r squared = .507

Table B.2 ANOVA table for % N recovered by Walker poplar at the Pasture site

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	24.156§	17	1.421	22.936	.000
Intercept	.728	1	.728	11.751	.002
Tissue	23.379	2	11.689	188.685	.000
Stock	.528	2	.264	4.262	.022
Prune	.010	1	.010	.167	.685
Tissue*stock	.050	4	.013	.203	.935
Tissue*prune	.026	2	.013	.212	.810
Stock*prune	.112	2	.056	.905	.413
Tissue*stock*prune	.049	4	.012	.199	.937
Error	2.230	36	.062		
Total	27.114	54			
Corrected total	26.386	53			

†Degrees of freedom
‡F ratio
§r squared = .915

Table B.3 ANOVA table for 2*M* KCL extractions from the Alfalfa site following one growing season.

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	10.277§	23	.447	3.861	.000
Intercept	876.201	1	876.201	7572.016	.000
Fertilized	.137	1	.137	1.187	.281
Stock type	.452	1	.452	3.903	.054
Depth	7.041	5	1.408	12.170	.000
Fertilized*stock type	.127	1	.127	1.102	.299
Fertilised*depth	1.226	5	.245	2.119	.079
Stock type*depth	.376	5	.075	.649	.663
Fertilized*stock type*	.918	5	.184	1.586	.182
Depth	5.554	48	.116		
Error	892.033	72			
Total	15.831	71			
Corrected total					

†Degrees of freedom

‡F ratio

§r squared = .649

Table B.4 ANOVA table for 2*M* KCL extractions from the Pasture site following one growing season.

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	2.297§	23	.100	1.017	.465
Intercept	555.043	1	555.043	5649.141	.000
Fertilized	.352	1	.352	3.582	.064
Stock type	.154	1	.154	1.563	.217
Depth	1.225	5	.245	2.493	.044
Fertilized*stock type	.091	1	.091	.926	.341
Fertilised*depth	.193	5	.039	.392	.852
Stock type*depth	.209	5	.042	.426	.829
Fertilized*stock type*	.074	5	.015	.151	.979
Depth	4.716	48	.098		
Error	562.057	72			
Total	7.013	71			
Corrected total					

†Degrees of freedom
‡F ratio
§r squared = .328

Table B.5 ANOVA table for tree height following the 2004 growing season at the Alfalfa site

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	9824.441§	7	1403.492	.817	.587
Intercept	818805.356	1	818805.356	476.537	.000
Stock type	171.710	1	171.710	.100	.756
Prune	78.215	1	78.215	.046	.834
Fertilizer	2546.079	1	2546.079	1.482	.241
Stock type*prune	881.022	1	881.022	.513	.484
Stock type*fertilizer	5649.415	1	5649.415	3.288	.089
Prune*fertilizer	.347	1	.347	.000	.989
Stock type*prune* fertilizer	497.654	1	497.654	.290	.598
Error	27491.841	16	1718.240		
Total	856121.638	24			
Corrected total	37316.282	23			

†Degrees of freedom
‡F ratio
§r squared =.263

Table B.6 ANOVA table for tree height following the 2004 growing season at the Pasture site

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	2618.555§	7	374.079	.750	.635
Intercept	635275.559	1	635275.559	1273.502	.000
Stock type	1462.899	1	1462.899	2.933	.106
Prune	629.813	1	629.813	1.263	.278
Fertilizer	171.908	1	171.908	.345	.565
Stock type*prune	97.006	1	97.006	.194	.665
Stock type*fertilizer	157.591	1	157.591	.316	.582
Prune*fertilizer	49.787	1	49.787	.100	.756
Stock type*prune* fertilizer	49.552	1	49.552	.099	.757
Error	7981.460	16	498.841		
Total	645875.574	24			
Corrected total	10600.015	23			

†Degrees of freedom
‡F ratio
§r squared =.247

Table B.7 ANOVA table for foliar N concentration following the 2004 growing season at the Alfalfa site

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	31.274§	7	4.468	.407	.883
Intercept	26094.147	1	26094.147	2377.107	.000
Stock type	.406	1	.406	.037	.850
Prune	.000	1	.000	.000	.996
Fertilizer	.222	1	.222	,020	.889
Stock type*prune	7.900	1	7.900	.720	.410
Stock type*fertilizer	6.264	1	6.264	.571	.462
Prune*fertilizer	10.922	1	10.922	.995	.334
Stock type*prune* fertilizer	3.786	1	3.786	.345	.566
Error	164.659	15	10.977		
Total	26748.109	23			
Corrected total	195.933	22			

†Degrees of freedom
‡F ratio
§r squared =.160

Table B.8 ANOVA table for foliar N concentration following the 2004 growing season at the Pasture site

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	47.841§	7	6.834	.969	.485
Intercept	25513.282	1	25513.282	3617.622	.000
Stock type	3.898	1	3.898	.553	.468
Prune	6.000	1	6.000	.851	.370
Fertilizer	3.618	1	3.618	.513	.484
Stock type*prune	26.083	1	26.083	3.698	.072
Stock type*fertilizer	6.151	1	6.151	.872	.364
Prune*fertilizer	.006	1	.006	.001	.976
Stock type*prune* fertilizer	2.085	1	2.085	.296	.594
Error	112.840	16	7.053		
Total	25673.963	24			
Corrected total	160.681	23			

†Degrees of freedom
‡F ratio
§r squared =.298

Table B.9 ANOVA table for foliar P concentration following the 2004 growing season at the Alfalfa site

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	.542§	7	.077	2.953	.037
Intercept	67.952	1	67.952	2592.751	.000
Stock type	.128	1	.128	4.872	.043
Prune	.077	1	.077	2.931	.108
Fertilizer	.155	1	.155	5.911	.028
Stock type*prune	.087	1	.087	3.320	.088
Stock type*fertilizer	.026	1	.026	.993	.335
Prune*fertilizer	2.55E-005	1	2.55E-005	.001	.976
Stock type*prune* fertilizer	.058	1	.058	2.225	.156
Error	.393	15	.026		
Total	70.632	23			
Corrected total	.935	22			

†Degrees of freedom
‡F ratio
§r squared =.579

Table B.10 ANOVA table for foliar P concentration following the 2004 growing season at the Pasture site

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	.560§	7	.080	.737	.645
Intercept	125.323	1	125.323	1155.524	.000
Stock type	.094	1	.094	.868	.365
Prune	.066	1	.066	.613	.445
Fertilizer	.281	1	.281	2.587	.127
Stock type*prune	.048	1	.048	.446	.514
Stock type*fertilizer	.003	1	.003	.029	.868
Prune*fertilizer	.007	1	.007	.067	.799
Stock type*prune* fertilizer	.060	1	.060	.550	.469
Error	1.735	16	.108		
Total	127.618	24			
Corrected total	2.295	23			

†Degrees of freedom

‡F ratio

§r squared =.244

Table B.11 ANOVA table for foliar P concentrations in August of the 2004 growing season at the Alfalfa site

Source	Type III sum of squares	df†	Mean Square	F‡	Sig.
Corrected Model	4.065§	11	.370	2.750	.019
Intercept	111.345	1	111.345	828.522	.000
Clone	1.845	3	.615	4.576	.011
Fertilizer	1.645	2	.823	6.122	.007
Clone*fertilizer	.575	6	.096	.713	.643
Error	3.225	24	.134		
Total	118.635	36			
Corrected total	7.290	35			

†Degrees of freedom
‡F ratio
§r squared =.558

Appendix C:

Supplementary soil data for chapter 3

Table C.1 Additional soil NO_3 and NH_4 data for the Alfalfa site.

Stock type	Depth	Treatment	NO_3	NH_4
Rooted Cutting	0-10	Fertilized	85.3	13.6
		Non fertilized	86.0	10.6
	10-20	Fertilizer	34.8	5.0
		Non fertilizer	56.3	7.3
	20-30	Fertilizer	54.7	8.8
		Non fertilizer	32.7	7.6
Rooted Plug	0-10	Fertilized	90.0	11.0
		Non fertilized	105.0	10.8
	10-20	Fertilizer	71.7	5.1
		Non fertilizer	56.0	6.0
	20-30	Fertilizer	60.0	6.9
		Non fertilizer	39.6	6.8

Table C.2 Additional soil NO_3 and NH_4 data for the Pasture site.

Stock type	Depth	Treatment	NO_3	NH_4
Rooted Cutting	0-10	Fertilized	29.1	7.9
		Non fertilized	26.7	8.4
	10-20	Fertilizer	18.4	8.6
		Non fertilizer	20.0	6.4
	20-30	Fertilizer	23.1	11.8
		Non fertilizer	22.3	7.8
Rooted Plug	0-10	Fertilized	26.8	11.8
		Non fertilized	26.5	10.4
	10-20	Fertilizer	25.9	8.2
		Non fertilizer	18.4	6.9
	20-30	Fertilizer	37.0	9.9
		Non fertilizer	23.0	9.7

Appendix D

Additional weather data for the Alfalfa and Pasture sites

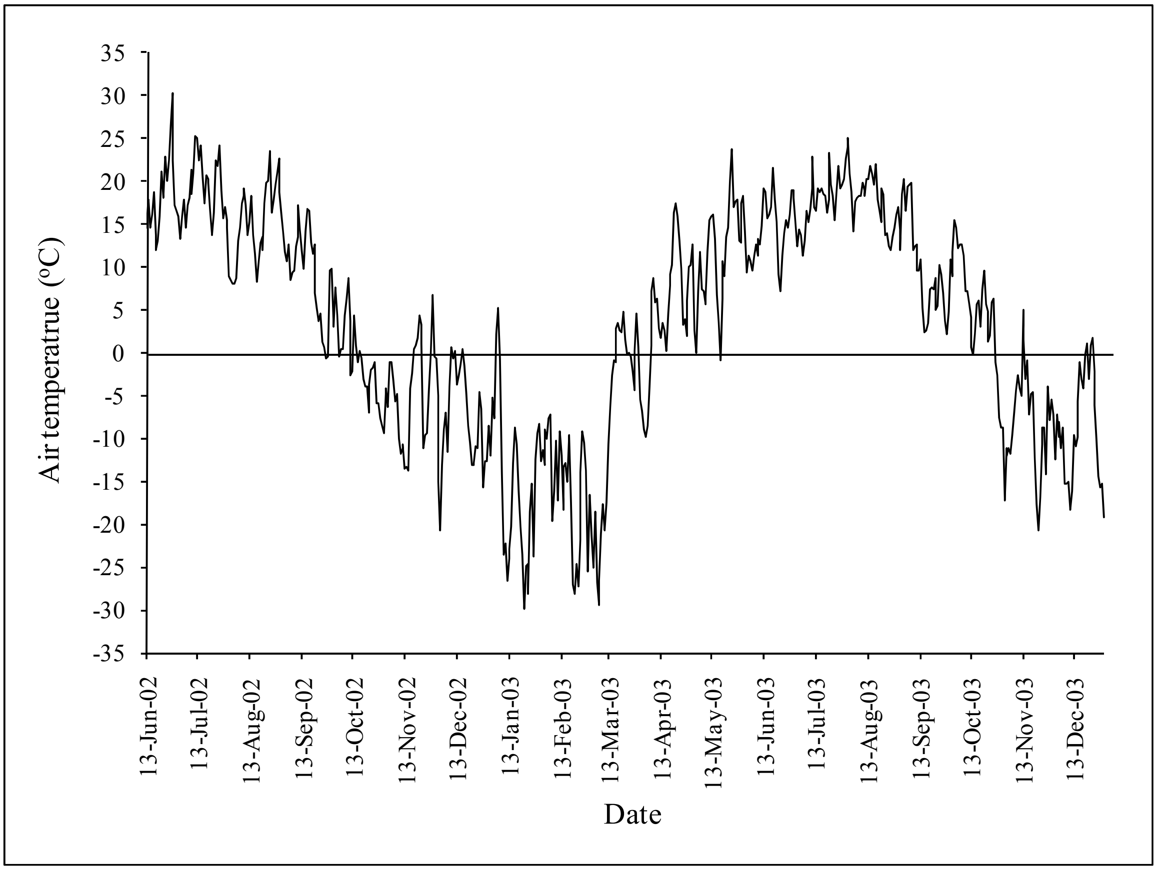

Figure D.1 Daily air temperatures at the Alfalfa site

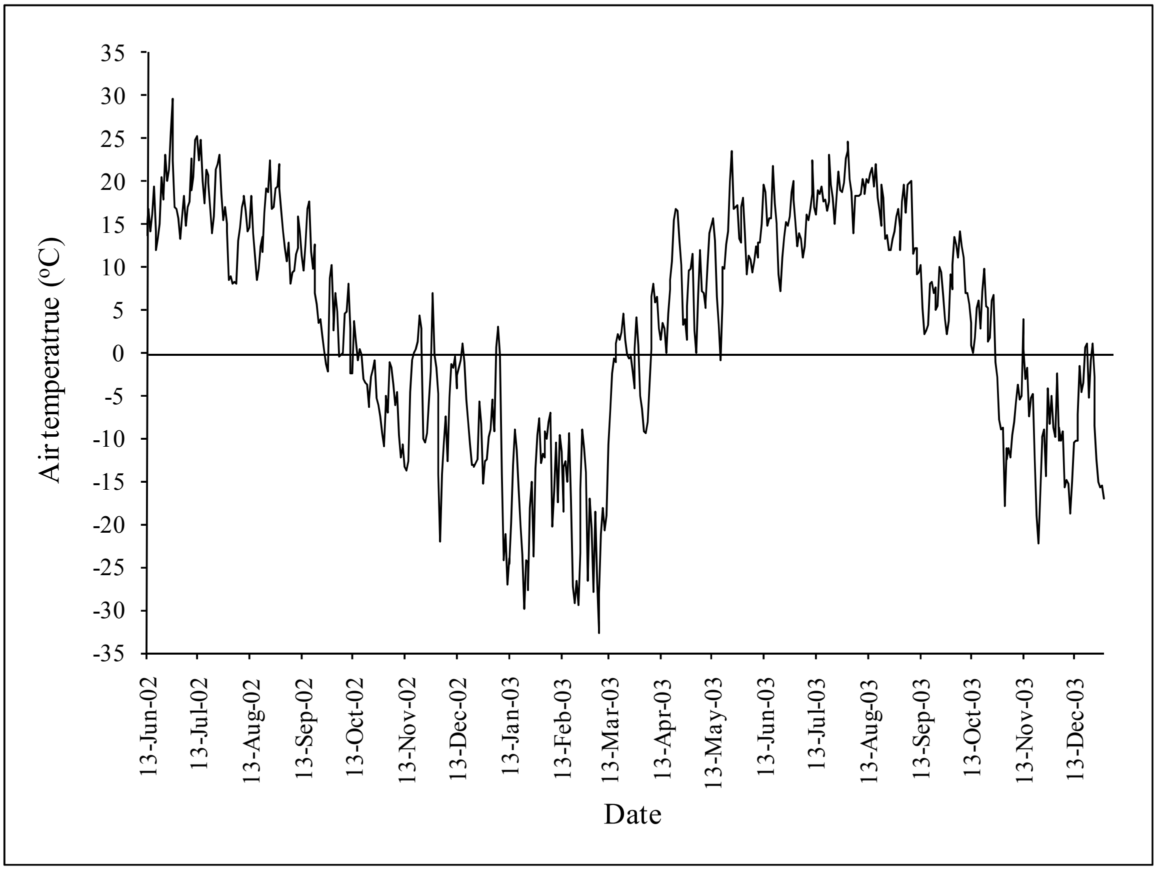

Figure D.2 Daily air temperatures at the Pasture site.

Table D.1 Average monthly air temperature at the Alfalfa and Pasture sites in 2003 and 2004.

Month	Average monthly temperature			
	2003		2004	
	Alfalfa	Pasture	Alfalfa	Pasture
	°C			
January	-15.3	-15.5	-19.4	-19.5
February	-15.0	-15.4	-8.8	-9.1
March	-8.8	-9.4	-4.0	-4.6
April	4.2	4.0	3.8	3.4
May	11.2	10.7	6.9	6.6
June	14.5	14.2	12.4	12.1
July	17.8	17.4	16.6	16.3
August	18.1	17.8	13.6	13.2
September	10.0	9.8	9.4	8.6
October	5.7	5.2	2.6	2.0
November	-8.2	-8.7	-1.1	-2.2
December	-8.7	-9.0	-13.2	-12.9

Table D.2 Average monthly rainfall at the Alfalfa and Pasture sites in 2003 and 2004.

Month	Average monthly rainfall			
	2003		2004	
	Alfalfa	Pasture	Alfalfa	Pasture
	mm			
January	0.1	0.5	0	0
February	0.1	0.4	0.1	0
March	11.9	15.7	0.7	0
April	26.6	51.1	0	0
May	35.3	33.5	22	26.5
June	73.9	67.2	79.7	86.1
July	92.1	74.1	89.8	82.2
August	73.9	68.3	32.2	47.4
September	75.2	93.6	70.6	80.8
October	16.9	14.7	14.9	11.8
November	0	0	0	0
December	0	0	0	0
Total	406	419	310	335

Table D.3 Average monthly rainfall at the Alfalfa and Pasture sites in 2002.

Month	Average monthly rainfall	
	Alfalfa	Pasture
	mm	
January†	0	0
February	1.3	1.3
March	9.5	9.5
April	30.8	30.8
May	4.3	4.3
June	38.1	10.0
July	27.5	28.6
August	61.2	52.4
September	15.8	17.7
October	22.3	22.5
November	2.0	1.9
December	1.1	1.2
Total	213.9	180.2

†Rainfall data from January-May was obtained from The Weather Network. [Online] Available at http://www.theweathernetwork.com/index.php?product=historical&placecode=cask0197

Appendix E:

Supplementary soil data for chapter 4

Table E.1 Spring soil NO_3 and NH_4 samples at the Alfalfa site

Clone	Depth	Fertilizer Treatment					
		0	150	300	0	150	300
			NO_3			NH_4	
		mg g^{-1}					
Hill	0-5	37.7	68.0	119.3	5.5	29.2	97.0
	5-10	18.3	36.3	56.0	3.6	13.6	29.0
	10-15	19.0	35.3	55.7	2.4	3.3	6.2
	15-20	17.7	26.3	41.0	2.3	2.4	2.0
	20-30	16.3	20.3	26.0	2.3	3.6	2.8
	30-40	16.7	18.3	21.7	3.1	3.5	5.5
	40-50	15.7	17.0	17.3	2.7	3.1	3.3
	50-60	13.0	15.0	15.7	2.4	3.1	3.0
Katepwa	0-5	45.7	75.0	119.7	7.3	27.7	71.3
	5-10	21.3	37.3	55.0	3.2	6.5	26.7
	10-15	18.0	34.3	58.7	2.4	2.2	9.8
	15-20	14.7	23.0	41.3	0.8	1.4	2.8
	20-30	13.0	19.0	28.7	1.5	2.8	3.5
	30-40	15.3	18.0	21.0	3.0	3.6	4.0
	40-50	12.9	16.0	17.7	2.7	3.2	3.3
	50-60	11.6	13.7	16.3	2.7	2.8	3.5
Walker	0-5	32.7	73.7	81.0	6.4	21.3	50.3
	5-10	24.7	34.7	46.3	3.4	8.3	21.7
	10-15	23.3	36.0	48.0	2.6	2.7	7.5
	15-20	18.0	25.0	49.3	2.3	1.6	1.8
	20-30	16.7	18.3	27.7	3.0	2.1	2.8
	30-40	17.3	17.0	25.7	4.1	3.2	3.4
	40-50	15.7	15.0	17.0	3.2	2.4	3.2
	50-60	13.9	14.0	16.7	2.7	2.6	3.6
WP69	0-5	24.0	79.0	63.7	5.6	31.7	63.7
	5-10	14.1	33.7	44.0	3.6	9.7	20.3
	10-15	15.9	33.0	46.7	2.2	3.2	3.8
	15-20	15.0	28.0	36.0	3.0	2.2	3.7
	20-30	11.2	20.7	24.0	2.1	3.0	4.3
	30-40	12.2	19.3	19.3	4.0	4.3	4.8
	40-50	12.0	17.7	17.0	3.4	3.8	4.8
	50-60	10.5	15.0	12.3	4.1	3.6	3.8

Table E.2 Mid-season soil NO_3 and NH_4 samples at the Alfalfa site

Clone	Depth	Fertilizer Treatment					
		0	150 NO_3	300	0	150 NH_4	300
		mg g^{-1}					
Hill	0-5	52.7	53.3	60.7	7.2	56.0	107.0
	5-10	28.0	37.7	54.7	4.1	8.7	34.3
	10-15	26.3	41.3	70.3	2.8	3.0	10.5
	15-20	27.0	31.0	60.7	1.8	3.7	5.7
Katepwa	0-5	32.7	48.0	59.0	6.0	50.7	85.0
	5-10	22.0	34.0	35.0	3.1	11.4	29.1
	10-15	25.3	41.7	57.3	1.8	2.2	16.3
	15-20	22.4	38.3	54.3	1.2	1.4	7.8
Walker	0-5	17.0	72.3	91.7	6.6	62.9	99.7
	5-10	15.7	57.7	62.0	3.5	14.0	26.7
	10-15	25.7	50.7	56.7	3.1	3.5	4.8
	15-20	29.0	43.3	43.3	2.1	2.0	3.3
WP69	0-5	28.3	43.3	93.7	7.8	31.9	156.7
	5-10	19.3	28.3	60.7	5.7	7.5	32.7
	10-15	22.0	35.2	65.0	3.4	3.2	5.6
	15-20	25.7	31.0	49.7	7.0	2.8	4.9

Table E.3 Fall soil NO$_3$ and NH$_4$ samples at the Alfalfa site.

Clone	Depth	Fertilizer Treatment					
		0	150	300	0	150	300
			NO$_3$			NH$_4$	
		mg g^{-1}					
Hill	0-5	79.7	54.3	148.7	5.3	31.7	76.3
	5-10	29.3	29.0	80.0	3.5	9.5	25.7
	10-15	20.7	23.7	70.3	2.8	8.2	4.9
	15-20	18.3	22.3	51.3	3.7	5.3	5.0
	20-30	17.7	23.7	33.0	4.9	6.6	4.9
	30-40	22.0	21.3	38.3	6.1	8.2	9.5
	40-50	17.0	19.3	22.0	6.6	6.9	5.8
	50-60	16.0	16.7	19.0	7.3	7.1	4.8
Katepwa	0-5	34.3	90.3	150.0	4.2	47.3	92.0
	5-10	21.0	58.3	84.0	3.0	9.8	29.1
	10-15	16.3	46.7	83.0	2.7	3.3	12.6
	15-20	11.4	31.3	50.0	2.9	2.6	5.5
	20-30	9.1	31.7	49.3	4.2	4.7	5.6
	30-40	16.3	33.0	49.3	5.3	7.7	7.5
	40-50	12.7	21.7	28.0	5.5	5.2	5.5
	50-60	14.0	17.7	21.3	6.0	5.5	5.7
Walker	0-5	29.0	85.0	83.3	3.7	38.0	66.0
	5-10	18.0	55.7	55.0	3.3	10.3	23.3
	10-15	16.7	37.7	36.0	2.6	3.0	4.0
	15-20	16.0	21.3	29.3	2.8	2.8	3.1
	20-30	15.6	21.7	25.3	6.0	5.2	3.8
	30-40	13.5	26.0	40.3	4.6	6.8	10.3
	40-50	12.3	19.0	21.7	4.5	5.7	6.2
	50-60	10.7	17.3	19.0	4.5	5.5	5.1
WP69	0-5	38.3	83.3	126.3	4.9	28.1	82.7
	5-10	19.7	51.0	78.0	3.3	12.0	28.3
	10-15	14.0	34.3	59.7	2.3	3.4	4.2
	15-20	10.7	20.0	45.3	2.4	2.6	3.7
	20-30	10.9	19.3	44.3	3.2	4.9	5.6
	30-40	9.9	23.3	40.7	4.4	5.9	8.5
	40-50	8.0	16.3	25.3	5.2	5.6	6.4
	50-60	6.6	14.1	17.7	4.3	5.8	5.3

Table E.4 Spring soil NO_3 and NH_4 samples at the Pasture site.

Clone	Depth	Fertilizer Treatment					
		0	150	300	0	150	300
			NO_3			NH_4	
		mg g^{-1}					
Hill	0-5	34.3	53.3	47.3	8.5	29.9	11.0
	5-10	20.0	38.3	33.7	6.1	13.3	9.0
	10-15	19.7	35.7	33.7	5.1	8.6	7.0
	15-20	16.3	31.0	27.0	2.5	16.8	7.0
	20-30	15.3	27.3	22.0	11.5	27.9	4.5
	30-40	16.3	31.3	24.0	7.4	20.2	8.5
	40-50	15.7	35.7	21.7	6.1	14.0	7.0
	50-60	14.4	44.3	17.0	6.3	6.3	7.9
Katepwa	0-5	24.0	44.3	64.0	8.4	16.7	16.3
	5-10	15.0	31.7	46.7	5.9	7.8	8.6
	10-15	10.4	27.7	42.0	4.9	4.9	7.2
	15-20	11.8	23.3	34.7	11.0	4.8	5.7
	20-30	12.3	21.3	35.0	6.1	4.5	2.6
	30-40	12.7	20.3	33.7	6.5	7.3	10.0
	40-50	10.3	16.7	27.7	6.0	7.7	6.6
	50-60	7.6	15.0	22.0	4.6	6.6	4.8
Walker	0-5	34.7	49.3	58.7	7.8	11.3	19.0
	5-10	18.3	28.3	42.6	5.3	5.9	8.9
	10-15	15.7	25.0	43.4	4.0	3.3	6.1
	15-20	14.7	23.3	36.4	5.1	3.0	4.8
	20-30	13.0	22.7	33.7	4.6	4.0	4.6
	30-40	14.7	23.3	31.3	8.2	8.7	8.4
	40-50	15.3	19.2	22.3	7.2	9.2	7.0
	50-60	13.3	17.3	19.3	7.5	7.6	6.3
WP69	0-5	37.0	35.0	53.0	4.9	7.7	33.5
	5-10	17.7	29.3	40.7	4.0	5.0	20.2
	10-15	16.0	27.7	48.0	6.5	5.2	7.4
	15-20	13.7	28.0	40.7	6.8	3.7	6.3
	20-30	14.0	28.7	31.0	5.0	5.3	4.1
	30-40	15.0	28.0	32.0	13.7	8.1	8.3
	40-50	16.7	18.3	29.3	7.4	7.7	8.2
	50-60	16.0	13.8	22.7	6.6	5.8	5.4

Table E.5 Mid-season soil NO_3 and NH_4 samples at the Pasture site.

Clone	Depth	Fertilizer Treatment					
		0	150 NO_3	300	0	150 NH_4	300
		mg g^{-1}					
Hill	0-5	20.0	35.7	36.3	7.4	17.8	31.0
	5-10	14.3	27.0	18.7	3.9	4.1	3.2
	10-15	13.5	27.0	19.0	2.7	3.0	3.8
	15-20	12.5	22.0	23.7	3.2	2.8	4.4
Katepwa	0-5	15.3	57.0	72.7	4.9	22.0	42.3
	5-10	10.9	31.3	40.3	2.8	3.5	5.6
	10-15	10.2	26.3	36.3	2.0	3.0	3.7
	15-20	11.0	21.3	25.7	1.9	3.0	4.2
Walker	0-5	17.3	54.7	92.0	6.2	31.3	114.7
	5-10	12.7	39.7	86.7	4.1	5.1	10.6
	10-15	15.0	30.3	71.0	2.8	3.0	5.3
	15-20	16.3	23.3	51.7	2.5	2.9	5.7
WP69	0-5	20.7	41.0	61.7	6.0	7.2	47.7
	5-10	16.0	23.0	51.3	3.7	3.8	5.0
	10-15	17.3	16.7	53.0	1.6	2.3	3.4
	15-20	15.7	16.3	32.7	1.4	1.6	2.1

Table E.6 Fall soil NO_3 and NH_4 samples at the Pasture site.

Clone	Depth	Fertilizer Treatment					
		0	150	300	0	150	300
			NO_3			NH_4	
				$mg\ g^{-1}$			
Hill	0-5	4.3	19.4	45.7	5.8	6.9	31.8
	5-10	5.7	33.2	41.3	4.7	3.9	10.1
	10-15	7.6	31.9	25.9	3.9	2.3	6.2
	15-20	9.6	36.7	27.8	4.0	3.6	6.2
	20-30	12.0	36.0	34.3	4.8	4.2	4.6
	30-40	14.3	35.3	32.3	5.0	4.5	5.2
	40-50	14.0	37.0	39.7	4.9	3.6	4.2
	50-60	13.7	38.0	33.7	4.4	3.7	4.5
Katepwa	0-5	5.3	13.2	21.0	4.9	7.7	19.2
	5-10	6.0	24.7	20.5	3.3	4.9	4.3
	10-15	7.6	31.3	21.6	3.6	3.1	3.5
	15-20	7.8	38.0	24.5	5.1	3.6	3.5
	20-30	9.1	41.3	31.3	5.5	4.2	4.9
	30-40	10.3	45.3	45.0	5.0	5.5	6.6
	40-50	10.9	39.0	44.0	4.4	4.7	4.7
	50-60	10.8	30.0	37.3	4.2	4.2	4.8
Walker	0-5	7.0	15.3	20.0	5.0	7.7	33.0
	5-10	6.4	18.3	23.0	3.6	3.3	4.1
	10-15	6.6	22.0	31.0	2.7	2.6	2.8
	15-20	7.9	19.0	44.0	3.0	2.5	3.2
	20-30	9.3	30.3	52.7	3.8	4.2	4.5
	30-40	8.9	27.3	60.7	4.4	5.0	7.0
	40-50	11.1	29.0	51.0	4.2	5.1	4.4
	50-60	12.7	25.0	46.3	4.7	5.4	4.3
WP69	0-5	4.4	6.7	26.3	4.5	5.5	11.5
	5-10	6.0	10.7	31.0	4.0	4.2	5.3
	10-15	8.2	12.0	36.3	3.3	3.1	3.2
	15-20	7.0	14.9	46.3	3.1	2.7	4.2
	20-30	9.1	23.0	54.7	4.9	4.1	4.3
	30-40	13.0	27.0	54.0	5.3	5.0	5.1
	40-50	15.0	32.3	43.7	4.6	5.7	4.6
	50-60	15.3	30.0	33.7	4.9	5.4	4.8

Appendix F:

Additional growth data for the Alfalfa and Pasture sites

Table F.1 Additional growth data during the 2004 growing season at the Alfalfa site.

Clone	Month	Height			RCD†			Volume		
		0‡	150	300	0	150	300	0	150	300
		cm			mm			cm^3		
Hill	Oct-03	64	58	71	11	10	11	22	16	25
	May-04	48	46	52	11	10	12	17	13	20
	Jun-04	53	49	55	11	10	12	20	14	23
	Jul-04	75	65	76	14	12	16	39	28	60
	Aug-04	113	94	109	19	16	18	115	66	101
	Sep-04	134	107	124	24	20	22	218	122	171
	Oct-04	135	107	126	24	20	23	230	127	184
Katepwa	Oct-03	90	82	88	14	13	12	46	37	37
	May-04	51	53	64	14	13	14	26	26	32
	Jun-04	55	56	67	14	13	14	30	29	36
	Jul-04	89	82	95	17	16	18	71	64	83
	Aug-04	155	135	144	24	22	24	250	184	219
	Sep-04	190	164	175	30	27	28	484	331	387
	Oct-04	193	168	178	31	28	29	526	360	421
Walker	Oct-03	48	49	42	10	9	10	13	12	10
	May-04	36	35	35	8	10	9	8	8	8
	Jun-04	41	36	36	9	10	9	10	8	8
	Jul-04	58	48	45	11	11	10	23	14	15
	Aug-04	104	87	69	14	13	12	74	48	39
	Sep-04	122	102	87	19	16	15	141	86	69
	Oct-04	124	105	88	20	16	16	116	68	81
WP-69	Oct-03	84	79	73	13	13	12	45	36	30
	May-04	67	67	63	13	13	12	35	32	28
	Jun-04	76	72	68	15	15	14	50	43	35
	Jul-04	115	107	97	21	20	17	148	116	78
	Aug-04	174	157	135	31	28	22	496	344	192
	Sep-04	191	167	142	38	33	26	775	491	281
	Oct-04	192	168	143	39	33	27	831	511	297

†Root collar diameter

‡Fertilizer application in kg N ha^{-1}

Table F.2 Additional growth data during the 2004 growing season at the Pasture site.

Clone	Month	Height			RCD†			Volume		
		0‡	150	300	0	150	300	0	150	300
			cm			mm			cm^3	
Hill	Oct-03	87	80	76	15	13	12	55	37	33
	May-04	65	61	54	15	13	13	43	30	24
	Jun-04	68	64	56	16	14	13	49	35	27
	Jul-04	92	81	75	20	17	16	109	69	57
	Aug-04	136	129	119	27	24	23	287	204	167
	Sep-04	168	159	148	32	29	28	496	371	311
	Oct-04	170	162	153	34	30	29	566	402	349
Katepwa	Oct-03	100	108	100	16	17	15	73	91	66
	May-04	82	86	73	16	18	16	67	82	55
	Jun-04	83	89	74	17	18	17	72	93	58
	Jul-04	109	112	91	21	23	21	146	176	117
	Aug-04	175	180	139	30	31	28	457	484	293
	Sep-04	219	220	172	37	35	31	840	766	460
	Oct-04	224	226	175	38	37	32	908	851	497
Walker	Oct-03	51	63	56	10	12	11	14	49	19
	May-04	34	51	44	11	13	10	11	41	14
	Jun-04	38	53	48	11	13	11	15	43	16
	Jul-04	52	64	61	14	16	13	31	74	33
	Aug-04	91	114	93	18	21	17	88	212	81
	Sep-04	131	148	127	23	26	22	206	377	209
	Oct-04	134	150	131	25	27	23	239	377	230
WP-69	Oct-03	87	95	84	15	17	14	61	79	49
	May-04	80	89	79	16	16	16	61	70	56
	Jun-04	87	91	84	18	18	17	79	91	67
	Jul-04	117	120	109	26	25	24	222	212	174
	Aug-04	179	171	166	37	35	33	704	611	519
	Sep-04	204	202	190	47	45	40	1246	1129	820
	Oct-04	205	203	193	48	46	41	1310	1207	887

†Root collar diameter

‡Fertilizer application in kg N ha^{-1}