# Site Productivity of Poplars in Canada: Relationships with soil properties and competition intensity

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# ABSTRACT

Site quality, or the ability of land to grow trees, is an important component for identifying the most appropriate locations for establishing plantations of fast growing tree species to meet society's demands for timber and other environmental benefits. The goal of this thesis project was to predict site quality for poplars using soil and site information in Saskatchewan, Alberta and Quebec and to examine the effect of site quality on competition control in hybrid poplar plantations in Saskatchewan.

The first study examined factors affecting trembling aspen productivity in the boreal shield ecozone of Quebec on till and fluvial parent materials using general map data and measured soil and site information. Relationships with productivity were stronger using measured soil and site variables for individual parent materials ($R^2$>0.6) than using general map data only ($R^2$<0.25). Including biological variables, such as overstory species composition, had a major impact on site quality with conifer dominance negatively impacting the growth of trembling aspen.

The second study examined the factors affecting trembling aspen productivity in the boreal transition ecoregion of Saskatchewan on three different soil parent materials: fluvial, lacustrine and till. Relationships with productivity were stronger using soil and site variables for individual parent materials ($R^2$ 0.48-0.58) than using agricultural capability classes or other soil properties for all plots combined ($R^2$<0.2). For fluvial and lacustrine sites, increasing clay content and nutrient availability (e.g. pH and total N) were positively related to productivity while tree productivity was negatively related to poor drainage for till sites.

The third study examined the factors affecting site quality for a single hybrid poplar clone in industrial plantations in Alberta at both the local scale (between plantations) and the microsite scale (within plantations). At the local scale, foliar P and Cu concentrations, soil water availability and drainage, and Ca and Mn in the C horizon were related to hybrid poplar productivity. There were also curved relationships with productivity and soil texture in the B horizon and pH of the A horizon, indicating an optimal range for poplar growth. At the microsite scale, soil texture was the best predictor of productivity with different relationships at each site depending on where the sites were in relation to the optimal soil texture.

The final study examined the response of hybrid poplar plantations in Saskatchewan to interspecific competition control on a range of site productivities. Competition control greatly increased tree growth with the greatest benefit being on the best quality sites. Both water and nutrients were highly competed for between trees and weeds. In the weed-free plots, tree growth was positively related to the amount of silt and clay in the soil and foliar P concentrations.

This series of studies has demonstrated that it should be possible to predict poplar productivity reasonably well using only soil and site information within limited areas across Canada. However, the important drivers of productivity varied between the regions studied and between site groupings, such as by parent material, within local areas. This information can now be used to help land managers make better decisions regarding the establishment and management of plantations of fast growing tree species, notably hybrid poplar plantations.

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# 1 INTRODUCTION

Site specific management of our forest resources is becoming the norm in Canada. No longer is the same management regime being applied across all sites. For certain areas of Canada, in particular northern Quebec and the prairie provinces, the TRIAD approach (Messier and Kneeshaw, 1999; Messier et al., 2003) is being advanced as a means of increasing timber production and maintaining other important ecosystem values. In this system, land is divided into three major components: 1) a fully protected zone where no timber management occurs, 2) an intensive timber production zone where plantations and tree farming of short rotation, high performance species such as hybrid poplar are favoured and 3) the remaining land area managed using ecosystem based management techniques where natural disturbances are emulated. In order for this TRIAD approach to be successful, the best growing sites must be identified for establishing plantations of fast growing tree species and the response of these trees to silvicultural treatments, e.g. competition control, must be examined.

For establishing plantations, suitable fast growing tree species have been identified from the genus *Populus*, which includes trembling aspen (*Populus tremuloides*) and hybrid poplars (*Populus X*). Trembling aspen is a fast growing, shade intolerant deciduous tree which has the widest natural range of any tree species in North America and can grow under a variety of different environmental conditions (Burns and Honkala, 1990). In Saskatchewan, it is common in pure and mixed stands in the boreal forest in the northern part of the province and throughout the aspen parkland and boreal transition ecoregions south of the boreal forest in isolated patches. Hybrid poplars are a related group of clones which are currently being bred to provide high growth rates for timber production or other management objectives such as carbon sequestration

(Schroeder et al., 2003). The yield of these trees can be up to 10 times higher than native tree species growing in the same area provided they are grown on the appropriate sites.

Tree growth in general is controlled by the availability of light, water and nutrients along with other factors, including temperature and soil aeration (Kozlowski et al., 1991; Kimmins, 1996). Competition from other plant species can reduce the productivity of the site for growing trees by using or altering the availability of these resources (Wagner et al., 2006). Fewer resources available for trees results in reduced growth and increased mortality. This is a major issue for intensively managed tree plantations such as those that are being proposed for Saskatchewan using hybrid poplars to provide an alternate and increased timber supply for mills, create another cropping option for agricultural producers and be part of the solution to meeting Canada's carbon sequestration commitments.

The general goal of my research is to better understand the factors controlling tree productivity in managed and natural forests and to use this information to improve forest management. These factors include both above-ground (i.e. light) and below-ground (i.e. water and nutrients) resources studied at both landscape and microsite scales. For all of my projects I have tried to include both theoretical components as well as an applied component linking this information to improved forest management. For this series of research projects, my specific objectives involve determining the soil, site and plant interactions determining the productivity of *Populus* trees, in particular trembling aspen and hybrid poplar. There are four specific projects which are individual scientific paper style chapters within this thesis: 1) determining site quality for trembling aspen in the boreal shield ecozone of central Quebec, 2) determining site quality for trembling aspen in the boreal transition ecoregion of Saskatchewan, 3) determining site quality for hybrid poplar in the boreal transition ecoregion of north-east Alberta, and 4) examining the effect of site quality on the competitive interaction between hybrid poplars and weeds in central Saskatchewan plantations.

# 2 LITERATURE REVIEW

## 2.1 Site Quality and Productivity

The combination of resources available (i.e. moisture, nutrients and light) determines how well a tree grows at a specific location and is referred to as site quality. Site quality is an important concept for land managers to understand since it can have a great impact on management decisions such as land use zoning which ensures that land is being used optimally. For the purpose of growing timber, better quality sites produce more timber of higher quality in a shorter period of time than poorer quality sites and are more responsive to silvicultural treatments (Carmean, 1996). In the context of the TRIAD approach to forest management this requires being able to identify the best sites for establishing fast growing tree plantations and implementing the appropriate stand tending regimes. One concern that is often raised with fast growing tree species is that they have high nutrient requirements (Fox, 2000) so that plantations growing on sites of marginal fertility may decrease nutrient levels enough to reduce the growth of second or third rotations. It is therefore important to choose appropriate sites to ensure sustained timber plantation growth.

Site quality has traditionally been determined by either measuring the actual tree growth on the site or by examining the soil and site characteristics which affect tree growth. Measuring tree or stand growth on a site has the advantage of integrating all of the relevant growth factors into a meaningful value, i.e. tree growth. A number of different growth parameters have been used such as tree height, basal area, stand volume or total biomass (Carmean, 1975). However, all of these measures except tree height are greatly affected by stand density so they may not give a reliable estimate of the inherent site quality/productivity. The average height of the dominant and co-dominant trees at a reference age (e.g. breast height age of 50 years), called site quality index (SQI), is therefore the most commonly used measure of site quality worldwide (Schonau, 1988).

There are a number of limitations to using SQI that must be considered. First of all, stand history is an important factor in SQI but it may not be related to the inherent site quality. For example, management practices such as site preparation, fertilization, lack of competition control, impacts of insect or disease infestations can all impact tree growth but do not affect the actual site quality (Schonau, 1988). Site quality index also offers no insight into the actual limiting factors for tree growth on a specific site. Finally, SQI cannot be used in young stands or for sites that are not currently forested (Carmean, 1996) which limits the potential for use in agricultural areas which are being considered for afforestation projects. Despite all of these limitations to using site index, the ease of determination and interpretation have made it popular in forest management.

Site quality can also be determined by measuring soil and site characteristics and relating this to actual tree growth, most often to SQI. The main advantage of this approach is that the actual factors limiting tree growth can be determined and once this relationship is formalized it can be applied to sites with young trees or sites that are not currently forested. For northern areas, SQI based on soil and site information has been completed for a variety of species including Douglas-fir (Monserud, 1984), black spruce (Lowry, 1975; Hamel et al., 2004), lodgepole pine (Dumanski et al., 1973), subalpine fir (Klinka et al., 1996), western hemlock (Kayahara et al., 1995), Norway spruce (Syvane et al., 2005), trembling aspen (Chen et al., 1998), jack pine (Hamel et al., 2004) and many other species.

The factors chosen for use in modeling SQI generally depend on the scale of the project. Large landscape scale models are dominated by climatic variables which can account for differences in tree growth across a wide area (e.g. Ung et al., 2001; Chen et al., 2002). These models often rely on analyzing permanent sample plot databases rather than intensive field surveys. Site specific models, on the other hand, are dominated by soil factors such as water and nutrient availability (e.g. Edmonds and Chappell, 1993). By focusing on a smaller, more homogeneous area, climatic influence can be greatly reduced and the specific soil factors examined. The choice of model scale chosen depends on the specific research question but often the landscape level models are developed first and then refined for use in specific local situations (e.g. Schroeder et al., 2003). For areas across Canada interested in implementing the TRIAD approach, such as Quebec (Gouvernement du Québec, 2008), the large scale identification of the best growing area has been completed; the site specific work identifying the best sites must now begin.

In these models, climate is normally characterized using some measures of past average temperature (e.g. degree days or monthly temperatures) and precipitation (e.g. monthly precipitation or vapour pressure deficit) (e.g. Ung et al., 2001). Lowry (1975) even took into account the amount of radiation received at different sites due to differences in cloud cover. Regardless of which variables are included in the model, usually only one temperature and one precipitation variable is included because different precipitation and temperature variables are highly correlated to one another. Location, usually in the form of geographical coordinates such as latitude, longitude, elevation, and aspect, is often used as a proxy for climate. These coordinates are either used directly in the model or used indirectly to estimate climatic parameters using a simulation program such as BIOSIM (Regnière and St-Amant, 2007). Rather than using specific climatic variables, sites can also be grouped according to general climatic zones and then subsequent analysis is done for each climatic zone.

The next site factor to be considered is topography which is normally used as an indirect measure of water-holding capacity of the soil. Slope steepness is included in models to account for higher water runoff and subsurface flow on steep slopes which reduces soil water-holding capacity (Dumanski et al., 1973). Slope position, such as ridge or depression, is often used as a categorical representation of soil water-holding capacity (Synave et al., 2005).

A variety of different mineral soil and forest floor properties have been used to characterize site quality including chemical properties related to nutrient availability and physical properties most often linked to soil moisture availability. Some of the chemical properties used include pH, total carbon (C), total nitrogen (N), mineralizable N, available phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) (Edmonds and Chappell, 1994; Chen et al., 1998; Hamel et al., 2004). These have also been expressed as C/N ratio, total base cations, cation exchange capacity and as a more general soil nutrient regime (Kayahara et al., 1995; Chen et al., 2002). Physical soil properties reported include soil texture, usually as per cent sand or clay, bulk density, water holding capacity and per cent coarse fragments (Fralish and Loucks, 1975; Hamel et al. 2004). Other soil properties that have been used as categorical variables include parent material, soil series and the presence of buried soil layers for fluvial systems (Dumanski et al., 1973; Esu and Grigal, 1979; Shaw et al., 2001). Another potential predictor of site productivity is bulk chemistry of the parent material which has been shown to be a reliable predictor of long term tree growth, nutrition and mortality (Kobe, 1996; Bailey et al., 2004; Moore et al., 2004; van Bremen et al., 1997). Forest floor chemical properties are generally the same as presented for mineral soils but depth of LFH layers and type of forest floor (i.e. mor, moder or mull) have also been included (Yamasaki et al., 2002).

Understory vegetation has been shown to be correlated to site factors such as moisture and nutrient availability, particularly in northern areas. Some of the properties used include understory vegetation composition, presence of specific indicator species, species richness and per cent cover of lichens and bryophytes (Hamel et al., 2003; Chen et al., 2004). These have also been summarized using categorical variables such as habitat type or ecosite which includes a measure of site moisture and nutrient levels (Monserud, 1984; Klinka and Carter, 1990). Stand successional stage, as represented by the Shannon index which describes the distribution of tree diameters, has also been shown to increase site quality predictive ability for shade tolerant species (Ung et al., 2001).

The final factor which has been used to model site quality is actual foliar analysis of trees to determine tree nutrition since it should be the best proxy for soil nutrient availability. It has also been shown to be a good predictor of site quality for a wide range of different sites and tree species when specific nutrients have been limiting tree productivity (Kayahara et al., 1995). This method has been used on sites with mature trees and would also be applicable to young plantations.

### 2.1.1 Populus Site Quality

The main focus of the following studies was on poplar species, in particular trembling aspen and hybrid poplars, which have some specific factors important in determining their productivity.

As with other tree species, climate is the most important factor affecting trembling aspen at broad regional scales. In particular, water deficit has been shown to be the most important limiting factor along the southern limit of its distribution (Hogg et al., 2005). When studying large geographic areas, sites with similar climates are often grouped together to improve the predictive ability of the study such as by biogeoclimatic zones in British Columbia (Chen et al., 2002) or separated into parkland and boreal areas for the prairie provinces (Hogg et al., 2005). Hogg et al. (2005) refined the use of average climatic information by looking at historical yearly growth rates which they found to be positively correlated with yearly moisture. They also found a lag effect of moisture into following years, meaning that trees may not respond immediately after a drought event to better growing conditions.

Location variables have also been used as proxies for climate. Chen et al. (2002) found that in southern British Columbia there was a negative correlation between latitude and aspen productivity but there was no relationship in northern British Columbia. This is most likely because in southern British Columbia an increase in latitude would result in lower temperatures but no more available moisture while in northern British Columbia there is no major difference in temperature or moisture with latitude. Elevation has also shown different trends for aspen productivity depending on location (Chen et al., 2002). In relatively hot and arid environments such as southern British Columbia, increased elevation results in cooler temperatures and more available moisture so that aspen growth increases. Conversely, in cool and wet environments, aspen growth increases with decreasing elevation as it results in warmer temperatures. The same pattern applies for aspect with north facing slopes retaining more moisture, resulting in greater growth in southern areas of the province. However, south facing slopes have higher temperatures that result in greater trembling aspen growth in northern areas (Chen et al., 2002).

At the local scale, soil moisture and nutrients become the major factors determining trembling aspen productivity with available soil water generally overshadowing the effects of nutrients (Carmean, 1996). Soil moisture availability or water holding capacity of the soil is positively correlated with trembling aspen productivity up until the point where the soil becomes excessively wet and starts to limit soil aeration. For northern Ontario, Carmean (1996) found that the best trembling aspen growth was on well drained sites with high clay content in the subsoil to hold the moisture. Soil moisture has also been related to topography and drainage with better growth rates on lower slopes and water collecting areas than on upper slopes or water shedding areas (Fralish and Loucks, 1975; Gustafson et al., 2003).

A variety of different soil chemical properties, including both forest floor and mineral soil properties, have been examined in relation to their effect on trembling aspen site quality. For the forest floor, positive correlations to trembling aspen growth have been found with pH, N, K, Ca and Mg (Chen et al., 1998). For mineral soils, pH, N, C, Ca, Mg and S have all shown positive correlations to growth (Coyne and Van Cleve, 1977; Chen et al., 1998; Paré et al., 2001). Negative correlations with trembling aspen growth have been found for mineral soil P (Chen et al., 1998). In general, the main nutrient limiting tree growth in northern areas tends to be N but other nutrients can also be very important in specific locations or with particular species (Turkington et al., 1998; Weetman et al., 1995; Carlyle, 1986). In the case of trembling aspen, Lu and Sucoff (2001) showed in a greenhouse experiment that Ca is important for growth. Other studies have also demonstrated the importance of base cations for poplar growth (Fralish and Loucks, 1975; Paré et al., 2001). Foliar nutrients have also been used to characterize trembling aspen productivity with Mn levels showing a negative correlation and B levels showing a positive relationship to tree growth (Chen et al., 1998).

Carmean (1996) used parent material to group sites and showed differences in trembling aspen growth between lacustrine, morainal and glaciofluvial groups. He also showed different factors controlling growth on these different parent material groups. This is likely because parent material type has a strong impact on soil water and nutrient regimes as it is associated with contrasted soil texture, cation exchange capacity, available nutrients present and water holding capacity.

The final soil property that has been used for determining poplar productivity is the quantity of available rooting space. This has been determined by the depth to a root restricting layer (e.g. bedrock), amount of coarse fragments in the soil or the depth to water table (Schroeder et al., 2003). The other factors that have been discussed have all looked at the quality of the soil but tree productivity also depends on the quantity of this soil.

Across Canada, hybrid poplars are expected to become important tree species for afforestation projects on agricultural lands as well as in forested areas as part of the TRIAD approach for forest management. Regional productivity models based mainly on climate have been developed for hybrid poplars in Saskatchewan and the prairie provinces (Schroeder et al., 2003), but site specific models using soil information have not been developed. Luckily, the factors controlling trembling aspen site quality are also likely proxies for hybrid poplar growth since they are both fast growing and intolerant species with relatively high nutrient demands.

## 2.2 Resource Competition in Fast Growing Tree Species Plantations

After plantations are established, the next stage is to ensure the trees can access all of the required resources in order to optimize growth. However, even on the best quality sites, if weeds are not controlled poor tree growth will result. For the purposes of this study, the emphasis is on hybrid poplar plantations but information from other plantation species is included where appropriate.

Plant competition is the interaction between plants competing for a resource which is in limited supply that results in a negative impact on growth or survival for at least one of the plants (Zindah, 2004). Competing plants can directly affect the amount of resources (i.e. water, light and nutrients) available to a tree by physically using them and therefore not allowing the tree to use them. These direct effects are the most commonly studied competitive interactions between plants. However, competing plants can also change environmental conditions such as soil temperature which can have a negative impact on trees. For example, leaf litter of the boreal grass species *Calamagrostis canadensis* has been shown to decrease soil temperatures (Lieffers et al.,

1993) which in turn greatly reduces trembling aspen productivity (Landhausser et al., 2001).

Competition is often divided into aboveground competition for light and belowground competition for water and nutrients (Wagner et al., 2006). Aboveground competition is most affected by foliage shading by the competing plants whereas belowground competition depends more on the rooting system of the competing plants. Competition for light is most common with taller, overtopping vegetation such as a taller tree as this can reduce both the quantity and the quality of light reaching the crop tree (Ballare et al., 1990; Horsley, 1993). Belowground competition is more common with relatively shorter competing plants that have dense root systems such as grasses. For example, competition for water has been shown by an increase in drought stress between trembling aspen and *Calamagrosis canadensis* in boreal settings (Powell and Bork, 2004), but competition is thought to be mainly for nutrients in young hybrid poplar plantations grown on the prairies.

Competition can occur between trees of the same species, referred to as intraspecific competition, or between different species, referred to as interspecific competition. Interspecific competition can have a particularly negative impact on tree growth when the competing species is efficient at obtaining the resources most limiting to tree growth, for example, agricultural land which has high infestation of aggressive weed species. Without proper stand tending, intraspecific competition can be even more intense and result in greater growth decreases since both plants have the same growth requirements and strategies for obtaining the resources (Zindahl, 2004). However, this competition between trees of the same species only occurs after the tree species is fully occupying the site and using all of the resources. Therefore, intraspecific competition can be regulated by controlling the density of trees on the site during planting or proceeding with thinning operations.

Competition reduces the growth and productivity of trees and as competitive pressures increase, the relative yield of the crop trees decrease (e.g. Perry et al., 1993). All growth measures are reduced by competition including stem volume, biomass, diameter and height although diameter growth appears to be the most responsive and is reduced before height growth (Morris et al., 1990; Morris and MacDonald, 1991).

Competition can also reduce the future growth potential of a tree by reducing the amount of leaf area and buds, resulting in a carryover effect of competition into future years. Trees whose vigour has been reduced by competition are also more susceptible to other damaging agents such as insects, diseases and other stresses. Final yields, either biomass or volume, can be significantly reduced by competition and/or rotation times are lengthened, both of which reduce the economic viability of a tree plantation. Finally, if competition is severe enough, tree death can occur and this is associated with either replanting costs or reduced final yields.

Different tree species respond very differently to competition depending on the stress tolerance levels of the species. For example, Engelmann spruce, a tolerant species, was found to be unresponsive to competition at low levels indicating that site resources were the ones governing growth rather than competition (Comeau et al., 1993). On the other hand, loblolly pine, an intolerant species, was very negatively impacted by even low levels of competition (Perry et al., 1993). Poplars, another intolerant species, behave similarly to loblolly pine in being very intolerant of competition as has been shown with trembling aspen and brome grass (Bailey and Gupta, 1973) and trembling aspen and *Calamagrostis canadensis* (Powell and Bork, 2004). Different hybrid poplar clones also respond differently to competition and their associated stresses. For example, certain clones have higher light use efficiency and are better able to photosynthesize and grow within dense tree canopies with reduced light levels (Green et al., 2001). This situation appears to be similar for other factors related to competition such as water use efficiency and nutrient use efficiency (Rytter and Stener, 2003) with specific clones being able to grow well even at reduced levels of these resources.

Site factors also play a role in determining the intensity of competition. There is an ongoing discussion in the ecological literature as to whether competition is more intense on good quality sites (e.g. Grime, 1973) or on poorer sites (see for example the meta-analysis by Goldberg et al., 1999) and may depend on the response variable being measured (i.e. growth or survival). Determining the resource for which competition is most intense is very difficult to do in practical field trials since not all resources can be controlled accurately. However, inferences can be made as to the relative importance of light, water and nutrients based on measures of light transmission, soil moisture, and foliar nutrients between weed-free and weedy plots.

Controlling competition is an important part of any crop management plan. However, most previous competition studies have only looked at a single site (Goldberg et al., 1999). Therefore, there is very little information on the effects of competition on different site types with different resource levels, making it difficult for plantation managers to determine the intensity at which weeds should be controlled. With better information about competition impacts on tree growth for different site qualities and the specific resources being competed for in afforestation plantations, the efficiency of weeding programs and success of prairie afforestation programs should improve.

# 3 RESEARCH OBJECTIVES

The general objective of the research project described in this thesis is to examine the factors controlling *Populus* productivity in managed and natural forests and to make recommendations regarding site selection for plantation establishment and competition control to maximize and sustain yields. The first three projects deal with site quality, with the goal of determining the soil and site factors responsible for controlling poplar productivity. The general hypothesis is that the soil and site factors affecting nutrient and water availability will be the major drivers of tree productivity, with water being more important on the relatively dry boreal transition sites and nutrients becoming more important in boreal shield Quebec sites which have more available moisture but have thin acidic soils with low productivity (Thiffault et al., 2007). It is also expected that trembling aspen and hybrid poplars will respond to the same soil and site factors meaning that trembling aspen could be used as a proxy for determining the best sites for establishing hybrid poplar plantations. The fourth component examines competition in hybrid poplar plantations established in Saskatchewan with the hypotheses being that competition control will increase tree growth, that competition pressures will be most intense on better quality sites and water will be the most limiting resource.

This thesis is composed of four research chapters which are written in the style of stand alone scientific papers:

**Chapter 4 – Predicting productivity of trembling aspen in the boreal shield ecozone of Quebec using different levels of soil and site information.** The goal is to model tree productivity using different types of site information. The first set of site information is from mappable databases developed from permanent sample plots and consists of climatic and soil variables such as texture and chemical composition. The second set of information is derived from measured microsite level soil and site variables.

**Chapter 5 – Predicting productivity of trembling aspen in the boreal transition ecoregion of Saskatchewan: influence of parent material**. The goal is to model the soil and site characteristics which influence tree productivity on soil types ranging from sandy fluvial deposits, through loamy tills to lacustrine clay deposits.

**Chapter 6 – Predicting the productivity of a hybrid poplar clone in industrial timber plantations in Alberta using soil and site information** This study utilizes a single hybrid poplar clone 4 years after it was planted on various sites with contrasting soil properties. The goal is to predict tree productivity using simple soil and site data for these genetically identical trees.

**Chapter 7 - Competition control in juvenile hybrid poplar plantations across a range of site productivities in central Saskatchewan** The goal of this project is to examine the impact of competition control in afforestation plantations in Saskatchewan on tree growth, the effect of site quality on competition intensity and determine the resource most competed for and that limits tree growth.

# 4 PREDICTING PRODUCTIVITY OF TREMBLING ASPEN IN THE BOREAL SHIELD ECOZONE OF QUEBEC USING DIFFERENT LEVELS OF SOIL AND SITE INFORMATION

## 4.1 Abstract

Site quality index (SQI) of trembling aspen in the Boreal Shield of Quebec was predicted using two levels of information: 1) mappable variables derived from permanent sampling plots and other sources and 2) measured soil and site properties. General mappable information did not produce strong relationships ($R^2<0.25$) with SQI, while measured variables were able to explain much of the trembling aspen SQI variability. For the two parent material types found in our study, i.e. fluvial and till, there was no difference between median SQI values between groups. However, different soil and site variables were better at predicting trembling aspen productivity for the individual parent material types. As much as 60% of the variability in trembling aspen productivity was explained when both biological and permanent site variables were considered in step-wise regression models. When treated individually, models developed for fluvial sites better explained trembling aspen productivity compared to models developed for till sites. Moreover, the ability of the model to predict trembling aspen productivity on till sites when using permanent site variables alone, e.g. soil texture, elemental chemistry and elevation, was decreased ($R^2<0.3$). This indicates that the inclusion of biological site variables such as overstory species composition and forest floor properties provide a major contribution to SQI prediction and are necessary to yield high $R^2$. Overall, the data indicates that the traditional mapping of landscape attributes such as drainage and deposit as well as inferred soil geochemistry do not contribute much to explaining SQI. At present, field measurements are needed to predict SQI with a reasonable degree of precision within a forest management unit.

## 4.2 Introduction

Over the last ten years, the province of Quebec has been under increasing pressures to set aside forested areas for full protection while maintaining timber production (Commission d'étude sur la gestion de la forêt publique québécoise, 2004). In that respect, Messier et al. (2003) have proposed a forest management scheme where the use of fast growing tree species plantations would be used as a means of achieving wood fibre production while promoting the protection and conservation of forest biodiversity in Quebec and Canada. This management scheme called the TRIAD uses an approach where land is divided into three major components: 1) a fully protected zone that covers about 12% of the forest land mass, 2) a high timber production zone where plantation forestry (about 10%) and tree farming (about 4-5%) are favoured, and 3) a zone (the remaining land area) where forest stands are managed in a manner that emulates as best as possible natural disturbances (i.e. ecosystem management).

Currently, the Quebec Government is strongly considering the implementation of the TRIAD approach throughout its forested land mass to solve some of the issues relating to low wood supply and biodiversity (Gouvernement du Québec, 2008). In that context, fast growing deciduous species such as hybrid poplar and hybrid aspen have become popular as plantation species. In order for (very) intensive forest management to be successful, however, the best sites for growing timber must be identified within a forest management unit because the trees on these sites will respond more favorably to silvicultural treatments and produce more timber of higher quality in a shorter period of time than on poorer quality sites (Carmean, 1975). Trembling aspen (*Populus tremuloides* Michx.) is a widespread and common tree species across North America, particularly in boreal regions, and is capable of growing on a wide variety of sites (Burns and Honkala, 1990). It may therefore be possible to use trembling aspen as a proxy for other fast growing deciduous species such as hybrid poplar and hybrid aspen, since trembling aspen, like poplars, is a fast growing, intolerant (Ung et al., 2001) and nutrient demanding (Maliondo et al., 1990; Camiré and Brazeau, 1998) species that reacts strongly to environmental conditions (Chen et al., 2002).

Many studies have shown the importance of landscape scale differences in climate (expressed as degree-days for example) on the productivity of trembling aspen and other tree species (e.g. Ung et al., 2001; Chen et al., 2002; Hogg et al., 2005). To our knowledge, however, scientists have been relatively unsuccessful in establishing a cause-and-effect relationship between soil physical and chemical properties and the growth of trees in the boreal forests of Canada despite the fact that experienced foresters are anecdotally attributing local (or micro) scale differences in growth to soil fertility/site variables. A few studies have shown benefits of including soil data and other site properties (e.g. topography and elevation which are generally related to water redistribution and microclimatic effects) to predict growth in the Boreal Shield but these data generally come as secondary or tertiary input variables and only slightly add to the predicting capability of the models developed (e.g. Hamilton and Krause, 1985; Carmean, 1996; Hamel et al., 2004). This is quite surprising considering these boreal forests grow on coarse-textured soils that are generally excessively well drained, nitrogen-limiting (Weetman et al., 1995; Yamasaki et al., 2002) and that slowly release base cations from mineral weathering (Kirkwood & Nesbitt, 1991; Bélanger et al., 2002). In this respect, the scale at which these studies have been conducted must be interfering in the establishment of relationships with soil and site data and favour variables that have the greatest divergence (e.g. climate or geologic discontinuities). This means that most growth models are lacking the spatial resolution needed for managers to make sound decisions that optimize productivity and ensure sustainability of the local forest.

In this study, we developed an experimental design where the effect of landscape scale divergence in climate on trembling aspen growth has been reduced to allow the prediction of trembling aspen productivity using two levels of information: 1) mappable variables derived from temporary sampling plots and other sources, and 2) measured soil and site variables. The goal was to identify the best soil and site types for growing poplar spp. in a forested area of Quebec where the TRIAD and hybrid poplar plantations are becoming the standard for forestry and to determine what type (level) of information is required in order to decide where within a forest management unit to establish these plantations for maximum yields.

## 4.3 Methods

### 4.3.1 Study Area and Field Sampling

This study is based in the Haute-Mauricie region of central Quebec within a limited area (75 km radius) north of the town of La Tuque (47º 24'N, 72º46'W) in the balsam fir – yellow birch and balsam fir – white birch ecological regions. The size of the study area was restricted in order to limit the macro-climatic influence on tree growth between sites and emphasize differences due to edaphic factors (Figure 4.1). The common tree species found in this forest area are balsam fir (*Abies balsamifera*), white birch (*Betula papyrifera*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*) and trembling aspen (*Populus tremuloides*). The topography is characterized by rugged Canadian Shield terrain with rock outcrops among deposits of glacial till and fluvial material. There is a general increase in elevation moving north and east in the study area. The soils are all coarse textured Orthic Humo-Ferric Podzols (Soil Classification Working Group, 1998). The climate is characterized by average temperatures ranging from -14.9ºC in January to 18.9ºC in July with an annual precipitation of 940 mm.

Within this region, 50 plots were located in naturally established trembling aspen stands. All selected stands were predominantly trembling aspen but other overstory tree species were also present in amounts up to 50% of the canopy cover. Visual assessment of canopy composition for each species was noted in each plot based on 10% increments. Beyond that threshold of other tree species, stands were not selected. No more than four plots were allowed in a single stand and these were at least 50 m apart and occupied different topographic locations such as upper and lower slopes. Stand ages ranged from 20 to 75 years old and canopy heights were at least 10 m. Sampling was done to capture the widest range of site productivities possible rather than just sampling the average sites. Thirty-four plots were glacial till and 16 were glaciofluvial or alluvial deposits (later referred to as fluvial).

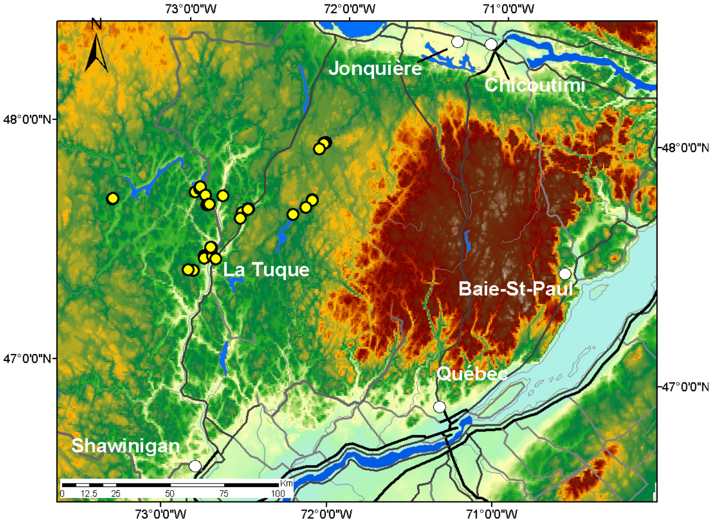

**Figure 4.1** Map of the study area with plot locations shown. Each dot represents more than one plot.

Plots were located randomly within selected stands and the three closest canopy trees (dominant and/or co-dominant) were measured for height and diameter. The plot trees were cored twice at both breast height (1.3 m) and 30 cm aboveground with the cores taken perpendicularly to each other at each height. The were cores then put in plastic straws and taken back to the lab for ring counting. A soil pit was dug at each plot with the thickness of the LFH, Ae and Bf1 horizons recorded. Soil samples were taken from the LFH, Ae, Bf1, Bf2 and BC horizons. Other site information that was recorded included soil drainage class, dominant understory plants, elevation, latitude and longitude, slope and aspect, and topographic position and is presented in Tables A.1 and A.2. This methodology allowed us to analyze microsite influences of soil properties on productivity but it does differ slightly from standard larger scale approaches (Carmean 1975).

### 4.3.2 Laboratory Analysis

Tree cores were dried and then sanded with progressively finer grits until the annual growth rings were clearly visible under a dissecting microscope. Both cores from each tree taken at breast height were counted and were always within two years of each other. Soil samples were air-dried and then sieved with a 2 mm mesh to remove any coarse fragments (e.g. twigs, needles, gravel). Particle size distribution was determined for the Bf1 and BC horizons using the Horiba Partica LA-950 Laser Particle Analyzer. Sonication was used to disperse the samples before measurement. Total carbon (C) and nitrogen (N) of the LFH and Bf1 horizons was determined on ground samples (≤60 μm) by dry combustion and infrared detection using the Leco CNS-2000 (1100ºC). Electrical conductivity and pH were measured in water for the LFH and Bf1 horizons. Elemental composition of the BC horizons ($SiO_2$, $TiO_2$, $Al_2O_3$, $Fe_2O_3$, MnO, MgO, CaO, $Na_2O$, $K_2O$, $P_2O_5$, BaO) was determined on fused beads prepared from a 1:5 soil/lithium tetraborate mixture using an automated x-ray fluorescence spectrometer system (Philips PW2440 4kW, Panalytical, Almelo, The Netherlands). Mineralizable N was determined with eight week incubations at 22ºC of 2.5 g of FH material and 10 g of Bf1 horizons which were watered twice per week to keep the samples moist. Samples were rinsed twice with deionized water prior to the incubation to remove soluble forms of N. After the incubation, $NH_4$ and $NO_3$ were extracted with a 2 *M* KCl solution and analyzed colourimetrically with a Technicon Auto-Analyzer. These results are only reported in Appendix C since they were not found to be significantly related to SQI.

### 4.3.3 Mappable Database

A first model was computed based on datasets that originate from maps or that can be easily derived to create maps. Climatic data such as degree-days of growth (summation of average daily temperature greater than> 5°C $y^{-1}$), available precipitation (mm), water vapour deficit (mm), Thornwaite potential evapotranspiration (mm), radiation (MJ $m^{-2}$) and aridity index (mm) were computed by the algorithms in the BIOSIM model (Regnière and St-Amant, 2007). BIOSIM was designed to simulate insect development at the regional scale based on climatic data. It matches the geo-referenced sources of climatic data (120 stations including data from 1965 to 1998) to the specified site. The selected sources of climatic data are then adjusted to the specified latitude, elevation, slope and aspect. BIOSIM is thus advantageous as it encompasses many geographical and climatic features into a small set of variables. Parent material type and soil drainage for our sites were determined according to the geo-referenced database (forest inventory and ecological maps) of the *Quebec Ministère des Ressources naturelles et de la faune* (MRNFQ). Silt and clay fractions, as well as soil depth when less than a meter, and coarse fragments were estimated based on the ecological surveys of the MRNFQ (Table 4.1). The average value per deposit type and ecological region was assigned to each plot. An ecological region represents a large landscape unit of approximately 20 000 $km^2$ characterised by vegetation dynamics of mesic sites and by the distribution of ecological types within this unit (Robitaille and Saucier, 1998). Finally, we attempted reconstructing soil potentially available nutrient reserves for Ca, Mg and K by using a database containing the acid extractable concentrations of these elements in soil and lake sediments (silt and clay fractions only). This database is provided by the Mine division of MRNFQ (Kirouac, 1996) that is available on the

SIGEOM website (http://sigeom.mrnf.gouv.qc.ca/signet/classes/I1102_indexAccueil?l=a). Lake sediments are considered reliable proxies for soils since in the Canadian Shield sediments are generally only transported over short distances (i.e. less than a few kilometers). Briefly, the fine fraction (<80 mesh) is ashed and extracted with 13.3% nitric acid heated at 90°C for one hour (method-SEAP-S-B-81 in Gagné (1990)). The average acid-extractable elemental concentrations values for all samples within a geological unit (see map by Thériault, 2002) was assigned to each plot within that unit (Table 4.2).

### 4.3.4 Data Analysis

Breast height age of each tree was combined with tree height to determine site quality index (SQI) at an age of 50 years using a site index curve formula for trembling aspen developed in Ontario (Carmean, 1996):

$$SQI_{BH50} = 25.7149 + 0.7182(H-1.3) + 6.2483[\ln(H-1.3)] - 4.5453[\ln(BHAge)] \\ -1.2334[\ln(BHAge)^2] - 6.5116(\frac{H-1.3}{BHAge}) + 0.01186[\ln(H-1.3)]BHAge \qquad \textbf{[4.1]}$$

Plot SQI was then averaged from each of the three trees. The Carmean (1996) equation was used since it is based on ages taken at 1.3 m and it is highly correlated ($R^2$=0.947) with an equation developed in Quebec using age at 1 m (Pothier and Savard, 1998).

**Table 4.1** Mean soil physical properties for till and fluvial parent material derived from the mappable database with standard deviations in parentheses.

| Ecological Region (database no.) | Glacial tills | | | Fluvio-glacial | | |
|---|---|---|---|---|---|---|
| | Stoniness (%) | Soil Profile Depth (cm) | % clay+silt | Stoniness (%) | Soil Profile Depth (cm) | % clay+silt |
| Mauricie Highland (3c) | 33 (3) | 39 (1) | 31 (3) | 10 (4) | 42 (4) | 21 (2) |
| Mid-Saint-Maurice Highland (4c) | 32 (3) | 37 (1) | 32 (1) | 10(6) | 43 (3) | 32 (1) |
| Upper Saint-Maurice Highland (5c) | 33 (5) | 40 (0.3) | 32 (1) | 10 (7) | 41 (6) | 28 (6) |

**Table 4.2** Mean soil extractable elemental concentrations for different bedrock types derived from the mappable database with standard deviations in parentheses.

| Bedrock type (database no.) | Number of samples | K cmol $kg^{-1}$ | Ca cmol $kg^{-1}$ | Mg cmol $kg^{-1}$ |
|---|---|---|---|---|
| Granodioritic and granitic gneiss (44) | 334 | 6 (3) | 10 (10) | 14 (7) |
| Migmatite (46) | 76 | 13 (8) | 12 (11) | 16 (15) |
| Paragneiss, quatzite, amphibolite (48) | 98 | 15 (3) | 8 (6) | 25 (8) |
| Syenite, monzonite, granodiorite, diorite (56) | 123 | 13 (5) | 8 (6) | 21 (10) |

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Correlation analysis was used to determine the suite of variables most closely related to SQI. Stepwise multiple linear regressions were then carried out to model plot SQI as a function of: 1) mappable information only, and 2) measured soil and site factors only. Topographic position and drainage class were input into the models as dummy variables. These multiple regressions were computed for all 50 plots together and then for each parent material type separately. The number of variables selected for the multiple regressions was kept to the minimum (i.e. less than five) to keep the model practical while trying to maximize prediction capability. For the measured soil and site factor models, two sets of variables were used for each prediction: Model 1 included all possible variables while model 2 excluded any stand overstory or forest floor information. Model 2 was intended to simulate non-forest situations where there is no existing tree overstory or forest floor, e.g. agricultural fields, which is common in the southern part of the forest area studied.

The use of ANOVA to compare between groups (e.g. parent material type) was not considered appropriate since the sites were specifically chosen to cover a range of site productivities and may not represent the normal range of values. However, the Mann-Whitney U test was used to test differences between parent material types and boxplot diagrams were used to give a visual representation of the range of values captured. Finally, threshold values for predicting good quality sites (i.e. site index of >20 m) and very good quality sites (>22 m) were determined based on the simple regressions developed for the measured soil and site variables. All statistics were conducted using SPSS version 15.0 (SPSS Inc., Chicago, Illinois).

## 4.4 Results

Site quality index varied considerably across sites ranging from 12.2 to 24.4 m. There was no difference (p=0.731) between the median SQI values for the fluvial (median SQI = 19.6 m) and till (median SQI = 19.7 m) parent material types. Within each plot, there was little variability between individual tree estimates of SQI with an average coefficient of variation for all 50 plots of 3.6%.

### 4.4.1 Mappable Information

The attempt to predict SQI of trembling aspen using only the mappable variables such as climatic data and general soil chemistry data was unsuccessful. For all plots combined and for till plots, climatic variables (degree days or precipitation) were the only variables significantly related to SQI, explaining less than 25% of the variation. For fluvial plots, no variable was significantly related to SQI of trembling aspen (Table 4.3). An indication of the lack of resolution in the mappable data is that it was only able to correctly identify fluvial parent material for less than half of the plots. One other important item to note is that degree days from the mappable database is highly correlated with elevation ($r=-0.923$) which was collected from each plot during the actual soil sampling and was used for subsequent model development (i.e. measured soil and site factors).

### 4.4.2 Measured Soil and Site Factors

The soil properties between the two parent material types differed slightly, with glacial till soils having higher median total N in the forest floor and Bf1 horizon and more silt and clay in the BC horizon than the fluvial soils (Table 4.4). There were no differences in pH in either the forest floor or Bf1 horizons between the parent material groups. The total chemical composition of the soils also differed between parent material types with fluvial soils having higher median levels of $SiO_2$ and $K_2O$ and till soils having higher MgO and $P_2O_5$.

The stand, site and soil properties that were correlated with SQI are presented in Table 4.5 along with their correlation coefficient and p-value. For all plots combined and for each parent material type, overstory stand composition and forest floor properties were highly correlated with SQI. Site quality index was negatively related to the percentage cover of conifer and the forest floor C:N ratios, and positively related to the percentage cover of trembling aspen and forest floor pH. There was no relationship

**Table 4.3** Regression models using the mappable database information

| Equation | $R^2$ | p-val | SEE† |
|---|---|---|---|
| All Plots | | | |
| 3.069 + 0.011(Degree Days) | 0.162 | 0.005 | 2.56 |
| Fluvial | | | |
| No significant relationships | | | |
| Till | | | |
| 48.933 - 0.089(Precipitation) | 0.219 | 0.006 | 2.38 |

†SEE is the standard error of the estimate (m).

**Table 4.4** Median soil properties for each parent material along with the p-val comparing them.

| | Site Index | % Silt + Clay | FH pH | Bf pH | FH C:N | Bf %N | $SiO_2$ | $K_2O$ | MgO | $P_2O_5$ | Elev |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Till | 19.7 | 16.7 | 5.06 | 5.10 | 20.7 | 0.202 | 62.3 | 2.5 | 1.3 | 0.25 | 340 |
| Fluvial | 19.6 | 5.0 | 5.18 | 5.09 | 22.0 | 0.115 | 66.6 | 3.0 | 1.2 | 0.21 | 210 |
| p-val | 0.731 | 0.000 | 0.803 | 0.723 | 0.183 | 0.004 | 0.004 | 0.020 | 0.070 | 0.069 | 0.000 |

**Table 4.5** Correlation analysis between soil properties for all plots combined and for each parent material separately. All significant relationships are shown.

| Variable | All Plots | | Fluvial | | Till | |
|---|---|---|---|---|---|---|
| | r | p-val | r | p-val | r | p-val |
| FH C:N | -0.619 | 0.000 | -0.568 | 0.022 | -0.676 | 0.000 |
| % Conifer | -0.591 | 0.000 | -0.79 | 0.000 | -0.448 | 0.003 |
| % Aspen | 0.456 | 0.001 | | | 0.545 | 0.001 |
| FH pH | 0.43 | 0.002 | 0.579 | 0.019 | 0.317 | 0.068 |
| FH %C | -0.382 | 0.006 | | | -0.39 | 0.023 |
| Elevation | -0.354 | 0.012 | | | -0.488 | 0.016 |
| FH Depth | -0.341 | 0.015 | | | -0.438 | 0.010 |
| BF1 % N | 0.315 | 0.026 | 0.764 | 0.001 | | |
| Ae Depth | -0.291 | 0.040 | | | -0.328 | 0.058 |
| Northing | -0.29 | 0.041 | | | -0.413 | 0.015 |
| Easting | -0.238 | 0.096 | | | -0.528 | 0.001 |
| Bfl %C | | | 0.713 | 0.002 | | |
| Bfl pH | | | -0.548 | 0.028 | | |

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between SQI and mineralizable N, soil drainage or understory plant composition. When grouped by parent material type, there were differences in some of the variables that were correlated with trembling aspen productivity. Site quality index of fluvial plots was positively related to total N and C concentrations and negatively related to pH of the Bf1 horizon, whereas SQI of the glacial till plots was negatively related to elevation, northing and easting.

Multiple stepwise linear regression models are shown in Table 4.6. All models showed greater $R^2$ than models developed from mappable information. Model 1 gave a better prediction of SQI than model 2 in all instances. Model 2 was a substantially poorer predictor for the glacial till sites alone and all plots combined but still had a reasonably high capacity to explain the variability in SQI within fluvial plots. As a whole, C:N, total N, total C and pH of the forest floor or Bf horizon, particle size distribution of the Bf horizon (expressed as percent very fine sand), and depth of the eluviated horizon (Ae) were important. Threshold values for important soil and site variables such as stand species composition, elevation and total N are given for good and very good quality sites in Table 4.7. Topographic position had a significant impact on SQI ($p=0.019$) with highest median SQI values for lower slope positions (21.5 m), lowest values for depressional areas (14.5 m) and mid-range values for upper slope positions (19.1 m) but it was not included in any of the stepwise multiple regression runs.

Measured versus predicted SQI plots for model 1 are presented in Figure 4.2 for all plots combined and for individual parent material type. These indicate that trembling aspen SQI for all plots combined and till plots slightly underestimate SQI at the higher range and overestimate SQI at the lower range. Fluvial plots have a good prediction across the entire range of values. Log-transforming SQI values did not improve model $R^2$ values or the distribution of the residuals.

**Table 4.6 Multiple regression prediction models using the measured soil and site variables.**

| | Equation | $R^2$ | p-val | SEE† |
|---|---|---|---|---|
| **All Plots** | | | | |
| Model 1 | 28.766-0.32(FHCN) – 0.526(Conifer) + 0.088(VFSand) – 0.012(Elev) + 0.005(FHEC) | 0.618 | 0.000 | 1.72 |
| Model 2 | 19.698 – 0.015(Elev) + 47.088(BfN) – 1.439(BfC) | 0.384 | 0.000 | 2.19 |
| **Fluvial** | | | | |
| Model 1 | 48.298 – 0.81(Conifer) +25.059(BfN) – 6.108(BfpH) | 0.884 | 0.000 | 1.08 |
| Model 2 | 63.644 + 42.915(BfN) -= 9.592(BfpH) – 0.100(VFSand) | 0.768 | 0.000 | 1.52 |
| **Till Plots** | | | | |
| Model 1 | 29.020 – 0.596(FHCN) + 0.166(VFSand) | 0.628 | 0.000 | 1.61 |
| Model 2 | 26.083 – 0.014(Elev) – 0.236(AeDepth) | 0.24 | 0.005 | 2.30 |

†SEE is the standard error of the estimate (m)
FHCN is the C:N ratio of the forest floor layer
Conifer is the amount of conifer in the overstory ranging from 0 (0%) to 10 (100%)
VFSand is the per centage of very fine sand in the sample (0.05-0.10 mm)
Elev is the elevation of the plot in m
FHEC is the electroconductivity of the forest floor
BfN is the % N in the Bf horizon
BFC is the % C in the Bf horizon
BfpH is the pH of the Bf horizon
AeDepth is the depth of the Ae horizon (cm)

**Table 4.7** Threshold values for selected soil and site properties for good (SQI=20m) and very good sites (SQI=22m).

| | Fluvial 20 m | Fluvial 22 m | Till 20 m | Till 22 m |
|---|---|---|---|---|
| % Conifer (<) | 10 | 0 | 20 | 0 |
| FH pH (>) | 5.3 | 6 | 5 | 5.5 |
| FH C:N (<) | 21 | 18 | 20 | 15 |
| Elevation (<) | | | 300 | 200 |
| Bf %N (>) | 0.15 | 0.20 | | |

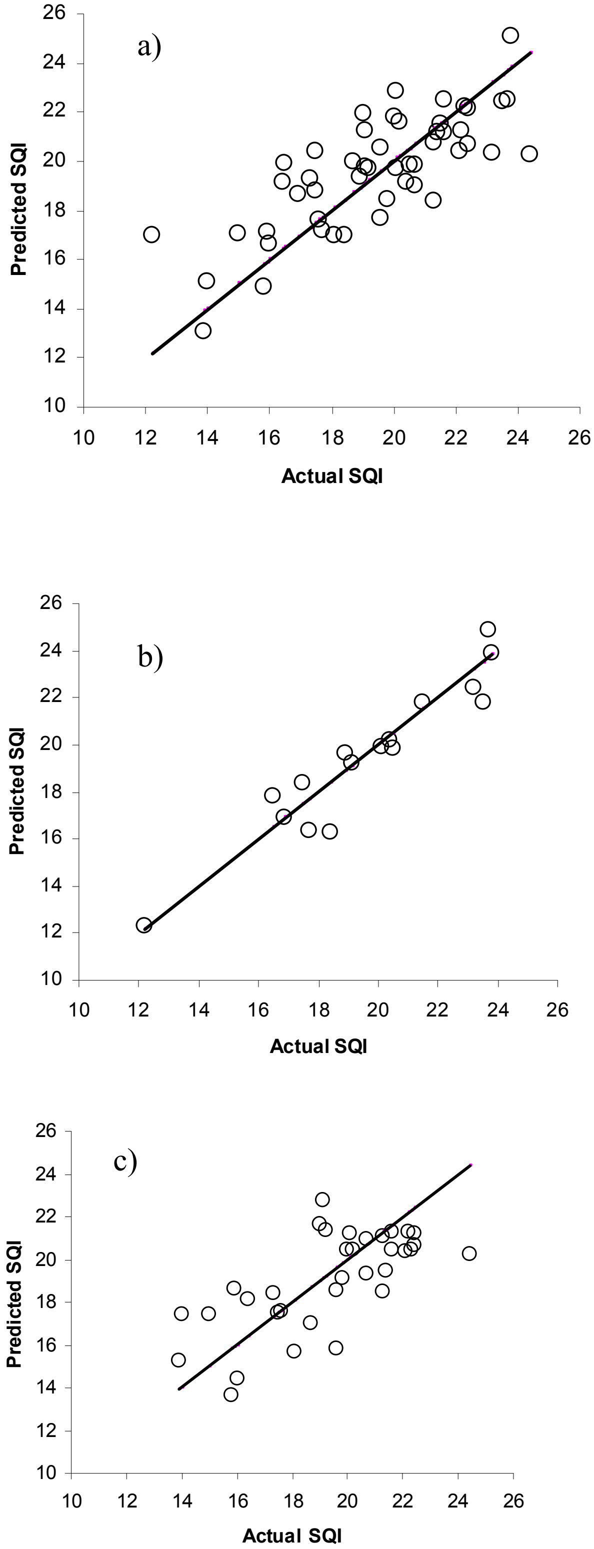

**Figure 4.2** Measured site quality index vs predicted site quality index using the multiple linear regression model 1 developed for all plots combined and each parent material separately in Table 3. Solid lines are the 1:1 lines. a) all plots combined, b) fluvial plots, c) till plots.

## 4.5 Discussion

### 4.5.1 Model Prediction

It does not appear possible to reliably predict trembling aspen SQI using only the general mappable data for this region of Quebec likely because the coarse resolution of the mapping information does not correspond with site specific measures of SQI done in this study. Although this approach has worked relatively well for large, province wide studies examining general growth patterns (e.g. Ung et al., 2001), it is not effective for geographically smaller areas requiring site specific information. This lack of predictive ability underscores the importance of using measured soil and site characteristics when trying to predict growth locally, which is the spatial scale where management decisions regarding the establishment of fast growing tree plantations are made. Also, the mappable database information includes only permanent site variables such as climate, soil texture and soil chemistry which are not as important as biological site variables in predicting SQI of trembling aspen.

Based on the results of the multiple regression analysis using measured soil and site variables, it does appear possible to reasonably predict trembling aspen SQI for this region of Quebec. This predictive ability is comparable to or better than other recent site quality studies for trembling aspen (e.g. Chen et al., 2002) and other northern species (e.g. Hamel et al. (2004) for black spruce and jack pine; Seynave et al. (2005) for Norway spruce). However, the prediction capability of the models become weaker if overstory species composition or forest floor data are omitted, particularly for glacial till alone. This means that our model for till sites would work best in areas that are currently forested or were recently harvested with a forest floor still intact. The fluvial parent material models would be applicable to both forested and non-forested areas. Interestingly, fluvial sites in the area are those that are mostly used for agriculture as they are generally characterized by a flat topography, rock-free soils and are near a water source for irrigation.

Most other studies on trembling aspen site quality index include climate variables relating to moisture and temperature (e.g. Ung et al., 2001; Hogg et al., 2005).

These variables have been shown to be very good predictors of tree growth, particularly across large geographic regions. In our study, however, the goal was to examine the effect of soil and site variables on trembling aspen productivity, and consequently we purposely eliminated macro-climate effects by only sampling in a restricted area where climate was quite constant across sites. The relatively strong relationship found between edaphic factors and trembling aspen productivity demonstrates how important soil and site properties are in determining trembling aspen productivity at a local level. However, there does appear to be a strong micro-climatic effect with degree days being positively related to aspen productivity and elevation being negatively related.

### 4.5.2 Permanent Site Variables

Permanent site variables such as parent material, texture, soil mineralogy and elevation represent static conditions that do not change over time or with site disturbance. These have proven to be useful in predicting SQI for a variety of different species including trembling aspen (e.g. Hamel et al., 2004). We found no difference in productivity between parent material groups, which is similar to findings reported for European aspen (*Populus tremulus*) in Sweden (Johansson, 2002). In our study, however, there were different soil and site factors responsible for controlling trembling aspen productivity between fluvial and till sites. Most often in the literature these differences between parent materials are related to soil water and texture (e.g. Paré et al., 2001; Martin and Gower, 2006) but this is not the case in our study.

Soil texture, which can be used as a proxy for soil water availability, was not related to trembling aspen productivity, even though there were differences in the amount of silt and clay within and between parent material types. This is different from other studies across North America focusing on soil properties in relation to trembling aspen productivity, where soil water availability or a related variable is the most common factor controlling aspen growth. For example, Paré et al. (2001) in northwestern Quebec found that mature aspen trees growing on clay-rich soils had greater height growth compared to coarser till soils. Martin and Gower (2006) in Manitoba also found that aspen trees were taller on clay soils as opposed to sandy soils in stands naturally established after a forest fire. In both cases, this was presumably because of the greater water holding capacity of the clay soils. However, our plots are all predominantly sandy (loamy sand or sandy loam) with small amounts of clay in them, creating no contrast with heavier soils in terms of available water and tree growth.

The bulk elemental chemistry of the lower soil horizons can give important information about the potential nutrient reserve for tree growth (Kobe 1996; van Breemen et al., 1997). However, we did not find it to be important in this study for predicting trembling aspen growth. For example, trembling aspen and the genera *Populus* are recognized as being Ca demanding species (Camiré and Brazeau, 1998). Despite efforts to characterize the parent material elemental chemistry, no relationship between Ca and SQI was found. These results are likely not reflecting an abundance of Ca for plants but rather reflect very homogeneous total Ca concentrations in the BC horizons across the sites, governed by a very large plutonic mass of granite in the study area. Also, we found greater total Si and K and lower total P and Mg concentrations in the BC horizons of the fluvial sites which are associated with the rivers or streams concentrating/depositing coarse (sand) quartz and K-feldspar minerals and transporting/dissolving apatite (P) and ferro-magnesian minerals that is originally contained in the rock. However, these differences in elemental chemistry did not promote a diverging aspen growth pattern between parent material types. We therefore suggest that total chemistry of the parent material is not a useful predictor of trembling aspen productivity if geologic discontinuities have not been captured (e.g. Kobe, 1996).

The final permanent site variable evaluated was elevation which was highly correlated to the other location variables of northing and easting. In till plots, which were found in upland areas with large differences in elevation, this was an important factor controlling trembling aspen productivity. Conversely, the fluvial sites were largely associated with river valleys where there was less difference in elevation. Chen et al. (2002), in the boreal white and black spruce zone of British Columbia, also found a decrease in trembling aspen productivity with elevation. This is because higher elevation sites experience lower temperatures throughout the year (a micro-climatic difference) resulting in lower productivity. This was also reflected in the models developed with degree days as affected by elevation. Interestingly, aspect does not seem to be related to productivity even though aspect should have the same effect as elevation with southern aspects experiencing warmer conditions than northern aspects (Chen et al., 2002).

### 4.5.3 Biological Site Factors

Biological site factors such as overstory composition, forest floor properties and soil N are a product of stand history and have the potential to change over time, such as the length of a timber rotation. They demonstrate the effect trees can have on their own growing environment and the individuals around them. The chemical composition and nutrient availability (pH and C:N ratios) of the forest floor appear to be the largest factors controlling the productivity of trembling aspen in our study and are highly correlated with the overstory stand composition. The forest floor is known to be important as a source of food and habitat for microorganisms and for protecting the underlying mineral soil (Prescott et al., 2000). The result is that the forest floor is a vital component of forest nutrient cycles/pools (e.g. Bélanger et al., 2003) and is home to a large percentage of tree roots in the boreal forests, including aspen stands (Strong and La Roi, 1983; Steele et al., 1997; Finer et al., 1997). Relationships between forest floor chemical properties and trembling aspen growth in the boreal forest have been found in other studies, in particular for base cations and nitrogen (Chen et al., 1998; Paré et al., 2001).

Trees have an impact on soil properties that affects their own fitness as well as that of other trees around them, both spatially and temporally (Binkley and Giardina, 1998). Stand composition controls forest floor chemical properties through the deposition of leaf litter (Van Cleve et al., 1983; Trofymow et al., 1995). In general, conifer needles tend to decompose and release nutrients slower than deciduous leaves due to higher lignin content and large C:N (Trofymow et al., 2002). These conifers tend to accumulate more biomass in the form of a forest floor while trembling aspen tends to cycle nutrients faster (Van Cleve et al., 1983; Bockheim et al., 1991), require more nutrients for growth (Maliondo et al., 1995; Paré et al., 2002) and store more biomass as wood (Alban, 1982). In mixed conifer-aspen stands in Quebec, increased amounts of trembling aspen was associated with increased forest floor pH, exchangeable base cations and nitrogen, thereby increasing potential fertility relative to pure conifer stands (Longpré et al., 1994; Légaré et al., 2005). In a related study, Légaré et al. (2004) also observed increased growth of black spruce when grown in mixed stands with trembling aspen, which verifies the hypothesis that aspen increases soil productivity for spruce. In our study, we suggest the reverse is occurring with conifers having a negative effect on forest floor chemical properties and nutrient availability, thereby reducing trembling aspen productivity.

Increases in mineral soil N resulted in increasing tree productivity for fluvial sites but not for till sites. Till soils did have higher median mineral soil N levels compared to fluvial soils, suggesting that trees supported by fluvial soils may be growing under a poorer nutritional environment and thus, an increase in N availability may be leading to increased trembling aspen growth. Reich et al. (1997) found that soil texture was an important control of N mineralization and aboveground biomass production of fifty forested sites in the United States including both hardwood and coniferous stands; N mineralization and forest growth was greater in soils with a higher silt and clay content. In our study, the coarser fluvial soils compared to the till soils may thus explain the divergence in mineral soil N between material types.

## 4.6 Conclusion

The variability in trembling aspen SQI was captured reasonably well locally using simple measured soil and site characteristics but not with data from mappable databases. This indicates that the precision of information needed to accurately predict SQI requires that actual field measurements be taken rather than relying on general mappable data. It also appears that biological site factors, rather than permanent site factors, have a greater influence on trembling aspen productivity in this area. This lack of response to permanent site variables is likely because we did not find a large gradient in soil texture or elemental chemistry among either plots or parent material types. With biological site factors however, there are still uncertainties as to the timeframe of change and whether they are related to some permanent site variables not measured in this study.  Does the overstory species composition tell us something fundamental about differences in site properties with conifers favouring certain site types or is it more a function of site history and disturbances?  If the latter is true this indicates that site quality may be capable of changing over time naturally during succession and, perhaps more importantly, by human management such as preferentially establishing desired tree species that can improve soil conditions.

# 5 PREDICTING PRODUCTIVITY OF TREMBLING ASPEN IN THE BOREAL TRANSITION ECOREGION OF SASKATCHEWAN: INFLUENCE OF PARENT MATERIAL

## 5.1 Abstract

Site quality index (SQI) of trembling aspen in the boreal transition ecoregion of Saskatchewan was predicted using soil and site information from stands growing on three different soil parent material types: fluvial, lacustrine and glacial till. It was not possible to predict SQI for all plots grouped together ($R^2<0.2$) using stepwise regression of soil and site properties or agricultural capability classes, indicating that agricultural and natural forest productivity are not governed by the same relationships with soil properties. There was no difference in median SQI between parent material groups but different soil and site variables were better at predicting trembling aspen productivity for the individual parent material types. Fluvial and lacustrine sites responded positively to increases in clay content and soil nutrient status while till sites responded negatively to excess water and poorer soil drainage. Between 48-58% of the variability in trembling aspen productivity was explained using using these common soil measurements. Including more sophisticated measures of soil nutrient reserve such as total elemental chemistry of the C horizon did not improve the prediction. Overall, this study indicates that it is possible to predict trembling aspen productivity provided that parent material is included in the analysis.

## 5.2 Introduction

In Canada, a current trend on marginal agricultural land in transitional areas between forests to the north and prairies to the south (e.g. the boreal transition ecoregion in Saskatchewan), is the establishment of plantations of fast-growing tree species to meet the timber needs of the forest industry as well as other goals such as sequestering carbon and increasing biodiversity (McKenney et al., 2004; Yemshanov and McKenney, 2008). On the Canadian prairies, the tree species of choice for these plantations are hybrid poplars (*Populus* X) which are very fast growing trees with high resource demands (Hansen et al., 1988; Shock et al., 2002) and can be easily regenerated from cuttings. One of the most critical aspects of plantation establishment is choosing to plant trees on the best growing sites to ensure maximum growth and sustainability of yields of future rotations by not depleting all of the soil resources (Carmean, 1975). There is currently very little research on the soil and site properties associated with the best growing sites for hybrid poplars plantations in the prairie provinces (Schroeder et al., 2003; Joss et al., 2007).

It may be possible to use trembling aspen (*Populus tremuloides* Michx.), a closely related species which is also a fast-growing, intolerant species with high resource demands, as a proxy for hybrid poplar. Trembling aspen is a widespread and common tree species across North America, particularly in boreal regions, and is capable of growing on a wide variety of sites (Burns and Honkala, 1990). Many studies have shown the importance of landscape scale differences in climate (often expressed as degree-days or climate moisture index) on the productivity of trembling aspen and other tree species (e.g. Ung et al., 2001; Hogg et al., 2008). However, at a more local level with minimal differences in climate, soil physical and chemical properties are likely the main factors governing tree productivity. This has been shown for some soil and site properties. For example, soil texture and topography are considered as proxies for soil water holding capacity and water availability (Gustafson et al., 2003; Martin and Gower, 2006). In terms of soil fertility, N is generally considered to be the nutrient most limiting tree growth in boreal and temperate environments (Reich et al., 1997; Turkington et al., 1998) but there is some evidence that trees growing on rich Chernozemic soils, such as found in the boreal transition ecoregion, can access all of the required N for optimal growth and that other nutrients, in particular P, have a major impact on tree productivity (Chapter 7). However, these soil and site effects have generally been overshadowed by landscape scale climate variables in studies which cover a large geographical area. Therefore, the goal of this study was to identify the specific soil and site properties associated with the best growing sites for trembling aspen within the limited climatic conditions of the boreal transition ecoregion of Saskatchewan.

## 5.3 Methods

### 5.3.1 Study Area and Field Sampling

This study is based in the boreal transition ecoregion of northeast Saskatchewan within a limited radius of approximately 75 km of the town of Tisdale (52º 51'N, 104º 03'W). The size of the study area was restricted in order to limit the climatic influence on tree growth between sites and emphasize differences due to edaphic factors. The climate is characterized by average temperatures ranging from -18.5ºC in January to 17.4ºC in July with an annual precipitation of 400 mm. The dominant tree species in the area is trembling aspen (*Populus tremuloides* Michx.) along with white spruce (*Picea glauca* Moench (Voss)) and jack pine (*Pinus banksiana* Lamb.). Forested areas are normally islands of trees ranging from 1 ha to 100 ha in size and surrounded by agricultural land. The soils in this area are classified mainly as Dark Gray Chernozems and Dark Gray Luvisols (Soil Classification Working Group, 1998) developed on glacial till, lacustrine and fluvial parent materials. This area of the boreal transition ecoregion in Saskatchewan was specifically chosen due to the wide range of parent materials and soil types common in the area. The topography for the area is relatively flat with hills only occurring in the till areas.

Within this region, fifty plots were located in naturally established, pure (>80%) trembling aspen stands. Stands with a significant component of other species such as balsam poplar or jack pine were not included in the study. Stands showing any evidence of cattle grazing, timber harvesting or other disturbance were also eliminated. No more than two plots were allowed in a single stand and then they were at least 100 m apart. Stand ages ranged from 20 to 75 years old and canopy heights were at least 10 m. A stratified design was used so that all major parent materials, i.e fluvial, lacustrine and till, were well represented. Thus, we selected one third of the plots from each of the parent material type. This sampling scheme helped capture a wide range of site productivities rather than just sampling average sites.

Plots were located within selected stands and the three closest canopy trees (dominant and co-dominant) were measured for height and diameter. The plot trees were cored twice at both breast height (1.3 m) and 30 cm aboveground with the cores taken perpendicularly to each other at each height. The cores then put in plastic straws and taken back to the lab for ring counting. Two soil pits were dug at each plot with the depth of the FH and Ah horizons recorded and then averaged to obtain a plot value. Soil samples were taken from the FH, Ah, B and BC horizons with the BC horizon considered to start at 50 cm if it was not encountered earlier. Other site information that was recorded included soil drainage class, ecosite phase (Beckingham et al., 1996), elevation, latitude and longitude, slope and aspect, topographic position, presence of earthworms and parent material. Soil drainage was grouped into two categories for use in modeling productivity: imperfect and moderately well drained sites assigned a value of 0 while well and rapidly drained sites were assigned a value of 1. Soil association and agricultural capability classes were later determined based on soil maps for the area (e.g. Saskatchewan Soil Survey, 1989). Agricultural capability classes rank soil from 1 to 6 with 1 being the most productive agricultural soil with no significant limitations for crop production and 6 being considered capable of producing only native forage crops.

### 5.3.2 Laboratory Analysis

Tree cores were dried and then sanded with progressively finer grits until the annual growth rings were clearly visible under a dissecting microscope so that the age of each core could be determined. Soil samples were air-dried and then sieved with a 2 mm mesh to remove any coarse fragments before being bulked by volume resulting in one sample per plot for each soil horizon. Particle size distribution was determined for the Ah and C horizons using the Horiba Partica LA-950 Laser Particle Analyzer. Both horizons were treated with sodium hexametaphosphate and sonication to disperse particles before measurement. The Ah samples were also treated with NaOCl due to the high organic matter levels and presence of aggregates.

Total carbon (C) and nitrogen (N) of the FH and Ah horizons were determined by dry combustion and infrared detection using the Leco CNS-2000 (1100ºC). Electrical conductivity and pH were measured in water for the LFH and Ah horizons. Inorganic C was quantified in the C horizons by measuring both organic and total C on the Leco CR-12 Analyzer at 800ºC and 1100ºC respectively (Wang and Anderson 1998). The inorganic C was then taken to be the difference between the two measurements.

Elemental composition of the BC horizon was determined from fused beads prepared from a 1:5 soil / lithium tetraborate mixture which were then finely ground. Two grams of the finely ground beads were digested in 15 ml of HCl and 5 ml of $HNO_3$ at 100ºC for six hours in Teflon beakers covered with a watch glass. Calcium, Mg, K, Na, Al and Fe were then analyzed using atomic absorption/emission. Phosphorus was analyzed colourimetrically (molybdenum blue) from the same digests with a Technicon Auto-Analyzer. The method was tested against X-ray fluorescence data for six samples of contrasted chemistries (Appendix B). The method showed high recoveries for all elements except P but all elements were very strongly correlated with the X-ray fluorescence data.

### 5.3.3 Data Analysis

Breast height age was combined with individual tree height to determine site quality index (SQI) at an age of 50 years using the formula for trembling aspen developed in northwest Ontario (Carmean, 1996) and then averaged for the plot:

$$SQI_{BH50} = 25.7149 + 0.7182(H - 1.3) + 6.2483[\ln(H - 1.3)] - 4.5453[\ln(BHAge)]$$
$$- 1.2334[\ln(BHAge)^2] - 6.5116(\frac{H - 1.3}{BHAge}) + 0.01186[\ln(H - 1.3)]BHAge \qquad \textbf{[5.1]}$$

Correlation analysis was used to determine the suite of variables most closely related SQI. This was done for all 50 plots together and for each parent material separately.

Significance was accepted at 0.05 for all 50 plots together and 0.10 for the individual parent materials. Stepwise multiple linear regressions were then carried out to model plot SQI as a function of soil and site factors. The number of variables selected for the multiple regressions was kept to a minimum (i.e. three or less) to keep the model practical while trying to maximize predictive capability. Log-transformation of SQI values was performed but this did not improve model $R^2$ values or the distribution of the residuals. Because of the non-normal distribution of the samples, the Mann–Whitney–Wilcoxon non-parametric test was used to determine whether the parent materials have the same SQI distribution. The null hypothesis was that two samples are not drawn from populations with different medians. The Mann–Whitney–Wilcoxon test likely produces less significant results compared to the standard Student's t-test due to one or more outliers, especially with smaller sample sizes (Snedecor and Cochran, 1989). Consequently, the null hypothesis was rejected if $P \leq 0.10$.

## 5.4 Results

Site quality index values ranged from 12.0 to 23.1 with no difference in the median for each of the three different parent material types (Table 5.1). Within each plot, there was little variability between individual tree estimates of SQI with an average coefficient of variation for all 50 plots of 4.4%. There were however significant differences in soil properties, in particular soil texture and total N concentrations in the Ah horizon, between parent material groups. Plots occurred on three ecosites, i.e. d, e and f, with most being characterized by mesic (d) ecosites (Beckingham et al., 1996). Ecosites e and f are considered progressively richer sites but these did not correspond to more productive sites (p=0.884). In terms of agricultural capability classes, the plots were on land ranked from class 1 (the best agricultural land) to class 6 (poor agricultural land). There was a difference in median ranking between parent material types but there was only a weak relationship to SQI (Figure 5.1). Nevertheless, the best growing sites with a SQI greater than 20 occurred on all agricultural capability classes 1 through 4 but no distinction could be made between these classes.

**Table 5.1** Median values for selected soil and site properties for the three parent material groups. Different letters indicate that the parent materials are significantly different at p=0.10.

| Parent Material | Site Index (m @ BH†Age 50) | Agricultural Capability Class | Sand (%) C horizon | pH Ah horizon | Total N (mg/g) Ah horizon | Total Ca (mg/g) C horizon | Total P (mg/g) C horizon |
|---|---|---|---|---|---|---|---|
| Fluvial | 18.5 | $4^{A}$ | $66.4^{A}$ | 6.36 | $1.6^{A}$ | $6.2^{A}$ | $0.07^{A}$ |
| Lacustrine | 18.1 | $2^{B}$ | $3.6^{B}$ | 6.77 | $3.5^{B}$ | $8.2^{AB}$ | $0.15^{B}$ |
| Till | 16.3 | $3^{C}$ | $16.4^{C}$ | 6.54 | $3.7^{B}$ | $14.7^{B}$ | $0.12^{B}$ |

†breast height

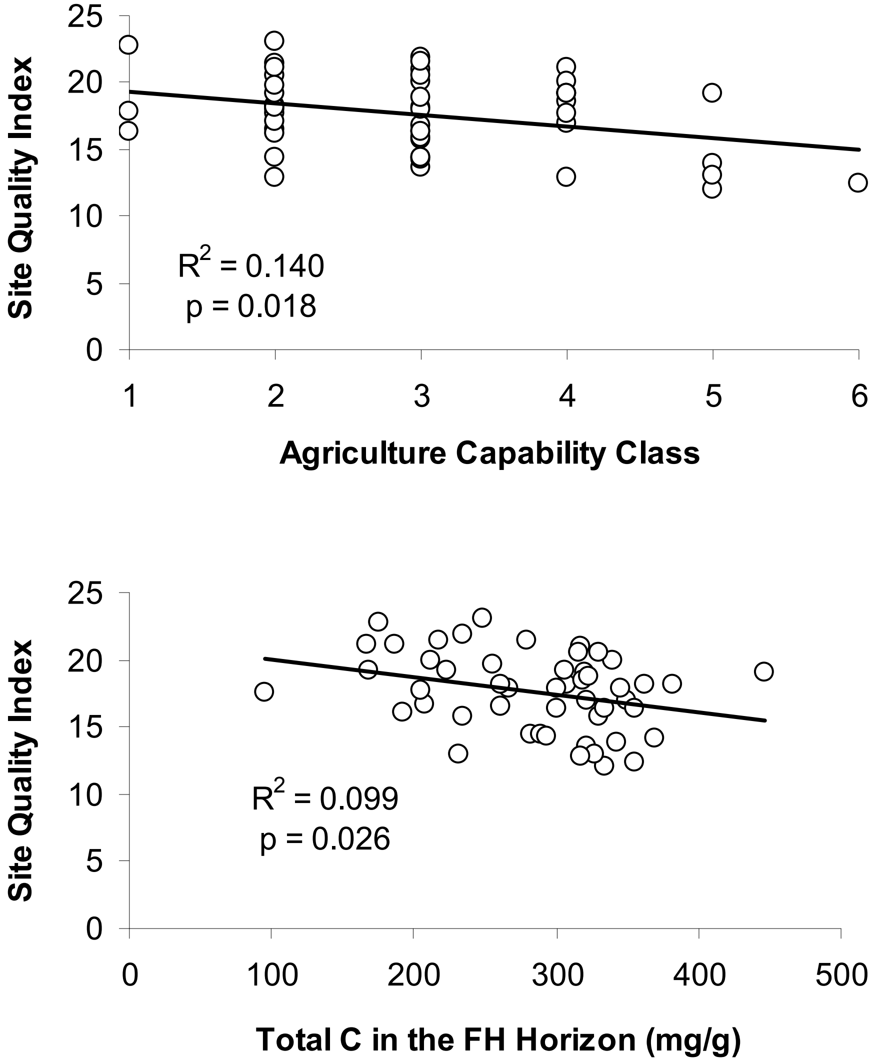

**Figure 5.1** Relationship between site quality index for all 50 plots and (a) agricultural site capability class and (b) total C in the FH horizon

Climate difference between plots was not a major controlling factor of trembling aspen productivity given that northing (p=0.455) and elevation (p=0.117) were not correlated with HP productivity, thereby placing the focus on the soil and site properties impacting HP productivity. Significant relationships between SQI and soil and site properties for all plots combined are shown in Figure 5.1. Multiple regression analysis did not improve the prediction of trembling aspen SQI when all plots were grouped together. The best model ($R^2$=0.16) included C concentrations in the FH layer and soil texture of the Ah horizon (Table 5.2). Mineralizable N and the presence of earthworms were not related to SQI. Since there were no satisfactory relationships for all plots combined, the analysis was conducted by separating the plots into the following categories: parent material group, ecosite type, agricultural capability class and soil great group. The only one of these grouping which improved site index prediction was parent material type. Therefore, all subsequent analysis was done separately for each of the three parent materials of fluvial, lacustrine and till.

For the fluvial sites, the best single predictor of SQI was the pH of the Ah horizon which was positively correlated with SQI, followed by soil texture where the amount of sand was negatively correlated (Figure 5.2). The multiple regression ($R^2$=0.48) included pH of the Ah horizon and electroconductivity of the Ah horizon (Table 5.2). For lacustrine sites, clay content in the C horizon and total N concentration in the Ah horizon were both positively correlated to SQI (Figure 5.3). The multiple linear model ($R^2$=0.54) included clay content in the C horizon and depth of the Ah horizon (Table 5.2). For till sites, soil drainage was positively related to SQI, whereas the amount of clay in the Ah horizon was negatively correlated to SQI (Figure 5.4). The multiple regression ($R^2$=0.58) included drainage class and the pH of the Ah horizon (Table 5.2).

Measured versus predicted SQI for all three parent material groups treated in combination or individually are presented in Figure 5.5. The results indicate that trembling aspen SQI was slightly underestimated at higher SQI values and overestimated at lower SQI values. Of the parent material groups, the fluvial plots have the best prediction throughout the entire SQI range.

**Table 5.2** Multiple regression prediction models for each parent material

| Equation | $R^2$ | p | SEE |
|---|---|---|---|
| **All Plots Combined** | | | |
| 23.91 - 0.11(FH%C) - 0.046(BChor%Silt) - 0.029(Ah%Sand) | 0.158 | 0.012 | 2.63 |
| **Fluvial** | | | |
| -3.22 + 3.878(AhpH) - 0.023(FHEC) | 0.482 | 0.004 | 2.17 |
| **Lacustrine** | | | |
| 11.61 + 0.214(Chor%Clay) - 0.267(AhDepth) | 0.536 | 0.003 | 1.97 |
| **Till** | | | |
| -7.230 + 5.087(DrainageClass) + 3.166(AhpH) | 0.581 | 0.001 | 1.76 |

Note: FH is forest floor; BChor is BC horizon; Ah is Ah horizon; SEE is the standard error of the estimate (m)

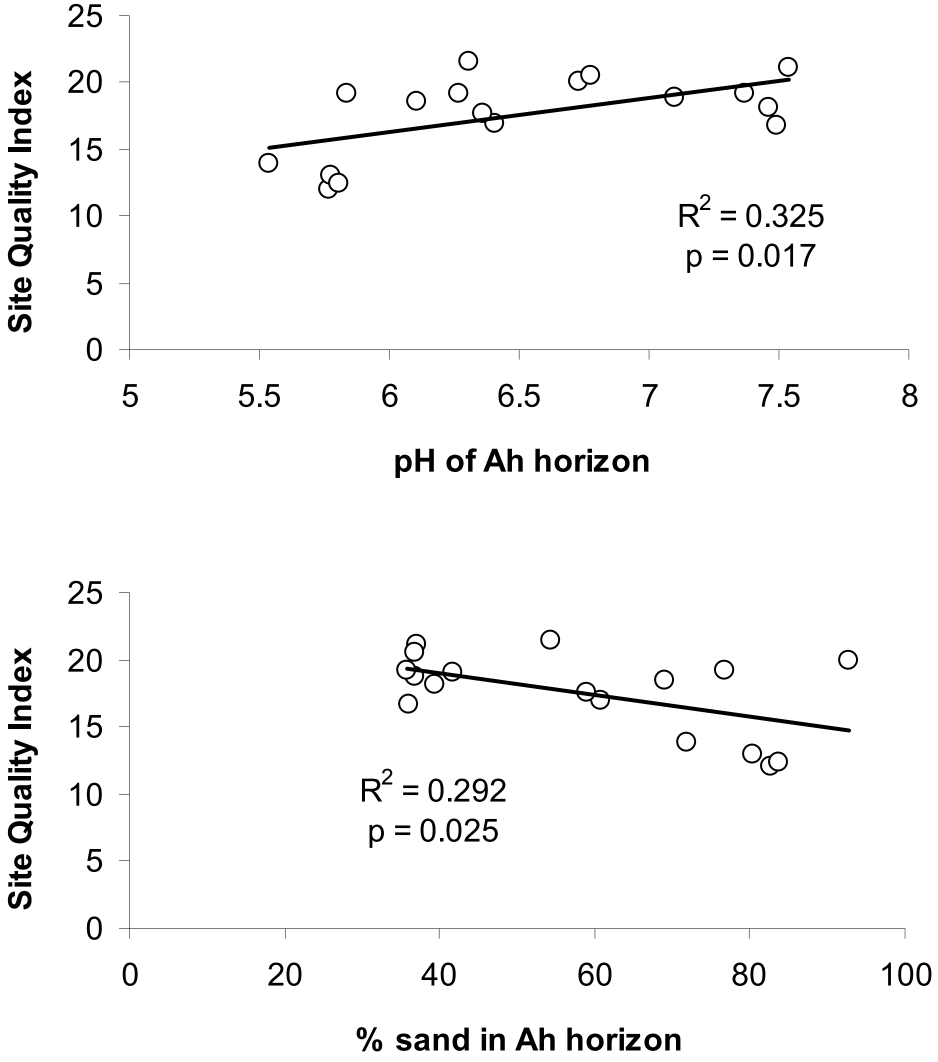

**Figure 5.2** Relationship between site quality index for fluvial plots and (a) pH of the Ah horizon and (b) % sand in the Ah horizon**.**

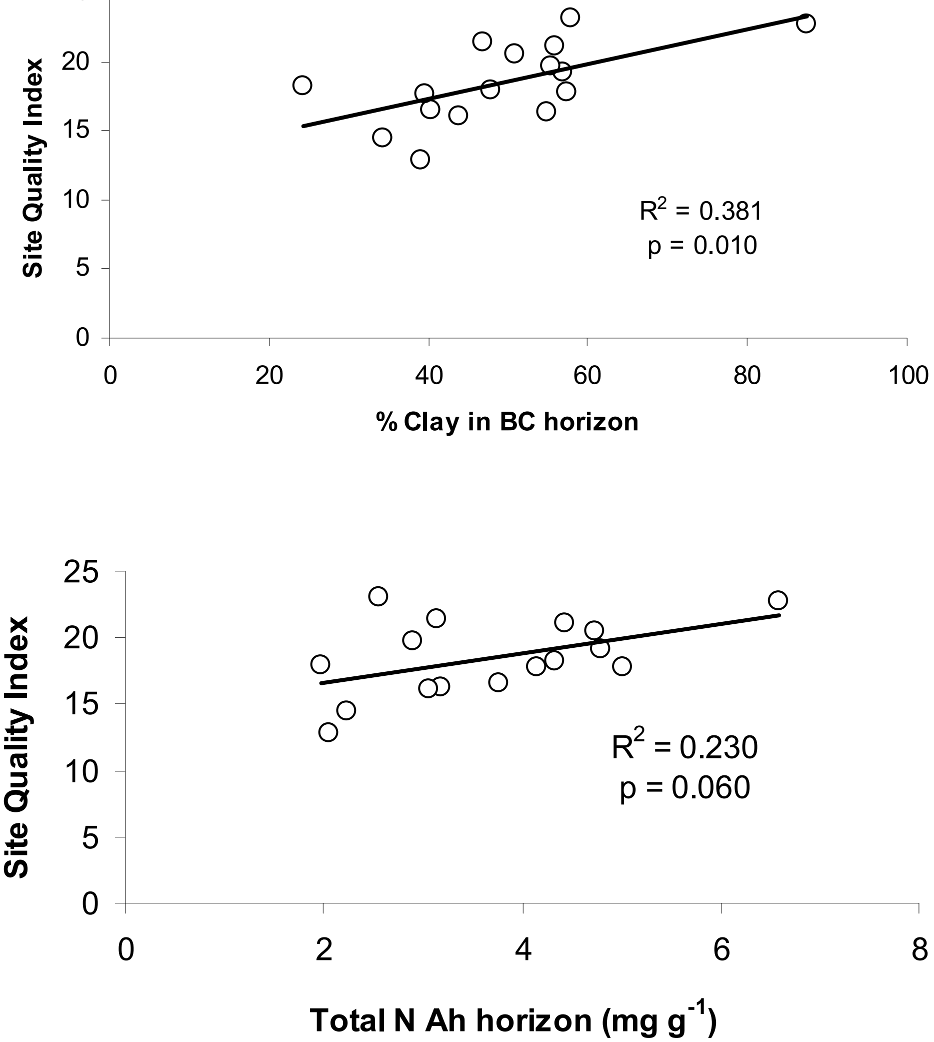

**Figure 5.3** Relationship between site quality index for lacustrine plots and (a) % clay in the C horizon and (b) total N in the Ah horizon

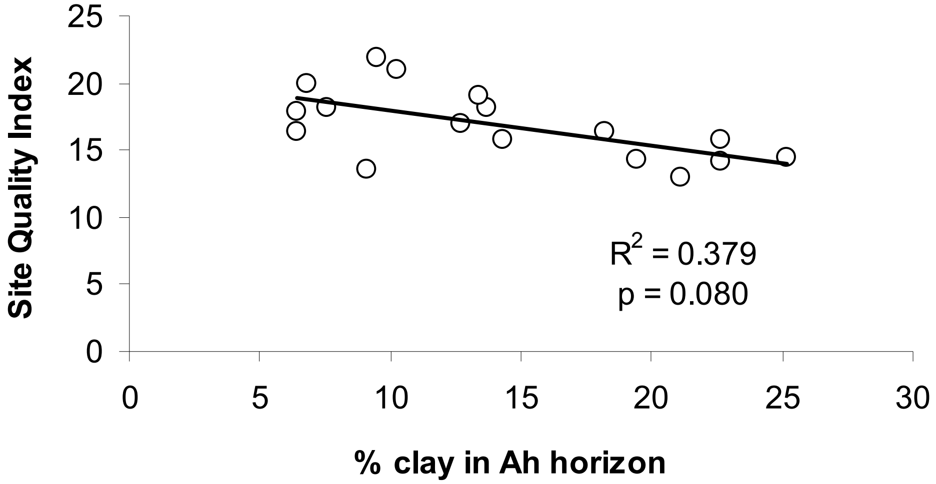

**Figure 5.4** Relationship between site quality index for till plots and % clay in the Ah horizon.

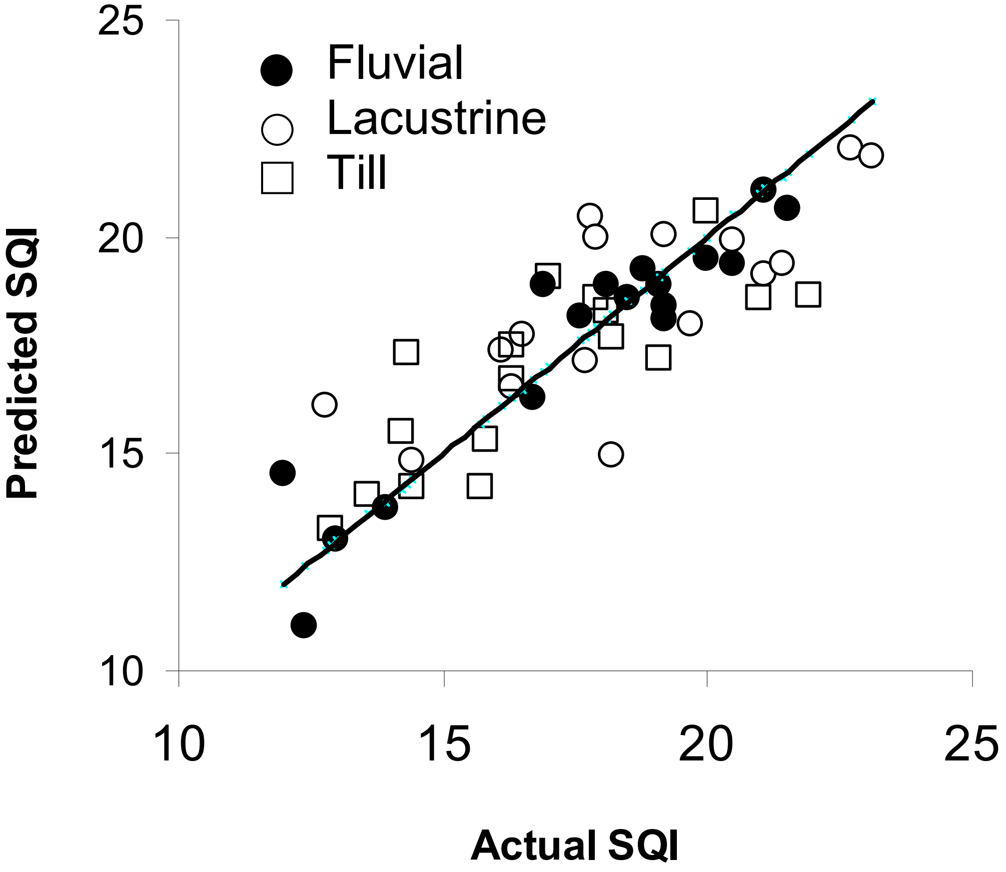

**Figure 5.5** Measured vs. predicted site quality index using the multiple linear regression models presented in Table 3 for each parent material. The solid line is the 1:1 line.

## 5.5 Discussion

### 5.5.1 Model Prediction

The results of the multiple regression analysis for the three separate parent material groups using soil and site properties show that it is possible to predict trembling aspen SQI on the different soil parent materials found in the boreal transition ecoregion of Saskatchewan. This predictive ability is comparable to other recent SQI studies for trembling aspen in British Columbia (Chen et al., 2002) and Quebec (Chapter 4) and other northern tree species (e.g. Hamel et al. (2004) for black spruce and jack pine; Seynave et al. (2005) for Norway spruce). Most other studies of trembling aspen SQI include climate variables relating to moisture and temperature (e.g. Ung et al., 2001; Hogg et al., 2005) which have been shown to be very good predictors of trembling aspen growth across large geographic areas. In our study, however, the goal was to examine the specific soil and site variables effect on trembling aspen productivity. The geographic extent of the study area was therefore purposely kept small, thereby reducing the influence of climatic differences as seen by the absence of relationships between SQI and northing and elevation. The relatively strong relationship we found between edaphic factors and trembling aspen SQI demonstrates the importance of soil and site properties in determining productivity at the local level. Since the local scale is the level at which management decisions are made regarding plantation establishment, it should be possible to use these soil and site variables to identify the best sites for growing trees.

### 5.5.2 Soil Texture

Soil texture, which can be used as a proxy for soil water availability, was an important factor predicting trembling aspen productivity for all parent material types. This is similar to what has been found for other poplar studies across Canada where soil water availability, or a related variable, is the most common factor controlling growth. For example, Paré et al. (2001) in Quebec and Martin and Gower (2006) in Manitoba found that trembling aspen trees were taller on clay soils as opposed to coarser textured soils, presumably because of the greater water holding capacity of the clay soils. Also, Pinno (Chapter 4) found that soil texture was the best predictor of hybrid poplar growth in central Saskatchewan with finer textures producing better growth.

In our study, however, the impact of soil texture differed depending on parent material type. For fluvial and lacustrine sites, finer textured soils with more clay and less sand resulted in better trembling aspen growth while for till sites, finer textures resulted in poorer growth. The till sites with finer textures were generally associated with depressional microsites and poorly drained soils, suggesting that trembling aspen growth responds positively to increasing soil moisture availability up until the point where the soil water becomes stagnant and poorly oxygenated. Carmean (1996) also found this pattern and suggested that trembling aspen grows best on well drained sites with clay subsoils to hold moisture.

### 5.5.3 Soil Fertility

General measures of soil fertility also appear to be an important factor controlling tree growth for fluvial and lacustrine sites. In these parent material groupings, SQI was correlated with pH and total N in the Ah horizon, respectively. The pH reflects the general nutrient availability of the soil with most nutrients available to plants in the 6 to 7 pH range (Havlin et al., 2005). Nitrogen is generally considered to be the nutrient most limiting tree growth in temperate and boreal environments (e.g. Reich et al., 1997; Turkington et al., 1998) and it appears to be important in lacustrine sites. On till sites however, it appears that excessive soil moisture in some plots is an overriding factor controlling trembling aspen productivity. This has also been found by Carmean (1996) who stated that inadequate soil moisture often overrides soil fertility in determining trembling aspen productivity.

The bulk elemental chemistry of the C horizon can give important information about the potential nutrient reserve for tree growth in the long-term (Kobe, 1996; van Breemen et al., 1997). For example, Ca and P have been shown to be important nutrients for trembling aspen and other poplars (Camiré and Brazeau, 1998) and there were significant differences between and within parent material groups. However, neither total Ca nor P were related to trembling aspen productivity. Combined with the lack of difference in SQI between parent materials, these results suggest that trembling aspen is capable of growing reasonably well on soils with a wide range of nutrient reserves.

### 5.5.4 Agricultural vs Forestry Productivity Classes

Despite the detailed soil information used to determine agricultural capability classes, they were not able to accurately predict trembling aspen productivity. For example, the best trembling aspen growing sites with SQI > 20 occurred on agricultural capability classes 1 through 4. This may be because agricultural capability ratings are based more on limitations to plant growth and mechanical operations rather than just potential plant growth (Saskatchewan Soil Survey, 1998). Therefore, they include factors such as stoniness and topography unfavourable for cultivation, factors which may have a large impact on annual crop production but would have negligible effect on longer-lived tree species such as trembling aspen. Also, natural plant communities such as the trembling aspen stands in our study are known to cycle nutrients much more efficiently than annual crops in which a large proportion of the above ground biomass is removed each year (Nair, 1984). Similarly, the fact that relatively homogenous growth rates of trembling aspen are measured despite a large range in parent BC chemical compositions suggests that a large proportion of the nutritional requirement of the trees are met via a tight recycling of nutrients within the ecosystem. Finally, trees do not require as high a concentration of nutrients in their rooting zone relative to annual crops because trees grow over a longer growing season and have more extensive rooting system that favour nutrient use and retention (e.g. reduced leaching) (Vance, 2000).

However, as we move towards more short rotation forest crops using agronomic production principles (van Oosten, 2007), it is likely that agricultural capability classes will be more closely linked to woody crop productivity (Vance, 2000). Overall, it appears that the best suited agricultural sites and the best suited timber producing sites are not the same, meaning that it may be possible to zone land uses in such a way that the best agricultural sites are available for food production and the best timber producing land is used for growing trees.

# 6 PREDICTING THE PRODUCTIVITY OF A HYBRID POPLAR CLONE IN INDUSTRIAL TIMBER PLANTATIONS IN ALBERTA USING SOIL AND SITE INFORMATION

## 6.1 Abstract

Site productivity of the hybrid poplar clone "Green Giant" was predicted using soil and site information from six four year old plantations in north-east Alberta. Predictions were made at both the local and microsite scales. At the local scale using plot means (n=35), the amount of Ca in the B and C horizons, foliar micronutrient concentrations (Mn and Cu) and soil water availability as indicated by $\delta^{13}C$ values were correlated with hybrid poplar productivity. However, multiple regression analysis was only able to explain 38% of the variation in hybrid poplar productivity. Using plantation averages (n=6), total B horizon MnO content, drainage, foliar P concentration and soil water availability were related to tree productivity and these single variables were able to explain more than 50% of the variability in poplar productivity. Soil texture and pH showed non-linear relationships with tree productivity with an optimal range between 55-70% sand and pH of 6. At the microsite scale, soil texture was the most important predictor of tree productivity and was able to explain greater than 50% of the variability within plantations but the relationship differed by plantation. In some plantations, sandier microsites were associated with increased growth while in other plantations finer textured microsites were more productive. This difference was due to where the plantations fell in relation to the optimal sand content.

## 6.2 Introduction

Establishing plantations of fast-growing tree species on marginal agricultural land in transitional areas between prairies to the south and forests to the north is currently being advanced as a means of meeting the timber needs of the forest industry as well as other goals such as increasing biodiversity and sequestering carbon (McKenney et al., 2004; Yemshanov and McKenney, 2008). This management scheme has been referred to in forestry as the TRIAD approach (Messier et al., 2003) where land is divided into three categories: 1) a fully protected zone where no forestry operations occur, 2) a high timber production zone which includes these plantations of fast-growing tree species, and 3) the remaining land which is managed using ecosystem based management principles such as emulating natural disturbances.

In Alberta, the tree species of choice for these intensively managed plantations are hybrid poplars (*Populus X* – later referred to as HP) which are very fast growing but have relatively high resource demands (Hansen et al., 1988; Shock et al., 2002). These trees have been specially bred over the last century for the conditions in western Canada for use as shelter-belt trees in agricultural areas and are now being used as plantation trees. There are currently many different clones available for land managers wanting to establish tree plantations and the specific clones are known to have quite different growth rates, show various levels of resistance to stress, e.g. cold temperatures and dry conditions, and have specific resource requirements (van Oosten, 2006).

In order for these intensively managed timber plantations to be as productive as possible, they must be established on the best growing sites since the trees on these sites will respond more favourably to silvicultural treatments and produce more timber of a higher quality in a shorter time period than on poorer quality sites (Carmean, 1975). In terms of predicting the best locations for establishing HP plantations, landscape scale differences in climate, expressed as degree-days or climate moisture index, are well known to have a major impact on tree growth (e.g. Ung et al., 2001; Hogg et al., 2008). This has resulted in a variety of HP suitability maps for the prairie provinces being developed by government agencies such as the Prairie Farm Rehabilitation Administration (Schroeder et al., 2003) and the Canadian Forest Service (Joss et al., 2007). However, it is at the local scale where management decisions are made regarding establishing tree plantations. At this scale, there is little climatic variation and differences in tree growth are likely linked to edaphic factors.

Thus far, there is very little information accumulated regarding the soil physical and chemical properties associated with the best growing sites for HP in the Prairie provinces and for Canada as a whole. The limited information available for agricultural land in the Prairies points to soil texture, as a measure of water holding capacity, and foliar nutrients, in particular P, as a measure of soil fertility (Chapter 7). The objective of this study was to identify the soil and site factors responsible for controlling productivity of a single HP clone in plantations established on agricultural land in Alberta in order to predict the best growing sites for future HP plantations in the area.

## 6.3 Methods

### 6.3.1 Study Area and Field Sampling

Six four year old HP plantations of the clone “Green Giant” [OP *P. deltoides (P. laurifolia x P. nigra*)] located on former agricultural crop land in east-central Alberta (Canada) near the communities of Athabasca (54º43’N, 113º17’W) and Lac La Biche (54º46’N, 111º59’W) were selected for the study which was conducted during the summer of 2007. The study area is in the boreal transition ecoregion receiving on average 500 mm of precipitation per year. The size of the study area was restricted in order to limit the climatic influence on tree growth between sites and emphasize differences due to edaphic factors. Sites were therefore purposely selected to create a range of site productivities that would be conducive to statistical analysis.

Site preparation consisted of herbicide application and mechanical weed control by discing before planting at a spacing of 3 m x 3 m. Competition control measures consisted of a combination of yearly herbicide applications and multiple discing each growing season done to operational standards. These plantations are expected to be harvested at a rotation age of 18 years.

Within each plantation, six plots were established each consisting of four trees of relatively similar size. One plantation had only five plots established within it due to sampling constraints, resulting in a total of 35 plots for the entire study. Plots were selected in order to capture the differences in tree productivity within each plantation. Soil samples from the A, B and C horizons were taken from one soil pit in the middle of the plot. Other soil and site information recorded included depth of A horizon, depth to mottling, drainage class, topographic position, geographic location, and elevation. Drainage classes were assigned numerical values ranging from 1 to 5 for poor through, imperfect, moderately well, well and rapid drainage, respectively (Beckingham et al., 1996). Foliar samples, 25 leaves from the upper third of the canopy of each tree, were collected in late July for nutrient and $\delta^{13}C$ analysis. At the end of the growing season in October, trees were measured for leader height growth, total tree height and diameter at 15 cm above ground and breast height (1.3 m).

### 6.3.2 Laboratory Analyses

Soil samples were air-dried and then sieved with a 2 mm mesh to remove any coarse fragments. Particle size distribution of all soil samples was determined using the Horiba Partica LA-950 Laser Particle Analyzer. The A horizon samples were treated with NaOCl because of the high C levels. Sodium hexametaphosphate and sonication were used on all samples for particle dispersion before measurement. Electrical conductivity and pH were measured in water for the A horizons. A horizon sub-samples were finely ground (<60μm) for determination of total C and N by dry combustion and infrared detection using the Leco CNS-2000 (1100ºC). Elemental composition of each horizon was determined on fused beads prepared from a 1:5 soil / lithium tetraborate mixture using an automated X-ray fluorescence spectrometer system (Phillips PW2440 4kW, Pananalytical, Almelo, The Netherlands).

Leaf samples were oven-dried at 40ºC and then finely ground prior to C and N determination using the Leco CNS-2000. The leaf samples were also digested in a concentrated $HNO_3$ solution at a ratio of 0.1g leaf sample and 5 ml $HNO_3$ for four hours at 100ºC in Teflon beakers covered with a watch glass. Calcium, Mg, K, Cu and Mn levels were then analyzed using atomic absorption/emission. Phosphorous was analyzed colourimetrically (molybdenum blue) from the same digests with a Technicon Auto-Analyzer. For the micronutrients Cu and Mn, only one tree from each plot was analyzed rather than all four. Leaf sub-samples of the four trees from each plot were combined and then very finely ground before being analyzed for $\delta^{13}C$ by mass spectrometry using a RoboPrep Sample Converter interfaced with a TracerMass Stable Isotope Detector (Europa Scientific, Crewe, UK). $\delta^{13}C$ values from tree leaves can be used as an integrative measure of soil moisture availability throughout the entire growing season with more negative values indicating more water available to the plant. This is because $^{12}C$ is preferentially used by plants but when the stomates close $^{13}C$ is trapped in the leaves and involved in photosynthesis resulting in higher $^{13}C$ concentrations and less negative $\delta^{13}C$ value relative to the PeeDee belemnite standard in plants that are drought stressed. This method has been used in forestry to examine the effects of harvesting and silviculture operations on seedling water status (Gomez et al., 2002) and differences in plant community moisture availability (Stewart et al., 1995).

### 6.3.3 Data Analysis

As in the determination of site index, average tree height for each plot at the end of the fourth growing season was used as a measure of site productivity (Carmean, 1996). Relationships between soil and tree variables were evaluated at both the local (between plantations and microsite (within plantations) scales. The local scale analysis was conducted using plot means (n=35) and plantation averages (n=6) calculated from plot means. The microsite scale analysis was done individually for each of the six plantations (n=6). Correlation analysis was used to determine the suite of variables most closely related to tree productivity at both the local and microsite scales with statistical significance recognized at $p = 0.10$. Non-linear and stepwise multiple linear regressions were then used to model site productivity as a function of soil and site factors, including foliar nutrients. All statistics were completed using SPSS version 15.0 (SPSS Inc., Chicago, Illinois).

## 6.4 Results

### 6.4.1 General Site Properties

Average plantation tree size values as well as foliar and soil properties are presented in Table 6.1. Plantation tree height averages after 4 years of growth ranged from 279 to 398 cm. This range was greater, i.e. 187 to 498 cm, when using the means of all 35 plots. Some foliar and soil properties also showed considerable variability between sites. For example, leaf P concentrations varied between 0.65 and 1.14 g $kg^{-1}$, whereas leaf N varied between 25 and 36 g $kg^{-1}$. A horizon pH varied between 5.7 and 6.7 and sand content in the B horizon varied between 34 and 77%. These large ranges provided us with a desirable gradient on which to analyze the impact of different soil and site factors on tree growth at both the local and microsite scales.

### 6.4.2 Local Scale Analysis

It appears that climate difference between plantations is not a major controlling factor of HP productivity given that northing ($p=0.456$) and elevation ($p=0.912$) are not correlated with HP productivity, thereby placing the focus on the soil and site properties impacting HP productivity. Significant relationships between soil properties, foliar nutrient status and tree height using all 35 plots are presented in Figure 6.1. The amount of MnO in the B horizon and foliar Cu concentrations were positively related to HP productivity while foliar Mn concentration and $\delta^{13}C$ were negatively related. Total CaO in both the B and C horizons was also positively correlated with tree height. Both MnO and $\delta^{13}C$ were selected in the stepwise multiple regression, but the model only explained 38% of the HP growth variability.

Significant relationships using plantation averages are presented in Figure 6.2. Total B horizon MnO and foliar P were positively related with tree height, while $\delta^{13}C$ and drainage were negatively related. Stepwise multiple regressions did not result in any better predictions of average plantation tree height than already accounted for with the single variables.

**Table 6.1** Average tree and soil characteristics for each plantation

| Site | Tree height (cm) | Tree Diameter (cm - 15 cm) | pH - A hor. | Total N - A hor. (g/kg) | Sand - B hor. (%) | MnO - B hor. (g/kg) | Drainage | Leaf N (g/kg) | Leaf P (g/kg) | $\delta^{13}C$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 279 | 5.3 | 5.7 | 2.1 | 77 | 0.21 | 3.2 | 36 | 0.77 | -25.09 |
| **2** | 299 | 4.7 | 5.6 | 2.5 | 34 | 0.22 | 2.8 | 32 | 0.65 | -25.62 |
| **3** | 398 | 6.2 | 6.1 | 1.8 | 66 | 0.47 | 2.3 | 36 | 1.14 | -27.30 |
| **4** | 360 | 5.7 | 6.0 | 1.7 | 61 | 0.40 | 2.3 | 29 | 0.88 | -25.54 |
| **5** | 308 | 5.2 | 6.7 | 2.3 | 77 | 0.28 | 3.2 | 29 | 0.96 | -26.16 |
| **6** | 373 | 6.0 | 6.1 | 2.3 | 57 | 0.44 | 2.4 | 25 | 0.89 | -26.67 |

Note: hor. means horizon; drainage is the mean of categories expressed from 1 to 5, with 1 being poor and 5 being rapid drainage.

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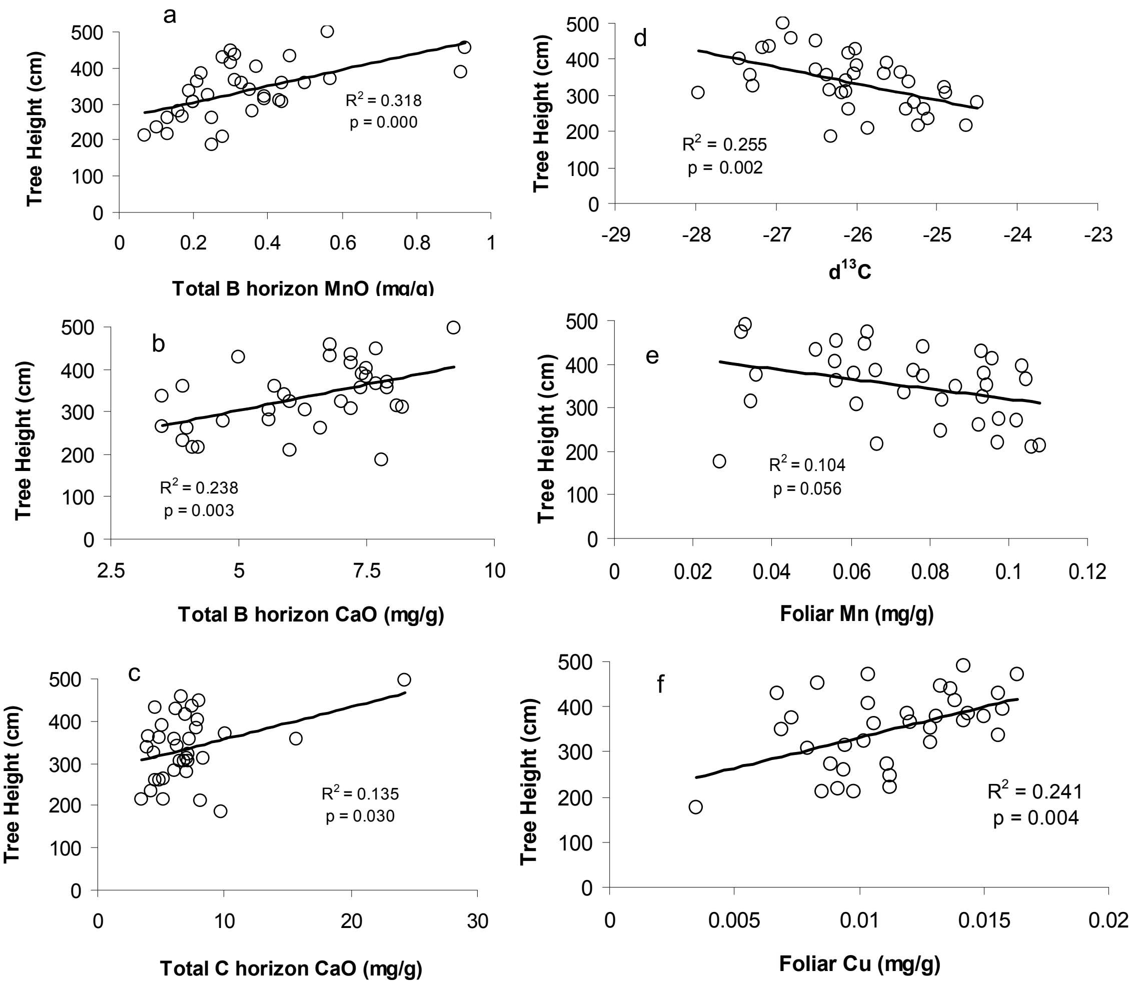

**Figure 6.1** Significant relationships between HP productivity and soil and site properties using all 35 plots for a).Total MnO in the B horizon, b) Total CaO in the B horizon, c) Total CaO in the C horizon, d) $\delta^{13}C$, e) Foliar Mn concentration and f) Foliar Cu concentration.

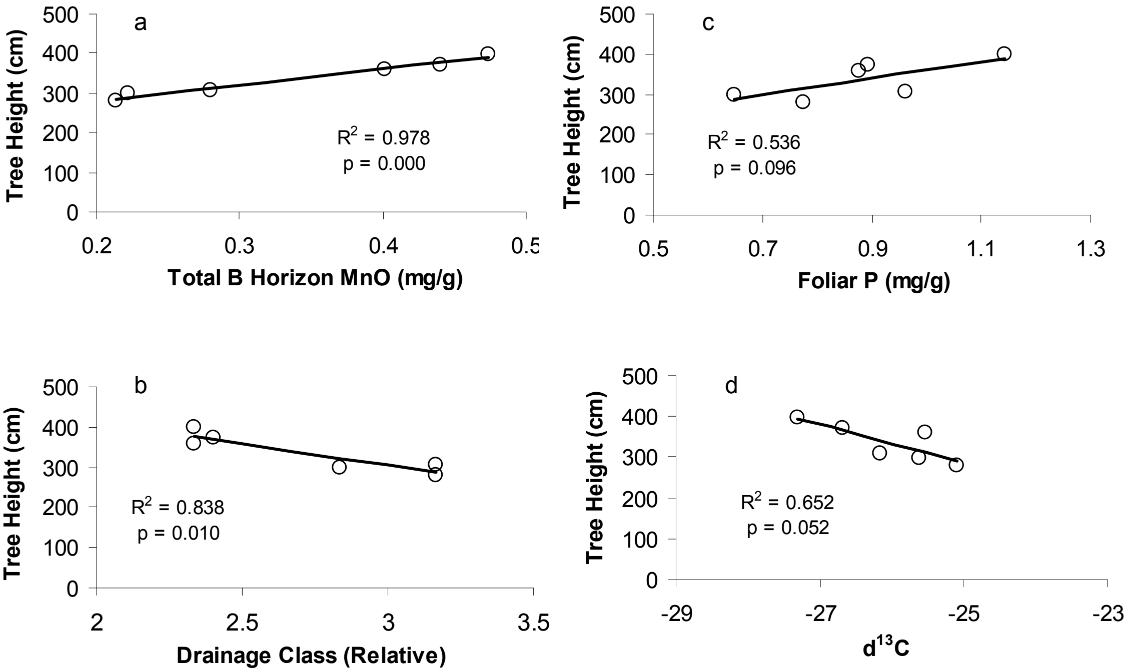

**Figure 6.2** Significant relationships between HP productivity and soil and site properties using plantation averages for: a) Total MnO in the B horizon, b) Average plantation drainage, c) Foliar P concentration and d) $\delta^{13}$C.

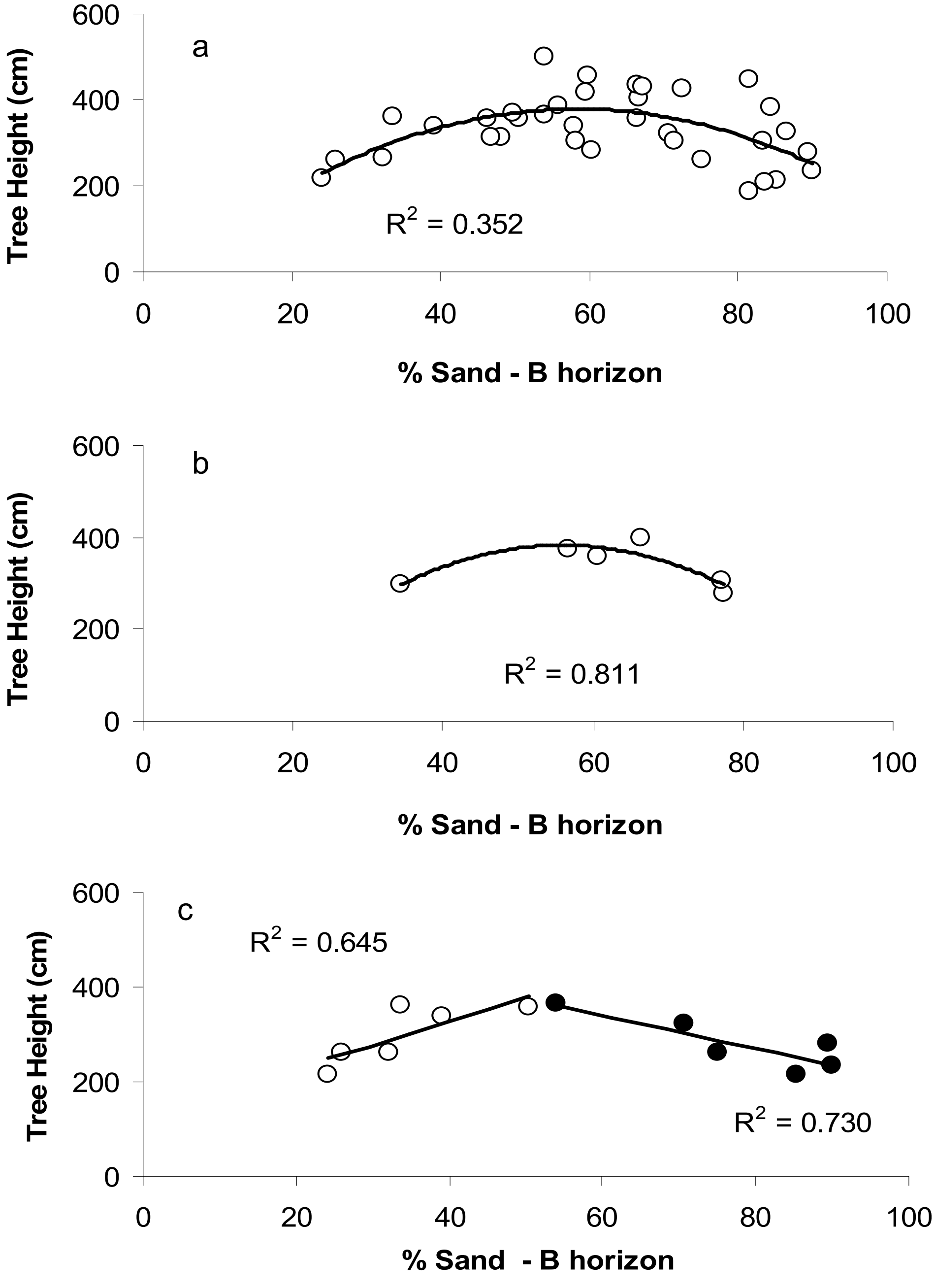

**Figure 6.3** Relationship between % Sand in the B horizon and HP productivity for a) all 35 plots, b) plantation and c) microsite analysis for the plantations at the extremes of the soil texture range.

Other variables were also related to tree growth at the local scale but showed parabolic relationships. The amount of sand in the B horizon was related to tree height with a distinctive optimal zone for tree growth between 55 and 70% (Figure 6.3). This trend was apparent whether plot means or plantation averages were used. A horizon pH also showed a curved relationship for the plantation average values with an optimal pH of 6 (Figure 6.4).

### 6.4.3 Microsite Scale Analysis

At the microsite scale, each plantation was analyzed individually resulting in six separate sets of analyses. For five of the six plantations, soil texture was significantly related to tree size (Table 6.2). Site 5 had no measured soil or site variables related to productivity. However, the influence of soil texture on tree productivity differed between sites. For example, at sites 1, 3 and 5, increasing sand in the B horizon was negatively related to tree productivity. Conversely, at sites 2 and 4, increasing sand in the B horizon was positively related to tree productivity (Figure 6.2). Specific soil chemical properties were significantly related to tree productivity. For example, $K_2O$ in the B horizon was positively related to HP growth at site 1 (r=0.863, p=0.027) and the amount of $SiO_2$ in the A horizon at site 6 was negatively related to tree growth (r=-0.894, p=0.041). However, there were no consistent trends across sites (results not shown). Interestingly, total soil MnO, foliar Mn and foliar Cu were not significantly related to microsite productivity within any of the plantations despite the fact that they were strong predictors of productivity at the local scale. Finally, analyses were also tried after grouping plantations with similar soil texture into 3 categories (high sand, medium sand, low sand), but this resulted in no significant relationship.

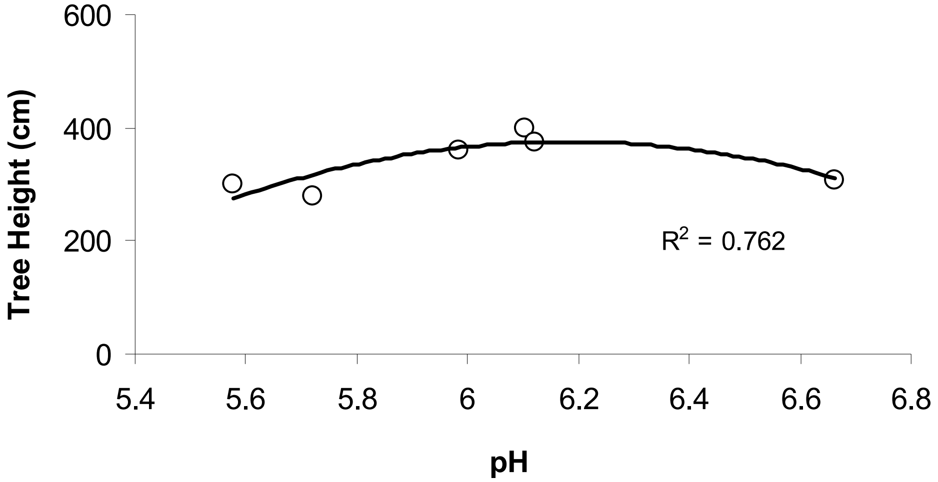

**Figure 6.4** Relationship between pH of the A horizon and HP productivity for the plantation averages

**Table 6.2** Microsite scale correlation analysis showing the most highly correlated soil variable with HP productivity.

| Site | Variable | r | p |
|---|---|---|---|
| **1** | % Sand - B horizon | -0.855 | 0.030 |
| **2** | % Sand - B horizon | 0.803 | 0.054 |
| **3** | % Sand - B horizon | -0.775 | 0.070 |
| **4** | % Sand - A horizon | 0.729 | 0.087 |
| **5** | No significant variable | | |
| **6** | % Sand - A horizon | -0.882 | 0.048 |

## 6.5 Discussion

### 6.5.1 Model Prediction

The multiple regression models developed from the 35 plots did not explain more than 38% of the variability in site productivity. This is substantially poorer than other recent site productivity studies on poplar growth which have been able to explain at least 50% of tree growth using simple soil variables such as texture or pH (Chen et al. 2002; Chapter 4; Chapter 7). However, using plantation averages, despite the low degree of freedom, we were able to produce much better results ($R^2>0.5$) with a single variable. The analysis at the microsite scale also yielded high $R^2$ for a few plantations. Interestingly, the important variables were different between scales and between plantations, indicating that different factors are driving HP productivity at different scales. For management decisions, which are generally made at the local scale, plantation averages for variables such as soil texture or pH may be the best criteria to use to predict the best growing sites. However, to fully understand the soil and site factors responsible for controlling HP productivity, it may be necessary to examine the relationships within each plantation (microsite). For this study, our goal was to identify the best growing sites for establishing plantations as well as to examine the underlying factors governing HP growth. Therefore, we will discuss relationships obtained at both local and microsite scales.

### 6.5.2 Moisture Availability

Soil texture, which can be used as a proxy for soil water availability, was an important factor predicting HP productivity at both the local and microsite scales. This is similar to what has been found from other studies for poplars across Canada where soil water availability, or a related variable, is the most common factor controlling poplar growth. For example, another study in central Saskatchewan (Chapter 7), found that soil texture was the best predictor of HP growth with finer textures producing better growth. For trembling aspen, Paré et al. (2001) in Quebec and Martin and Gower

(2006) in Manitoba found that aspen trees were taller on clay soils as opposed to coarser textured soils, presumably because of the greater water holding capacity of the clay soils.

In our study however, HP is not linearly related to texture. Rather, there appears to be an optimal soil texture range and outside of this range productivity decreases. In sites with high sand contents, productivity is favoured by increasing amounts of silt and clay, likely leading to more available moisture for plant growth. On finer textured sites, productivity is favoured by increasing sand content perhaps because this favours better soil aeration and drainage. At the local scale, the importance of soil water is supported by the $\delta^{13}C$ and drainage data which indicate that more available water is beneficial to HP productivity. The negative relationship between HP growth and foliar $\delta^{13}C$ indicates that available soil moisture is positively related to HP productivity since more negative values of $\delta^{13}C$ indicate more available water during the growing season. However, at the microsite scale, it appears that HP is quite sensitive to excess soil water as shown by the poor growth of the heavier (clayey) soil microsites. This microsite effect is also supported by field observations that tree growth was reduced on topographically lower sites with poor drainage.

### 6.5.3 Nutrient Availability

Nitrogen is generally considered to be the nutrient most limiting tree growth in temperate and boreal environments (e.g. Reich et al., 1997). However, the trees in our study accessed all the N required for optimal growth based on foliar concentrations (optimal level of 33 g N $kg^{-1}$ have been suggested by Hansen, 1994). This resulted in no relationship between foliar N and HP productivity. Such observations were also made for a HP plantation grown on silt loam in northern Wisconsin (Hansen et al., 1988). No further increase in foliar N is expected to impact growth rates since other nutrients may become limiting and the nutrient ratios will not be optimal for the trees (Knecht and Göransson, 2004). These high N levels are likely due to the agricultural history of the sites with repeated annual applications of N fertilizers and/or pulse crops.

Foliar P was the nutritional variable most related to HP productivity. Foliar P values (average = 0.88 g P $kg^{-1}$) were much lower than the optimal value of 3.3 g P $kg^{-1}$ proposed by Hansen (1994) for hybrid poplars, indicating that any increase in P nutrition should improve growth. This low foliar P level and strong positive relation to growth has also been found for other studies of HP plantations in central Saskatchewan (Chapter 7). The lack of response of HP to N fertilization in plantations on old agricultural fields may also be partly explained by this importance of P. If P and not N is the limiting nutrient for HP growth, then any further increases in N availability/uptake could result in P imbalances in HP (Booth, 2008).

Total CaO in the B and C horizons was also positively related to HP productivity. This is reasonable given that base cations, in particular Ca, are very important for growth of trees in HP plantations (Bowersox and Ward, 1977; Wittwer and Immel, 1980) and trembling aspen seedlings grown in solution (Lu and Sucoff, 2001). Total Mn in the B horizon was also very strongly (r=0.988) correlated with HP productivity across the six plantations. These soils appear to be very low in Mn with the average total B horizon MnO level in these soils (0.34 mg/g) being less than half that found in boreal shield BC horizons of Quebec (0.88 mg/g) and boreal plain C horizons of Saskatchewan (0.73 mg/g) (Bélanger, unpublished data). The high dominance of quartzite in the Athabasca region of Alberta, i.e. a metamorphic rock which was originally sandstone and composed mainly of $SiO_2$, is likely associated with this low MnO content in the soil. However, this low soil Mn and positive relation to HP productivity was not reflected in foliar Mn which shows as negative relationship with HP productivity. Similar relationships between foliar Mn and tree growth have been observed in Eastern North American sugar maple stands growing on acidified soils (e.g. Houle et al., 2007; Horsley et al., 2000). Copper showed a different pattern with foliar Cu concentration being positively related to HP productivity but no relationship with soil Cu levels was found. This is reasonable for this area which is known to have Cu deficiencies for small grain crops grown on sandy soils (Havlin et al., 2005). In short rotation intensive forestry plantations, micronutrient deficiencies are more common than in natural forests due to the fast growth rates and high resource demands of the trees (Ericssonn, 1992). It is thus possible that Cu may be deficient for these soils, but only fertilization trials could fully elucidate the role of micronutrients on HP productivity in this region.

In general, the bulk chemistry of the B and C horizons, but not the A horizon, showed a significant effect on HP productivity. One of the reason the A horizon may not be as important is that it is highly influenced by biological processes such as litterfall and decomposition of foliage. For example, the A horizons show much higher MnO concentrations compared to B and C horizons due to the recycling of Mn from deeper soil sources and translocation into surface soil horizons by vegetation. These processes tend to overshadow any differences in the original chemical signal of the horizon since foliage tends to have relatively stable chemical compositions and ratios (Knecht and Göransson, 2004). Most previous studies on forest productivity have focused on the upper mineral horizons and the forest floor but these horizons may not provide the best indication of long-term nutrient availability for deep-rooted tree species. Bailey et al. (2004) also found a similar importance of the chemistry of the B horizon in Pennsylvania where sugar maple dieback was correlated with subsoil properties more so than the more biologically influenced upper horizons.

## 6.6 Conclusion

It appears possible to reliably predict and identify the best growing sites/microsites for this particular HP clone based on simple soil and site factors. The choice of scale, local or microsite, depends on the desired use of the information, i.e. management decisions regarding plantation establishment may require only average site values while identifying the underlying drivers of tree productivity requires the use of more detailed microsite information. The importance of site specific management in maximizing timber production should not be overlooked, starting with the crucial decision of determining the best location to establish a timber plantation. Given the wide range of clones currently available, future studies could examine the soil and site factors related to productivity of different clones. For example, the clone Green Giant appears to be best adapted to specific soil textures and pH ranges. Other clones are likely adapted to texture and pH ranges above and below that of Green Giant, thereby increasing the precision with which plantation management decisions can be made.

# 7 COMPETITION CONTROL IN JUVENILE HYBRID POPLAR PLANTATIONS ACROSS A RANGE OF SITE PRODUCTIVITIES IN CENTRAL SASKATCHEWAN

## 7.1 Abstract

This study examined the response of hybrid poplar plantations established on former agricultural land in Saskatchewan to competition from weeds on a range of site productivities. Specifically, the impact of competition control on the growth of juvenile trees and tree responses to competition control as affected by the productivity gradient were examined. We also wanted to determine which resource was most highly competed for and was most important in determining tree growth. Eight sets of paired plots in juvenile hybrid poplar plantations were established in central Saskatchewan across a range of site productivities. In each pair, one plot had complete weed control while in the other plot weeds were allowed to grow. The best soil predictor of tree growth was soil texture, represented by % silt + clay, with finer textures showing better growth. Competition control significantly increased tree growth on all sites, diameter growth increases ranging from 19 to 408%, with the benefit being greatest on the higher productivity sites. Soil water appeared to be highly competed for between trees and weeds and was a dominant resource controlling growth. For soil nutrients, nitrogen and phosphorus were highly competed for between trees and weeds. However, leaf phosphorus concentration of the weed-free plots had a strong positive relation to tree growth while nitrogen did not, indicating that when trees are free of competition they can access sufficient nitrogen from these soils.

## 7.2 Introduction

Afforestation projects establishing tree plantations on agricultural land are currently being advanced on the Canadian prairies as a means of supplying timber for the forest products industry and for a variety of other environmental benefits such as sequestering carbon and increasing landscape biodiversity (McKenney et al., 2004). The transitional zone between forest to the north and prairie to the south has been suggested as a prime candidate area for these projects (Schroeder et al., 2003). The natural soils of the area are generally Chernozems with a topsoil layer rich in organic matter and nutrients. However, a wide range of site productivities is observed within this zone due to differences in soil factors such as texture and organic matter content.

Hybrid poplar (HP) clones bred specifically for the growing environment of the northern prairies, i.e. dry climate and short growing season, have shown the most promise for meeting these afforestation goals but they are intolerant of competition and have relatively high resource demands (Wittwer and Immel, 1980; Hansen et al., 1988; Shock et al., 2002). These HP plantations are expected to grow on a 20 year rotation with yields averaging about 12 $m^3$ $ha^{-1}$ $year^{-1}$ (van Oosten, 2006). The major impediment to successfully establishing these plantations is the severe interspecific competition the trees face from agricultural weeds which can lead to greatly reduced tree growth or even plantation failure if the weeds are not controlled.

There have been many studies examining the effects of interspecific competition in young tree plantations but almost all of these studies have focused on coniferous trees in forested landscapes (see review by Wagner et al. (2006)). Moreover, most experiments have been designed using only one or two sites so that the differences in tree responses to competition across a range of site productivities cannot be examined. Similarly, there have been significant challenges in ecological research in determining how interaction intensity between plant species varies as a function of site productivity. The most recognized theories are that competition intensity augments with increasing site productivity (Grime, 1973) or it can be about the same across a range of site productivities (Newman, 1973; Tilman, 1988), but other models now suggest that competition intensity decreases with site productivity (e.g. Goldberg et al., 1999). Clearly, more work is needed to elucidate this important question.

This study is unique in that it deals with the response of HP plantations to competition from weeds on a range of site productivities. In particular, the goals of this study are to examine: (1) the impact of competition control on the growth of juvenile trees, (2) how tree responses to competition control differ across a gradient of site productivities and (3) which resource is most highly competed for and is most important in determining tree growth.

## 7.3 Methods

### 7.3.1 Study Area

Four HP plantations located on former agricultural crop land in central Saskatchewan, Canada, near the cities of Saskatoon (52º08'N 106º39'W) and Prince Albert (53º12'N 105º42'W) were selected for study. This is a relatively dry area receiving on average 380 mm of precipitation per year and having a significant summer moisture deficit. However, the summer of 2006 when this study took place had higher than normal precipitation (400 mm of rain during the growing season) which was approximately the same between all of the sites. A summary of soil and site properties for each of the plots is given in Tables 7.1 and A.7.

The sites were planted in the spring of 2005 at a spacing of 3 m by 3 m which is the recommended spacing in Saskatchewan for pulpwood crops (van Oosten, 2006). Operational weed control was performed by the individual land owner at each site during the year of planting and consisted of either cultivation or mowing of the weeds. At each plantation, two sets of paired plots were established with 10 trees in each plot. Plots were generally arranged in a 4 tree by 3 tree pattern since there were almost always 2 trees in this area that were missing or dead resulting in 10 trees per plot. Both plots for each pair were placed in similar topographic positions within the plantation and were separated by less than 15 m. However, the two pairs within each plantation were in different topographic positions; one of the pairs of plots was located in an upper slope position and the other pair was located in a lower lying area. This selection of plots

**Table 7.1** General soil properties of the study plots.

| Plot | Silt + Clay† (%) | pH | Total C (mg/g) | Total N (mg/g) |
|---|---|---|---|---|
| 1 | 34.9 | 7.8 | 21 | 2.5 |
| 2 | 38.6 | 7.0 | 25 | 2.9 |
| 3 | 52.7 | 8.1 | 19 | 2.2 |
| 4 | 38.7 | 7.7 | 16 | 1.9 |
| 5 | 25.6 | 6.3 | 29 | 3.2 |
| 6 | 23.8 | 6.4 | 30 | 3.1 |
| 7 | 18.4 | 6.0 | 14 | 1.6 |
| 8 | 9.2 | 6.2 | 10 | 1.2 |

†Silt + clay is the content of silt and clay combined

enabled us to get the widest range of site productivities. A single HP clone was used in each of the plantations but the specific clone used varied by site resulting in three different clones: Assiniboine, Hill and Walker. For each pair of plots, one of the plots was randomly chosen to have complete weed control and the other was allowed to have weeds grow. Weed control was completed manually by hoeing the plots every two weeks to a radius of at least 1.5 m around each tree and resulted in more complete weed control than the standard operational practice in other plantations in the area. This weeding treatment has likely reduced most, but not all, of the impacts of weeds on competition with the trees for resources because the roots of hybrid poplars grown at the sites had probably expanded slightly more than 1.5 m laterally over 2 years (Guillemette, 2006) and would thus have experienced competition with the weeds outside of the cleared area. All of the plantations were heavily infested with common agricultural weeds such as lambsquarters (*Chenopodium album*), kochia (*Kochia scoparia*) and Canada thistle *(Cirsium arvense).*

### 7.3.2 Field Sampling

Throughout the growing season from mid-May until early September, the plots were sampled every two weeks (i.e. total of eight sampling dates in 2006). Each sampling period consisted of plot weeding, measuring the height and basal diameter of each tree, measuring soil moisture around each tree at a depth of 15 cm using a Field Scout time domain reflectometry 300 probe (Spectrum Technologies, Plainfield, Illinois) and measuring soil temperature at a depth of 10 cm at four locations in each plot. During August, before significant retranslocation of nutrients occurs within trees, fifteen leaves were collected from the top of each tree for nutrient analysis. At the end of the growing season, topsoil to a depth of 15 cm was collected from each plot for texture and nutrient analysis. Given the history of cultivation at all sites, this depth of 15 cm was consistent with the Ap horizon and did not vary between sites. Also at this time, all of the weeds within a 0.5 m radius of four of the trees in each weedy plot were collected, dried and weighed for competition biomass estimates and species identification.

Foliage weights were estimated using a linear regression equation developed during the third growing season of the plantations and involved stripping all of the leaves off of the second largest tree in each plot. In total, eight weed-free and eight weedy trees were used for developing the equation. For both treatments, the best fit between leaf weights and tree growth variables was obtained with the cross-sectional area of the stem (calculated as $\pi r^2$) at 5 cm above ground (Figure 7.1). This is a reasonable relationship as the leaf/sapwood ratio changes according to canopy and competition dynamics (Pothier et al., 1989; Reid et al., 2003). Because the equation does not encompass the lower end of tree sizes encountered at the end of the second growing season, it was forced to intercept with zero.

### 7.3.3 Laboratory Analysis

Soil samples were air-dried and then sieved through a 2 mm mesh to remove any coarse fragments before analysis. To determine the particle size distribution, samples were first treated with NaOCl due to the high carbon levels. Sodium hexametaphosphate and sonication were then used to disperse the samples before measurement on the Horiba Partica LA-950 Laser Particle Size Analyzer. Soil sub-samples were also ground (<60μm) for determination of total C and N by dry combustion and infrared detection using the Leco CNS-2000 Analyzer (1100ºC). Exchangeable cations were determined using atomic absorption after extraction with an unbuffered 0.1 M $BaCl_2$ solution (Hendershot et al., 1993). Cation exchange capacity on a mole per charge basis was calculated as the sum of Ca, Mg, K, Na, Fe, Al, and Mn.

Weed and leaf samples were oven-dried at 40ºC and then weighed to determine biomass. The leaf samples were then coarsely ground prior to leaf C and N determination using the Leco CNS-2000 Analyzer. Leaf samples were digested in a concentrated $HNO_3$ solution at a ratio of 0.5 g leaf sample and 5 ml $HNO_3$ for four hours at 100ºC in Teflon beakers covered with a Teflon watch glass. Calcium, Mg and K levels were then analyzed using atomic absorption/emission. Phosphorus was analyzed colourimetrically (molybdenum blue) from the same digests with a Technicon Auto-Analyzer. Total leaf nutrient content was calculated by multiplying nutrient concentration with the estimated leaf mass.

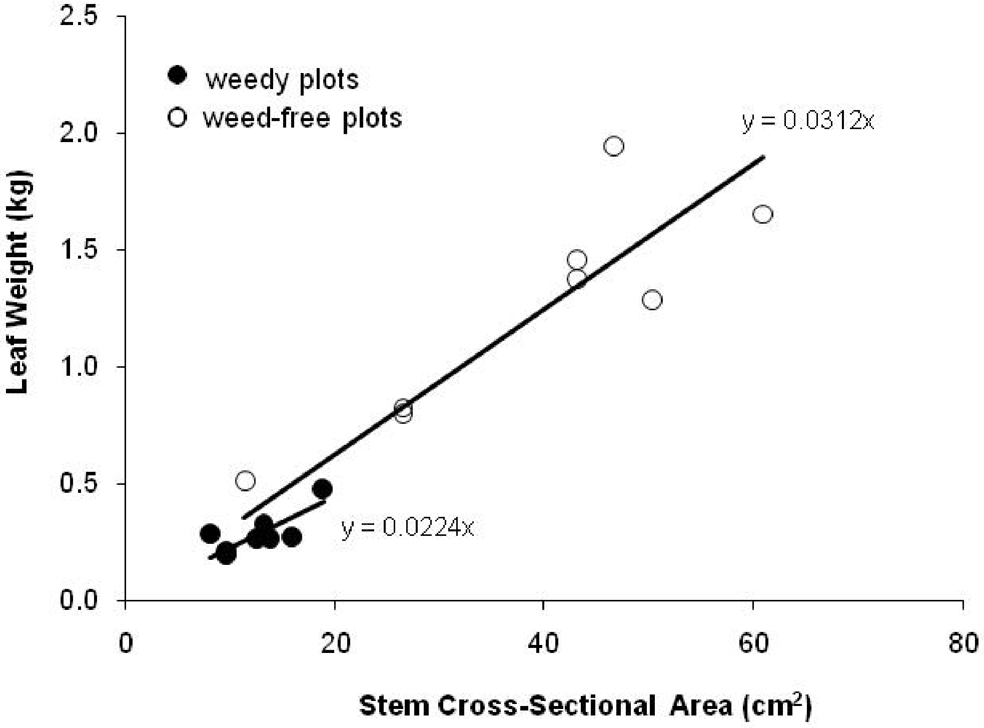

**Figure 7.1** Linear regression model for estimating total leaf weight using the cross-sectional area of the stem ($\pi r^2$) at 5 cm above ground [weed-free ($R^2$=0.742, p=0.004) and weedy ($R^2$=0.527, p=0.033)]. Note that the intercepts of the regressions were not significantly different than zero and thus, the regressions were forced to pass through the origin.

Leaf samples from the four largest trees from each plot were also finely ground (<60μm) and then analyzed for $\delta^{13}C$ by mass spectrometry using a RoboPrep Sample Converter interfaced with a TracerMass Stable Isotope Detector (Europa Scientific, Crewe, UK). The working standard was lentil (*Lens culinaris*) straw with a $\delta^{13}C$ of –27.6‰ relative to the PeeDee belemnite (PDB) standard. $\delta^{13}C$ calculations for hybrid poplar leaves were performed as followed:

$$\delta^{13}C = \frac{R_{sample} - R_{s\tan dard}}{R_{s\tan dard}} \times 1000 \quad \textbf{[7.1]}$$

where $R_{sample}$ and $R_{standard}$ are the ratios of $^{13}C/^{12}C$ in the sample and standard, respectively. The average difference of duplicate samples was less than 0.1‰. $\delta^{13}C$ values from tree leaves can be used as an integrative measure of soil moisture availability throughout the entire growing season with more negative values indicating more water available to the plant. This method has been used in forestry to examine the effects of harvesting and silviculture operations on seedling water status (Gomez et al., 2002) and differences in plant community moisture availability (Stewart et al., 1995).

### 7.3.4 Statistical Analysis

A mixed-model ANOVA was used to compare the effects of competition control on tree growth (Little et al., 1996). This model incorporated both plantation and plot level variability since the plots were specifically chosen to have the widest range of productivity possible and were not randomly selected. Paired t-tests were used to compare nutrient levels and soil moisture availability variables between treatments based on the results of the mixed-model ANOVA (see results section for details). Simple linear regression and Pearson correlation analyses were used to examine the relationships between soil properties, foliar nutrient status and tree growth for both competition treatments. Both absolute and relative growth differences were used to evaluate the impact of competition across a gradient of site productivities. Relative growth parameters account for differences in site productivity and eliminate the effects of the environment on the response (Goldberg et al., 1999). We thus chose to use the relative interaction intensity (RII) index as proposed by Armas et al. (2004) with our response variable being tree diameter growth. Using this variable, potential values range from -1 to +1 with more negative values indicating more intense competition and positive values indicating facilitation. Comparisons with other relative indices of plant interaction suggest that RII is the most reliable: (1) it has defined limits, (2) it is symmetrical around zero with the same absolute values for competition and facilitation, and (3) it can be used in statistical analyses because it is linear and shows no discontinuity within its range. The equation for RII as adapted for our study is:

$$RII = \frac{DGrowth_{w} - DGrowth_{wf}}{DGrowth_{w} + DGrowth_{wf}} \quad \textbf{[7.2]}$$

where *DGrowth* is diameter growth, $_{wf}$ is the weed-free treatment and $_{w}$ is the treatment with weeds. All statistics were completed using SPSS version 15.0 (SPSS Inc., Chicago, Illinois).

## 7.4 Results

### 7.4.1 Site productivity

Site productivity was based on the height growth of weed-free plots, similar to the determination of site index in forestry (Carmean, 1975), and represents the ability of the land to grow HP trees. Average height growth of the weed-free plots ranged from 46 cm to 234 cm year$^{-1}$, indicating a large range in potential site productivities that is conducive to statistical analysis (Table 7.2). The best soil characteristic for predicting height growth was soil texture expressed as the percentage of silt + clay (ΣSilt+Clay) for both weed-free ($r^2$=0.562, p=0.020) and weedy plots ($r^2$=0.691, p=0.006) (Figure 7.2). The best sites had a loamy texture with more silt and clay particles than the poorer sites which were either of loamy sand or sand texture. Other soil factors such as total C concentration (p=0.217), total N concentration (p=0.124) or C/N (p=0.796) were not well correlated with height growth. The only other soil characteristics significantly correlated to average height growth was pH (r=0.712, p=0.048). The soil textures in this

**Table 7.2** Summary information (average of the 10 trees) for all plots for weed-free (WF) and weedy (W) treatments. Weed weight is the average weed dry weight from 0.5 m radius plots around 4 trees per plot in the weedy treatments (g/0.8m$^2$). Leaf weight is the modeled average dry weight of leaves per tree for each treatment (kg tree$^{-1}$).

| | Weed-free Plots | | | Weedy Plots | | | |
|---|---|---|---|---|---|---|---|
| Plot | Height Growth (cm) | Diam. Growth (cm) | Leaf biomass (kg tree$^{-1}$) | Height Growth (cm) | Diam. Growth (cm) | Leaf biomass (kg tree$^{-1}$) | Weed biomass (g) |
| 1 | 234 | 4.0 | 0.73 | 81 | 1.1 | 0.08 | 126 |
| 2 | 224 | 2.6 | 0.47 | 86 | 0.9 | 0.05 | 130 |
| 3 | 195 | 3.2 | 0.43 | 112 | 1.3 | 0.09 | 261 |
| 4 | 165 | 2.8 | 0.32 | 105 | 1.0 | 0.06 | 361 |
| 5 | 150 | 2.4 | 0.30 | 46 | 0.8 | 0.08 | 151 |
| 6 | 145 | 2.4 | 0.26 | 31 | 0.5 | 0.06 | 317 |
| 7 | 114 | 2.1 | 0.19 | 81 | 1.3 | 0.05 | 238 |
| 8 | 46 | 0.9 | 0.07 | 48 | 0.8 | 0.02 | 59 |

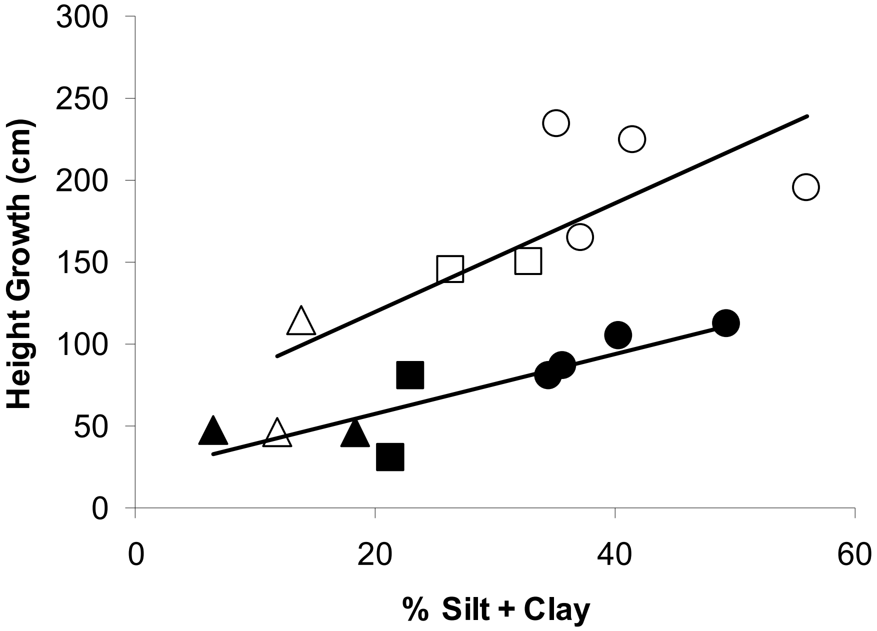

**Figure 7.2** Average height growth of weed-free ($R^2$=0.562, p=0.020) and weedy ($R^2$=0.691, p=0.006) plots in relation to the sum of % silt and clay in the soil**.** Open symbols are weed-free plots. Circles represent the clone Walker, squares are Assiniboine and triangles are Hill.

study did not include heavier textured soils such as silty clay loams and heavy clays. However, because these heavier soils are considered to provide more productive agricultural land, we believe the range of soil textures covered here represents the soils on which HP plantations will be established.

### 7.4.2 Competition Control

Results from the mixed-model ANOVA show that competition control had a significant positive impact on diameter and height growth ($p < 0.001$). The plantation and plot effects nested within the plantation were also both significant ($p<0.001$), indicating that there are differences in responses between plantations and between the individual pairs of plots in each plantation. Therefore, each pair of plots was subsequently treated as a distinct data point which was the original intent of the plot selection.

The absolute benefit of competition control on diameter growth was greater on better quality sites. This is shown graphically between soil texture and the absolute differences in tree diameter between treatments (Figure 7.3a). Relative differences in growth potential between treatments expressed as RII (Armas et al., 2004) also showed that the intensity of competition control increases ($p=0.10$) as the amount of silt and clay increases in the soil (Figure 7.3b). By the end of the growing season, diameter was significantly ($p<0.05$) greater in all weed-free plots compared to weedy plots and height was significantly ($p<0.05$) greater in all but the poorest site. Leaf biomass was also significantly greater in weed-free plots ($p=0.001$).

### 7.4.3 Site Resources

Almost no weeds were present above approximately 50 cm in height which was below the level of tree leaves at most sites. Consequently, there was little negative effect on the light status of the trees due to weeds (data not shown). The average soil temperature was slightly higher in weed-free plots (0.5ºC, $p=0.003$) but this difference in soil temperature between treatments was not correlated to any differences in tree growth ($p=0.654$).

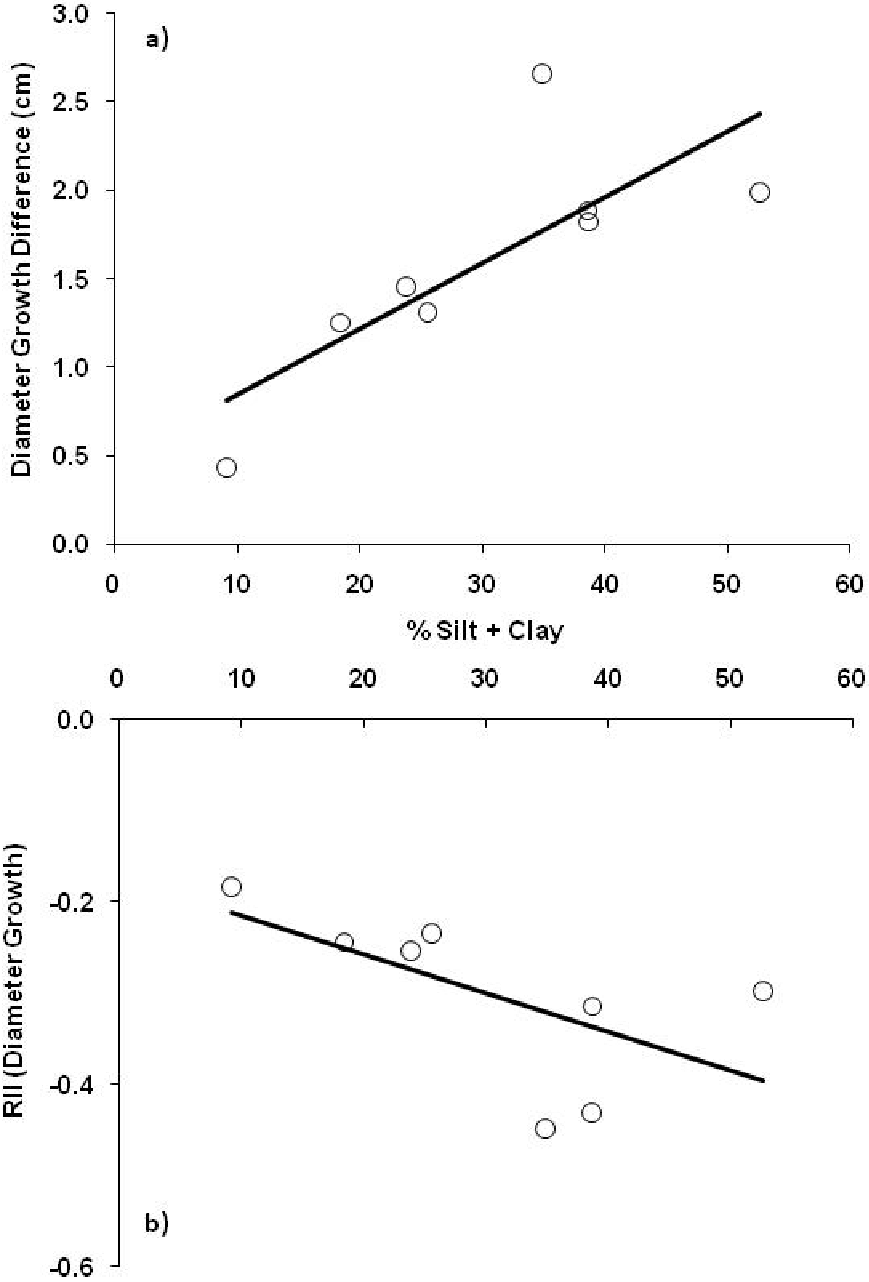

**Figure 7.3** Diameter growth benefit of competition control in relation to % silt + clay for both (a) absolute difference ($r^2$=0.516, p=0.027) and (b) relative difference – RII ($r^2$=0.275, p=0.10).

Summer soil moisture was significantly higher in weed-free compared to weedy plots ($p=0.003$) and was strongly related to tree growth (Figure 7.4) and to the amount of silt and clay in the soil ($r=0.914$, $p=0.002$). These general trends are supported by $\delta^{13}C$ values which show the weed-free trees had significantly lower ($p=0.025$) average $\delta^{13}C$ values (-27.1‰) than weedy trees (-26.0‰), indicating that weed-free trees had more water available to them throughout the growing season.

Tree nutrition was assessed by comparing foliar nutrient concentrations between weeding treatments and to optimal foliar N, P, K, Ca and Mg levels developed from HP plantation fertilizer studies in the north-central United States (Hansen, 1994; Coleman et al., 2006) with similar growing conditions to those experienced in central Saskatchewan. Foliar N concentrations were significantly higher in the weed-free plots ($p<0.001$) but foliar N was not strongly related to diameter growth in either weed-free ($p=0.119$) or weedy plots ($p=0.232$) (Figure 7.5). Most of the weed-free plots were also above the optimal N concentrations. The foliar N content per tree was also significantly greater ($p=0.003$) in weed-free plots and the difference between treatments was greatest on the better quality sites (Table 7.3).

Foliar P concentration showed a different response to competition control with no difference between competition treatments ($p=0.204$) while showing a very strong relationship to growth in the weed-free plots ($r^2=0.770$, $p=0.003$) but not in the weedy plots ($p=0.656$). In all plots, P concentrations were well below the optimal levels. Foliar P contents were, however, significantly greater ($p=0.014$) in weed-free plots and again the differences were greatest on the better quality sites (Table 7.3). The N:P ratio also showed a strong negative relationship to growth in the weed-free plots ($r^2=0.798$, $p=0.003$). For base cations, foliar K, Ca and Mg concentrations were not different between competition treatments ($p=0.602$, 0.836, 0.059, respectively). They were also not significantly related to diameter growth in either the weed-free ($p=0.135$, 0.584, 0.614, respectively) or weedy plots ($p=0.965$, 0.858, 0.464, respectively). Foliar K and Ca were well above optimal levels for most of the weed-free and weedy plots (Figure 7.5).

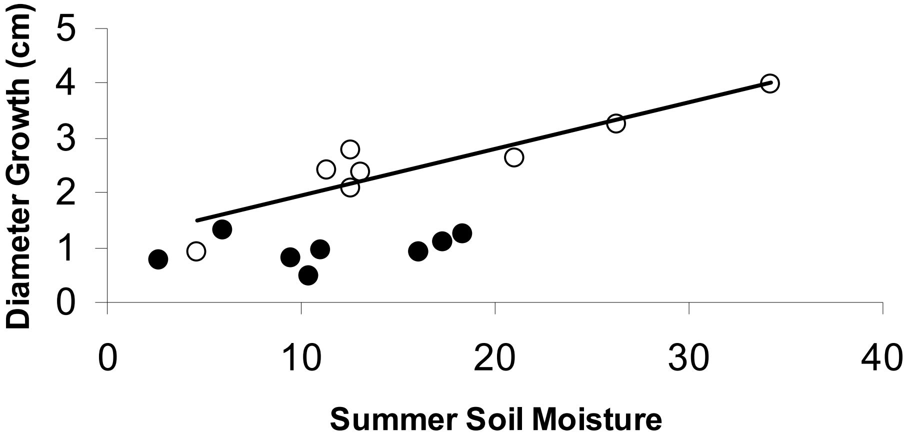

**Figure 7.4** Average summer soil moisture in relation to tree diameter growth for weedy and weed-free plots ($R^2$=0.827). Open circles are weed-free plots and closed circles are weedy plots.

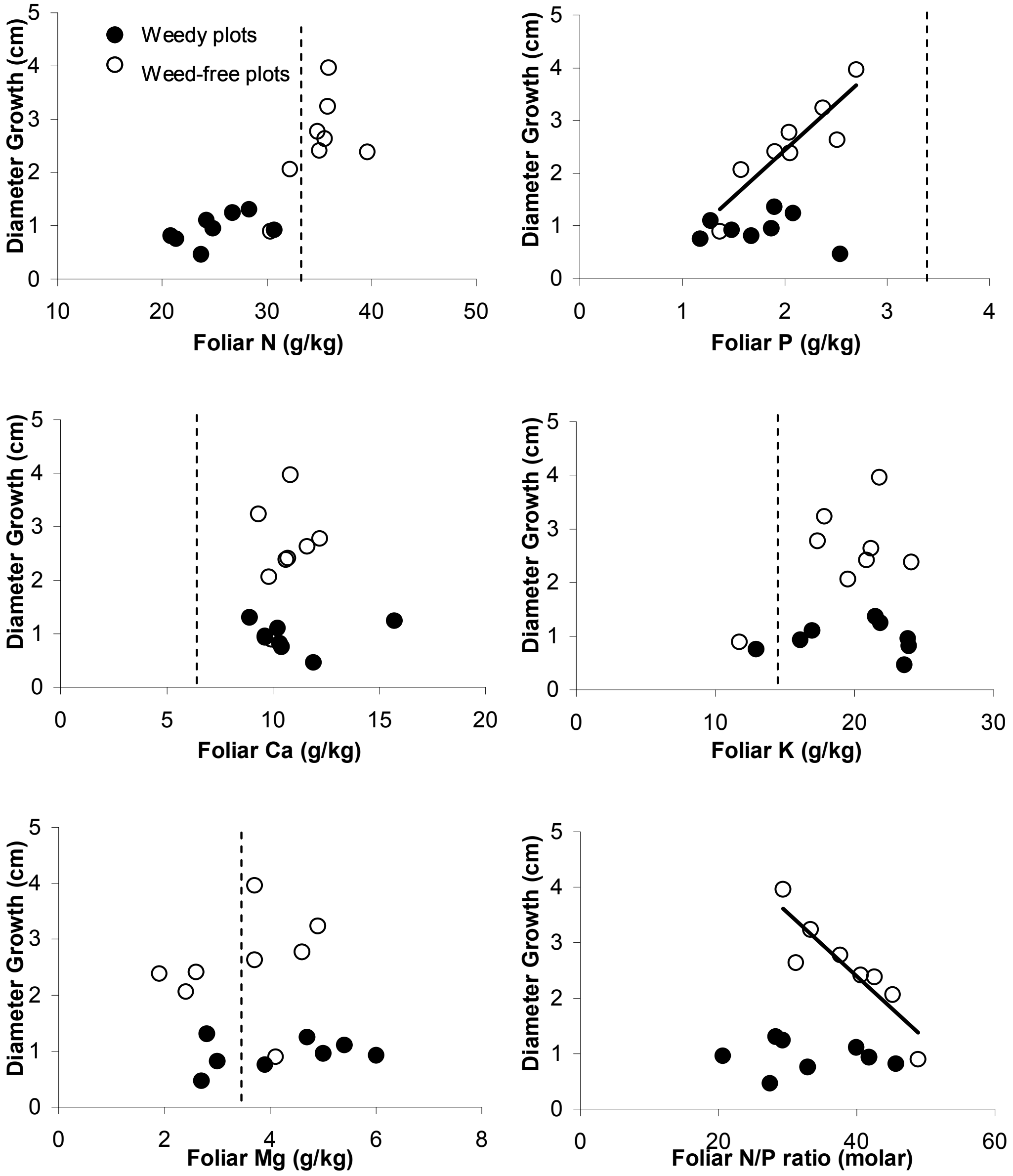

**Figure 7.5** Diameter growth in relation to foliar nutrient concentrations. The only foliar nutrient concentrations significantly related to tree diameter growth was P and P:N for the weed-free treatment ($r^2$=0.770, p=0.003 and $r^2$=0.798, p=0.003, respectively). The vertical dashed line represents the optimal nutrient concentrations for hybrid poplar from Hansen (1994).

**Table 7.3** Foliar nitrogen (N) and phosphorous (P) concentrations and contents for all plots for weed-free and weedy treatments

| | Weed-Free Plots | | | | Weedy Plots | | | |
|---|---|---|---|---|---|---|---|---|
| Plot | N Conc (g/kg) | N Content (g/tree) | P Conc (g/kg) | P Content (g/tree) | N Conc (g/kg) | N Content (g/tree) | P Conc (g/kg) | P Content (g/tree) |
| 1 | 35.9 | 26.0 | 2.69 | 1.96 | 24.2 | 1.8 | 1.28 | 0.10 |
| 2 | 35.5 | 16.6 | 2.51 | 1.17 | 30.7 | 1.6 | 1.48 | 0.08 |
| 3 | 35.8 | 15.5 | 2.37 | 1.02 | 26.7 | 2.4 | 2.08 | 0.19 |
| 4 | 34.8 | 11.0 | 2.04 | 0.64 | 24.8 | 1.5 | 1.87 | 0.11 |
| 5 | 35 | 10.6 | 1.90 | 0.57 | 20.8 | 1.7 | 1.67 | 0.14 |
| 6 | 39.6 | 10.1 | 2.05 | 0.52 | 23.7 | 1.5 | 2.5 | 0.16 |
| 7 | 32.2 | 6.3 | 1.57 | 0.31 | 28.3 | 1.5 | 1.89 | 0.10 |
| 8 | 30.3 | 2.1 | 1.37 | 0.09 | 21.3 | 0.5 | 1.18 | 0.03 |

## 7.5 Discussion

### 7.5.1 Tree Growth

Competition control significantly increased tree growth on all sites which was a response similar to that observed in many other studies for a variety of different species and locations (e.g. Mason and Milne (1999) for *Pinus radiata* in New Zealand, Löf and Welander (2004) for *Fagus* and *Quercus* in Sweden and Cain (1999) for pines in the southeast United States). The response to competition control in our study was immediate with significant differences in tree growth appearing during the same growing season as the competition control treatment. This immediate response has also been seen for other fast-growing, intolerant tree species such as loblolly pine (Perry et al., 1993) but slower growing species with determinate growth patterns, such as Engelmann spruce, have taken up to three years after repeated competition control to show any growth response (Biring et al., 2003). The treatment effect in our study, i.e. the growth difference between weed-free and weedy plots, was very large with the greatest difference in height of 150 cm for the best sites. These effects might have been even greater if a larger area had been cleared of weeds around the trees. Regardless, the impact of competition control after a single season in our study is comparable to the response shown by Jylhä and Hytönen (2006) for Scots pine in an old agricultural field in Finland 11 years after weed control. This large and immediate response of the HP trees in our study may be due to the growth characteristics of the trees which have been bred specifically for this climatic region but which are highly intolerant of competition or reduction in resource availability (Hansen et al., 1988; Shock et al., 2002). When these HP trees have the required resources, they can quickly utilize these resources and grow very fast. However, when they experience reduced resource availability, either through competition or abiotic factors, growth is greatly reduced.

Weed control on more productive growing sites had the largest absolute and relative benefit to tree growth while weed control on the very poorest site, which was of sandy texture, resulted in almost no improvement in tree growth. This is consistent with the theory of Grime (1973) that competition is more intense on richer sites than on poor sites, since tree growth is controlled more by abiotic factors than by competition on these poor sites (Goldberg and Novoplansky, 1997). Other studies looking at tree growth response to competition on different site qualities have shown contrasting results. For example, Ladd and Facelli (2007) showed a similar response to our study for eucalypt trees in Australia with tree establishment only responding positively to competition control in the richer environments. On the other hand, ponderosa pine growth in northern California and southern Oregon showed the largest response to competition control on the poorest sites (Powers and Reynolds, 1999; Zhang et al., 2006).

The impact of competition control on future stand growth cannot be directly examined in this one year study but it is expected that there will be a Type I response in which the impact of the treatment is carried into the future but does not get larger over time (Snowdon, 2002). This is the common response to competition control treatments which advance the stage of stand development but do not change the long-term growth rates and has been seen in other competition control studies (Mason and Milne, 1999). However, if the density of these plantations results in significant intraspecific competition, we speculate that the initial growth benefit of competition control may actually decrease over time. Continued monitoring of these plantations will help determine the intensity and impact of this competition.

### 7.5.2 Site Resources

This study was designed to demonstrate the effects of competition control in an operational setting and therefore did not include fertilization or irrigation which would have alleviated water and nutrient stress. Determining which resource is actually being competed for between weeds and trees, however, is not usually possible since there is always a combination of water and nutrients being competed for below-ground (Nambiar and Sands, 1993). We can, however, make some inferences as to the importance of the different resources of light, water and nutrients based on observed soil moisture and foliar nutrient levels along with $\delta^{13}C$ indicators of water stress and light measurements.

Competition for light between weeds and trees was not considered to be very important in these plantations since almost all of the leaves were above the level of weeds on the site. We thus observed no reduction in light reaching the tree leaves, meaning that competition is for the below-ground resources of water and nutrients. This has been found in other plantations developed on old agricultural fields such as in Sweden (Löf and Welander, 2004). In our plantations, however, there may be intraspecific competition for light between the trees once crown closure is reached which has been seen in short rotation intensive culture of willow (Sage, 1999).

Water appears to be highly competed for between trees and weeds as shown by the significantly reduced soil water and the corresponding increase in $\delta^{13}C$ values in weedy treatments. There is also a site effect with competition on better quality sites causing the greatest decrease in soil water, paralleling the impact of competition on growth. Competition for water has also been noticed in trembling aspen trees grown with alfalfa and reedgrass in Alberta (Powell and Bork, 2004) and in afforestation plantations in Sweden (Löf and Welander, 2004). Interspecific competition for water and the associated water stress is a common feature in young plantations but becomes less significant as trees grow and develop deeper and more extensive root systems which can often tap water reserves that weeds cannot access (Nambiar and Sands, 1993).

Foliar base cations (at least for K and Ca) were present in high levels in all trees and do not appear to be strongly competed for. Also, there was no strong relation to growth. This is different from other studies which have found that base cations, in particular Ca, are very important for growth of trees in HP plantations (Bowersox and Ward, 1977; Wittwer and Immel, 1980) and trembling aspen seedlings grown in solution (Lu and Sucoff, 2001). This lack of response to base cations is probably associated with the Chernozemic soils in our study which are characterized by high base cation levels (Soil Classification Working Group, 1998) and consequently base cations are not a factor limiting tree growth.

Although the influence of competition for nutrients is often overpowered by competition for water for controlling poplar productivity (Carmean, 1996), there is strong evidence in our study of competition for nutrients, particularly N. Nitrogen is the nutrient most often studied in competition trials and is usually the most important nutrient in determining tree growth in northern environments (Carlyle, 1986; Reich et al., 1997; Binkley and Högberg, 1997). In our study, there was a significant increase in foliar N concentration and content with competition control which was expected given that $NO_3^-$ and $NH_4^+$ are mobile in the soil (Havlin et al., 2005) and in high demand by the competing weeds (Kabba et al., 2007). From these data, it can be said that tree growth benefits from greater N availability. However, it appears the trees accessed all the soil N they needed in the weed-free plots for optimal growth based on foliar concentrations [levels being between 3.0 and 3.4 g N $kg^{-1}$ (Hansen et al., 1994)], resulting in the relationship between foliar N and growth being lost for the weed-free trees. Such observations were also made for a HP plantation grown on silt loam in northern Wisconsin (Hansen et al., 1988). No further increase in foliar N is expected to impact growth rates since other nutrients may become limiting and the nutrient ratios within the trees will not be optimal (Knecht and Göransson, 2004). These high N levels are probably due to the naturally high organic matter and N contents of the Chernozemic soils and the agricultural history of the sites with repeated annual applications of N fertilizers.

Foliar P concentrations were not statistically different between weeding treatments, but foliar P contents were significantly higher in the weed-free plots. There was a strong relationship between foliar P concentration and growth in the weed-free treatments and all foliar P concentrations were below the optimal levels. Similarly, the decreasing foliar N:P ratio for weed-free trees indicate that weed-free trees responded to the gradient in soil P availability created with the experiment. It is therefore not unreasonable to think that P is an important nutrient controlling productivity and that it is also highly competed for. This importance of P may help explain the lack of response in N fertilizer trials in HP plantations in Saskatchewan located on medium quality sites (Van Rees et al., 2006) and in plantations developed on agricultural fields in Sweden (Löf and Welander, 2004); the trees in weed-free plots could have access to ample N but not P or water.

## 7.6 Conclusion

For our HP plantations in Saskatchewan, the results support the theory that plant competition, as expressed through tree growth, is more intense on better quality sites. If large scale tree planting programs do occur on the Canadian prairies in the future, there will be a need to prioritize the limited resources for plantation management activities such as competition control. Our recommendation is that the best quality sites be given the highest priority for competition control in order to maximize tree growth. This study further illustrates the need for site specific plantation management rather than trying to incorporate the same management regime on all sites, regardless of potential benefits.

# 8 CONCLUSION

## 8.1 General Discussion

The general goal of this project was to better understand the dominant soil and site factors controlling the growth of poplars so as to enable identification at the local scale of the best sites for growing trees. This is a refinement of previous studies which looked at tree productivity across very large areas with distinct differences in climate.

All plant growth is controlled by the availability of light, water and nutrients as well as biotic interactions such as competition by weeds. The growth of trembling aspen and hybrid poplars in these studies was no different. For example, in the three site quality studies, trembling aspen and hybrid poplar productivity was consistently related to some measure of either water availability or soil fertility. In the competition study, both water and nutrients appeared to be strongly competed for.

One of the important aspects of this project was being able to examine poplar site productivity all across Canada. It is obvious that different factors are driving productivity in the different regions. In Quebec, soil fertility is the major soil factor controlling trembling aspen productivity, while water availability plays a much larger role in Saskatchewan and Alberta. This importance of soil fertility in Quebec may be because the experimental study in Quebec was located in an area of almost continuous boreal forest with other species, in particular conifers, almost always present in the stands. These conifers appear to have a major negative impact on soil fertility variables such as pH and C:N ratio, resulting in poorer trembling aspen growth. The variability between stands in conifer abundance was therefore a major determinant of trembling aspen productivity. In Saskatchewan, the stands studied were almost pure trembling aspen. Thus, I did not capture this biological impact of other tree species on soil fertility and trembling aspen productivity. In Alberta, the hybrid poplar plantations were located on former agricultural crop land. Past site history and management such as fertilization and crop selection could play a major role in current soil fertility and site productivity but this project was not designed to capture such differences.

Soil moisture availability may not be as important in Quebec as in the western provinces because the study area in Quebec receives approximately double the precipitation of the study areas in Saskatchewan and Alberta. Therefore, the trees may not be as limited by low moisture availability. The apparent lack of response to soil moisture availability may also be due to the soil distribution in the study areas. For both western provinces (but especially Saskatchewan), there were major differences in soil texture between sites, ranging from loamy sand to heavy clay in Saskatchewan, resulting in large differences in soil moisture holding capacity which were related to poplar productivity. This was not the case in Quebec, where all of the study plots were located on similar sandy loam textured soils, thus leading to a small moisture gradient and no relationship to trembling aspen productivity. Also, in the Alberta study, it appears that hybrid poplar productivity has an optimal range of soil textures, outside of which productivity is reduced, indicating that this particular clone has very exacting soil moisture requirement.

The hybrid poplar competition control study adds to the general understanding of the factors controlling poplar productivity and expands on this general theme by examining the impacts of competition control on different site qualities. The resources being competed for between weeds and trees are the same below-ground resources found to be controlling poplar productivity in the other studies, i.e. water and nutrients. Competition control appears to have a greater benefit to hybrid poplar growth on the better quality sites. This adds to the understanding of the impacts of plant competition across productivity gradients by applying some of the same principles derived from natural plant communities, such as the relative interaction intensity, to intensively managed hybrid poplar plantations.

## 8.2 Management Implications

Based on the results of the research, management recommendations can be made arising from the theoretical understanding of trembling aspen and hybrid poplar site productivity. In order to make intensive plantation management or the TRIAD approach successful in Canada, good information is required on site productivity at the local level where management decisions are made. The site quality studies have identified these soil and site properties associated with the best growing sites for poplars in Quebec, Saskatchewan and Alberta, and this information can now be used to help the forest industry and private landowners in making the best decisions on where to establish plantations. The Saskatchewan study showed that trees do not correspond very well to agricultural productivity ratings, indicating that general suitability maps are not sufficient for predicting tree productivity. This is also supported by the Quebec study which showed that it is not possible to identify the best growing sites based only on general map data but rather field sampling must be completed to get the most reliable information. Moreover, the Alberta study showed that the variability of poplar growth rates could be explained by capturing differences in microsite quality within a plantation. With time and effort, this other level of information could lead to precision tree farming where the site specific nutrient and water requirements for tree growth are known and proper treatments performed to maximize their performance.

Another phase of plantation management is stand tending which includes interspecific competition control. The competition control study indicates that the largest benefit in terms of relative and absolute hybrid poplar growth to competition control is on the best quality sites. This means that in terms of prioritizing stand tending operations highest priority should be given to plantations on the best quality sites when resources are limited.

The overall message from these studies is that site specific management prescriptions should be implemented rather than having the same treatment across all site types. These studies have shown that it is possible to use soil and site information to predict poplar productivity reasonably well at the local scale. This information on site quality can now be used to improve on all aspects of plantation management starting with selecting the most productive sites for plantation establishment, through prioritizing sites for stand tending and all the way to achieving better predictions of plantation yields on different site types when harvested. There is also the potential for ensuring long-term sustainability of timber plantations by establishing them on sites with higher reserves of resources so plantation growth will not decrease in future rotations.

## 8.3 Future Research

Intensive plantation forestry is still relatively new in Canada so there is a need for continued theoretical and applied research to help ensure successful plantations, whether they are for timber production or other environmental benefits. Starting with poplar site quality, the next step is to validate the empirical relationships from these studies with independent data sets. This could be done with natural trembling aspen stands as well as when establishing new plantations of hybrid poplar to determine if trembling aspen can really be used as a proxy for hybrid poplar plantations. It is also important to examine other hybrid poplar clones since it is likely that different clones will have different resource requirements and growth responses to soil properties.

Most afforestation research on the prairies is currently focused on hybrid poplars for timber production, but it would also be interesting to examine other tree species which naturally occur on the prairies and may be suitable for plantation establishment, particularly for environmental benefits such as wildlife habitat and biodiversity conservation. This might include tree species such as bur oak, Manitoba maple and green ash, all of which are relatively common on prairie landscapes. It would also be interesting to look at site quality for other common timber plantation tree species such as pines and larches since these species have the potential for becoming significant components of plantation forestry.

For competition in hybrid poplar plantations, in order to fully elucidate the resources being competed for and driving productivity, fertilization and irrigation studies could be conducted where sufficient levels of all resources are available. This would allow thresholds to be established for adequate water and nutrient levels. Future fertilization studies should also examine all nutrients including N, P and micronutrients rather than just focusing on N as has been done in previous forestry fertilization studies. Competition control could also be continued on into the future at the eight plots in this study to monitor how long competition control is required before the trees overtop and shade out competing weeds.

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# APPENDIX A

## Soil and Site Information for all Plots

**Table A.1**: Soil and site information for the fluvial sites from the Quebec site quality study (Chapter 4).

| SI | Easting | Northing | Elevation (m) | Slope (%) | Aspect (°) | Topographic Position | Drainage | % Sand BC horizon | % Clay BC horizon | % Conifer in Overstory | pH FH layer | pH Bf horizon | % N Bf horizon | Thickness of Ae Horizon (cm) | Thickness of Bf Horizon (cm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12.2 | 618717 | 5282208 | 364 | 2 | 64 | toe | rapid | 68.1 | 2.1 | 60 | 4.1 | 5.3 | 0.08 | 9 | 22 |
| 16.5 | 682307 | 5283233 | 233 | 5 | 84 | lower | rapid | 69.1 | 7.6 | 20 | 5.7 | 5.3 | 0.14 | 17 | 22 |
| 16.9 | 667632 | 5259781 | 236 | 55 | 24 | upper | rapid | 61.6 | 3.0 | 40 | 4.6 | 5.0 | 0.10 | 3 | 11 |
| 17.5 | 669895 | 5288252 | 207 | 5 | 279 | crest | rapid | 98.5 | 0.0 | 0 | 4.1 | 5.2 | 0.08 | 15 | 23 |
| 17.7 | 669249 | 5258899 | 204 | 47 | 334 | upper | rapid | 97.9 | 0.0 | 30 | 4.4 | 5.2 | 0.10 | 5 | 7 |
| 18.4 | 618986 | 5282560 | 348 | 5 | 184 | upper | rapid | 95.8 | 0.6 | 40 | 4.6 | 5.1 | 0.12 | 12 | 7 |
| 18.9 | 669919 | 5288247 | 214 | 72 | 174 | upper | rapid | 99.2 | 0.0 | 10 | 5.5 | 5.0 | 0.10 | 6 | 15 |
| 19.1 | 669856 | 5288238 | 201 | 67 | 244 | mid | rapid | 83.6 | 2.5 | 0 | 6.4 | 5.0 | 0.06 | 3 | 23 |
| 20.1 | 667676 | 5259883 | 181 | 2 | 14 | crest | rapid | 97.1 | 0.0 | 0 | 5.2 | 5.1 | 0.11 | 4 | 24 |
| 20.4 | 715532 | 5317094 | 410 | 7 | 184 | lower | rapid | 92.3 | 0.6 | 0 | 5.2 | 5.4 | 0.18 | 11 | 8 |
| 20.5 | 669945 | 5288257 | 200 | 45 | 164 | lower | modwell | 73.2 | 3.6 | 0 | 4.6 | 5.1 | 0.10 | 6 | 16 |
| 21.5 | 666607 | 5263801 | 182 | 17 | 54 | lower | rapid | 99.2 | 0.0 | 0 | 5.3 | 5.0 | 0.17 | 6 | 28 |
| 23.2 | 658840 | 5290456 | 250 | 5 | 154 | mid | rapid | 92.2 | 0.8 | 0 | 6.4 | 5.0 | 0.19 | 9 | 31 |
| 23.5 | 658887 | 5290463 | 240 | 45 | 79 | lower | rapid | 66.4 | 3.4 | 0 | 5.8 | 5.1 | 0.19 | 11 | 31 |
| 23.7 | 666436 | 5263789 | 201 | 20 | 24 | upper | rapid | 55.4 | 4.4 | 0 | 5.0 | 5.0 | 0.28 | 6 | 11 |
| 23.8 | 666539 | 5263727 | 198 | 12 | 44 | upper | rapid | 65.0 | 2.5 | 0 | 5.8 | 4.9 | 0.22 | 4 | 15 |

**Table A.2**: Soil and site information for the till sites from the Quebec site quality study (Chapter 4).

| SI | Easting | Northing | Elevation (m) | Slope (%) | Aspect (°) | Topographic Position | Drainage | % Sand C horizon | % Clay C horizon | % Conifer in Overstory | pH FH layer | pH Bf horizon | % N Bf horizon | Thickness of Ae Horizon (cm) | Thickness of Bf Horizon (cm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13.9 | 711590 | 5290092 | 435 | 2 | 214 | toe | poor | 66.2 | 0.0 | 70 | 4.3 | 4.6 | 0.14 | 21 | 20 |
| 14 | 703063 | 5282475 | 402 | 2 | 264 | toe | imp | 64.0 | 6.2 | 70 | 4.6 | 5.2 | 0.08 | 8 | 22 |
| 15 | 715508 | 5317077 | 420 | 5 | 194 | toe | poor | 79.9 | 1.9 | 40 | 4.6 | 5.2 | 0.11 | 9 | 21 |
| 15.8 | 659016 | 5291395 | 278 | 22 | 154 | mid | rapid | 42.9 | 5.4 | 50 | 6.0 | 5.3 | 0.11 | 17 | 8 |
| 15.9 | 714641 | 5316692 | 440 | 20 | 334 | upper | rapid | 57.3 | 5.0 | 30 | 4.9 | 4.9 | 0.31 | 4 | 12 |
| 16 | 711649 | 5289952 | 431 | 5 | 184 | upper | rapid | 56.4 | 4.9 | 0 | 4.2 | 4.7 | 0.33 | 8 | 18 |
| 16.4 | 682102 | 5283145 | 247 | 5 | 104 | upper | well | 62.5 | 3.3 | 30 | 5.1 | 5.6 | 0.17 | 5 | 22 |
| 17.3 | 714654 | 5316685 | 434 | 2 | 14 | crest | rapid | 58.0 | 9.9 | 0 | 4.8 | 5.1 | 0.27 | 8 | 16 |
| 17.5 | 682060 | 5283220 | 248 | 10 | 114 | lower | rapid | 73.0 | 3.2 | 10 | 5.2 | 5.3 | 0.26 | 10 | 21 |
| 17.6 | 708923 | 5286355 | 438 | 57 | 144 | upper | rapid | 85.0 | 1.5 | 20 | 5.1 | 5.1 | 0.25 | 6 | 16 |
| 18.1 | 714691 | 5316629 | 439 | 27 | 139 | mid | rapid | 48.8 | 7.6 | 10 | 4.3 | 5.4 | 0.14 | 6 | 11 |
| 18.7 | 662799 | 5283318 | 414 | 17 | 304 | lower | well | 58.6 | 6.0 | 0 | 4.7 | 4.9 | 0.27 | 8 | 16 |
| 19 | 659168 | 5252564 | 325 | 22 | 194 | upper | rapid | 77.0 | 2.7 | 0 | 5.1 | 4.9 | 0.16 | 11 | 12 |
| 19.1 | 679487 | 5281389 | 315 | 25 | 124 | upper | rapid | 73.3 | 1.3 | 30 | 5.8 | 4.8 | 0.07 | 8 | 9 |
| 19.2 | 708938 | 5286338 | 437 | 42 | 134 | lower | rapid | 61.0 | 4.8 | 10 | 5.5 | 4.8 | 0.30 | 5 | 14 |
| 19.6 | 659027 | 5291366 | 270 | 22 | 134 | mid | rapid | 46.9 | 5.1 | 20 | 5.8 | 5.3 | 0.15 | 9 | 27 |
| 19.6 | 661875 | 5287889 | 345 | 7 | 14 | upper | rapid | 56.0 | 4.4 | 10 | 5.0 | 5.3 | 0.20 | 11 | 29 |
| 19.8 | 663845 | 5283860 | 389 | 5 | 84 | upper | well | 69.5 | 4.0 | 40 | 4.6 | 4.9 | 0.22 | 8 | 14 |
| 20 | 679589 | 5281171 | 265 | 47 | 174 | mid | rapid | 82.4 | 2.2 | 20 | 6.5 | 5.3 | 0.12 | 7 | 24 |
| 20.1 | 663746 | 5258708 | 218 | 15 | 104 | lower | well | 71.6 | 3.3 | 0 | 4.9 | 5.0 | 0.11 | 9 | 27 |
| 20.2 | 661853 | 5287849 | 341 | 5 | 164 | crest | rapid | 62.0 | 4.1 | 10 | 5.7 | 5.2 | 0.16 | 0 | 20 |
| 20.7 | 714660 | 5316829 | 439 | 20 | 84 | mid | rapid | 61.9 | 3.8 | 10 | 4.9 | 5.0 | 0.19 | 8 | 14 |
| 20.7 | 663806 | 5283796 | 391 | 5 | 204 | upper | rapid | 58.4 | 7.3 | 40 | 4.4 | 4.9 | 0.24 | 5 | 24 |
| 21.3 | 662860 | 5283282 | 441 | 10 | 224 | upper | rapid | 59.0 | 5.2 | 10 | 5.3 | 5.1 | 0.20 | 6 | 24 |
| 21.3 | 682110 | 5283193 | 229 | 50 | 104 | upper | well | 38.4 | 6.9 | 50 | 5.9 | 5.4 | 0.18 | 7 | 10 |
| 21.4 | 661949 | 5287942 | 324 | 2 | 74 | toe | rapid | 71.3 | 3.0 | 20 | 5.3 | 4.9 | 0.28 | 7 | 27 |
| 21.6 | 656831 | 5288839 | 241 | 5 | 334 | lower | rapid | 85.8 | 0.6 | 0 | 5.6 | 4.7 | 0.24 | 6 | 18 |
| 21.6 | 678896 | 5278509 | 272 | 17 | 354 | toe | well | 63.3 | 4.3 | 20 | 4.7 | 5.0 | 0.22 | 5 | 33 |
| 22.1 | 712591 | 5314065 | 406 | 22 | 164 | lower | rapid | 76.1 | 2.9 | 10 | 4.8 | 5.0 | 0.24 | 10 | 19 |
| 22.2 | 659311 | 5252582 | 312 | 10 | 194 | lower | modwell | 45.3 | 6.6 | 10 | 4.8 | 5.0 | 0.26 | 12 | 13 |
| 22.3 | 663746 | 5258761 | 231 | 15 | 144 | upper | well | 57.5 | 5.8 | 0 | 5.2 | 5.1 | 0.15 | 12 | 14 |
| 22.4 | 656823 | 5252521 | 338 | 30 | 214 | lower | rapid | 42.0 | 6.4 | 20 | 4.9 | 5.2 | 0.25 | 2 | 14 |
| 22.4 | 663851 | 5259800 | 262 | 35 | 254 | lower | rapid | 67.0 | 4.1 | 0 | 5.5 | 5.1 | 0.19 | 5 | 29 |
| 24.4 | 678904 | 5278491 | 285 | 22 | 4 | upper | well | 63.3 | 4.3 | 20 | 5.4 | 5.2 | 0.21 | 8 | 12 |

**Table A.3**: Soil and site information for the fluvial sites in the Saskatchewan site quality study (Chapter 5).

| SI | Easting | Northing | Drainage | % Sand C horizon | % Clay C horizon | pH A horizon | % N A horizon | Ah horizon Depth (cm) | Ca mg/g FH layer | Ca mg/g C horizon | P mg/g C horizon | Soil Association | Ag Cap Class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 528877 | 5891449 | rapid | 76 | 4 | 5.8 | 0.16 | 9 | 10.8 | 5.0 | 0.046 | Pine | 5 |
| 12.4 | 529177 | 5890410 | rapid | 72 | 4 | 5.8 | 0.10 | 13 | 20.2 | 7.5 | 0.118 | Pine | 6 |
| 13 | 528829 | 5891473 | rapid | 8 | 11 | 5.8 | 0.17 | 8 | 15.1 | 5.0 | 0.137 | Pine | 5 |
| 13.9 | 529180 | 5890482 | rapid | 55 | 6 | 5.5 | 0.42 | 8 | 18.0 | 4.7 | 0.191 | Pine | 5 |
| 16.7 | 531317 | 5835262 | mod well | 20 | 26 | 7.5 | 0.22 | 17 | 23.2 | 53.6 | 0.125 | Glenbush | 3 |
| 16.9 | 542819 | 5890542 | well | 69 | 4 | 6.4 | 0.88 | 7 | 17.3 | 5.5 | 0.000 | Nisbet | 4 |
| 17.6 | 594445 | 5832929 | well | 44 | 5 | 6.4 | 0.15 | 8 | 20.0 | 4.7 | 0.068 | Sylvania | 4 |
| 18.1 | 533439 | 5832105 | imperfect | 37 | 9 | 7.5 | 0.44 | 35 | 35.5 | 25.4 | 0.035 | Perley | 2 |
| 18.5 | 595245 | 5833038 | rapid | 76 | 4 | 6.1 | 0.16 | 5 | 20.4 | 6.2 | 0.000 | Sylvania | 4 |
| 18.8 | 608444 | 5832126 | well | 15 | 15 | 7.1 | 0.12 | 12 | 25.1 | 9.0 | 0.007 | La Corne | 3 |
| 19.1 | 592409 | 5909753 | well | 85 | 4 | 7.4 | 1.67 | 17 | 44.5 | 28.6 | 0.069 | Carrot River | 4 |
| 19.2 | 595205 | 5833128 | well | 81 | 3 | 5.8 | 0.11 | 6 | 15.0 | 10.2 | 0.122 | Sylvania | 4 |
| 19.2 | 594485 | 5832932 | rapid | 62 | 5 | 6.3 | 0.14 | 6 | 23.2 | 5.8 | 0.000 | Sylvania | 4 |
| 20 | 592319 | 5909723 | rapid | 92 | 0 | 6.7 | 0.10 | 12 | 6.9 | 7.4 | 0.000 | Carrot River | 4 |
| 20.5 | 608418 | 5832081 | rapid | 66 | 4 | 6.8 | 0.12 | 21 | 22.7 | 5.4 | 0.099 | La Corne | 3 |
| 21.1 | 549302 | 5900417 | mod well | 69 | 4 | 7.5 | 0.30 | 8 | 30.9 | 12.9 | 0.000 | Nisbet | 4 |
| 21.5 | 605104 | 5834339 | well | 34 | 7 | 6.3 | 0.10 | 6 | 17.6 | 6.0 | 0.081 | La Corne | 3 |

**Table A.4**: Soil and site information for the lacustrine sites in the Saskatchewan site quality study (Chapter 5).

| SI | Easting | Northing | Drainage | % Sand C horizon | % Clay C horizon | pH A horizon | % N A horizon | Ah horizon Depth (cm) | Ca mg/g FH layer | Ca mg/g C horizon | P mg/g C horizon | Soil Association | Ag Cap Class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12.8 | 602550 | 5920422 | mod well | 19 | 39 | 7.1 | 0.21 | 15 | 26.3 | 67.8 | 0.065 | Tisdale | 2 |
| 14.4 | 602524 | 5920465 | mod well | 35 | 34 | 8.0 | 0.22 | 16 | 17.9 | 66.8 | 0.111 | Tisdale | 2 |
| 16.1 | 574876 | 5848115 | imperfect | 3 | 44 | 6.7 | 0.31 | 14 | 20.0 | 6.2 | 0.076 | Tisdale | 2 |
| 16.3 | 588021 | 5886958 | mod well | 3 | 55 | 6.8 | 0.32 | 26 | 16.5 | 5.3 | 0.270 | Tisdale | 1 |
| 16.5 | 573105 | 5851400 | mod well | 10 | 40 | 6.6 | 0.38 | 10 | 26.6 | 7.6 | 0.148 | Tisdale | 2 |
| 17.7 | 574947 | 5848125 | imperfect | 4 | 40 | 6.9 | 0.42 | 11 | 27.7 | 6.7 | 0.104 | Tisdale | 2 |
| 17.8 | 588018 | 5886986 | imperfect | 2 | 57 | 6.9 | 0.50 | 13 | 16.7 | 8.3 | 0.279 | Tisdale | 1 |
| 17.9 | 573065 | 5851489 | mod well | 4 | 48 | 6.7 | 0.20 | 7 | 24.1 | 8.0 | 0.048 | Tisdale | 2 |
| 18.2 | 528494 | 5836540 | imperfect | 31 | 24 | 6.8 | 0.43 | 7 | 22.6 | 7.4 | 0.016 | Pathlow | 2 |
| 19.2 | 604429 | 5915102 | poor | 3 | 57 | 7.5 | 0.48 | 14 | 24.8 | 20.3 | 0.193 | Tisdale | 2 |
| 19.7 | 575366 | 5861766 | mod well | 2 | 55 | 7.0 | 0.29 | 21 | 28.7 | 6.1 | 0.134 | Tisdale | 2 |
| 20.5 | 604270 | 5925438 | imperfect | 15 | 51 | 6.5 | 0.47 | 10 | 21.9 | 27.7 | 0.155 | Tisdale | 2 |
| 21.1 | 575371 | 5861690 | mod well | 2 | 56 | 6.1 | 0.44 | 17 | 23.7 | 4.8 | 0.152 | Tisdale | 2 |
| 21.4 | 604448 | 5915149 | poor | 2 | 47 | 7.7 | 0.31 | 9 | 20.3 | 17.8 | 0.185 | Eldersley | 2 |
| 22.7 | 547022 | 5872627 | mod well | 0 | 87 | 5.8 | 0.66 | 31 | 24.0 | 19.8 | 0.183 | Melfort | 1 |
| 23.1 | 604296 | 5925413 | imperfect | 6 | 58 | 6.4 | 0.26 | 8 | 21.3 | 34.8 | 0.156 | Tisdale | 2 |

**Table A.5**: Soil and site properties for the till plots in the Saskatchewan site quality study (Chapter 5).

| SI | Easting | Northing | Drainage | % Sand C horizon | % Clay C horizon | pH A horizon | % N A horizon | Ah horizon Depth (cm) | Ca mg/g FH layer | Ca mg/g C horizon | P mg/g C horizon | Soil Association | Ag Cap Class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12.9 | 514236 | 5826672 | mod well | 4 | 34 | 6.5 | 0.37 | 24 | 26.0 | 54.7 | 0.141 | Yorkton | 4 |
| 13.6 | 527135 | 5825754 | mod well | 16 | 23 | 6.7 | 0.66 | 3 | 25.4 | 22.4 | 0.117 | Waitville | 3 |
| 14.2 | 540322 | 5822637 | poor | 0 | 32 | 7.2 | 0.30 | 11 | 31.2 | 69.4 | 0.163 | Whitewood | 3 |
| 14.3 | 587245 | 5874785 | well | 23 | 49 | 6.1 | 0.29 | 4 | 24.8 | 7.4 | 0.050 | Waitville | 3 |
| 14.4 | 540394 | 5822659 | imperfect | 0 | 20 | 6.8 | 0.91 | 14 | 24.8 | 11.3 | 0.036 | Whitewood | 3 |
| 15.7 | 527073 | 5825684 | imperfect | 18 | 33 | 6.8 | 1.00 | 2 | 31.0 | 67.3 | 0.144 | Waitville | 3 |
| 15.8 | 527745 | 5839479 | mod well | 8 | 34 | 7.1 | 0.41 | 11 | 22.3 | 7.9 | 0.000 | Pathlow | 3 |
| 16.3 | 514367 | 5830515 | well | 14 | 22 | 6.2 | 0.68 | 3 | 19.0 | 5.3 | 0.168 | Waitville | 3 |
| 16.3 | 587286 | 5874774 | well | 15 | 18 | 6.0 | 0.18 | 4 | 24.0 | 14.7 | 0.041 | Waitville | 3 |
| 17 | 527709 | 5839198 | rapid | 67 | 18 | 6.7 | 0.23 | 13 | 11.8 | 6.5 | 0.133 | Pathlow | 2 |
| 17.9 | 604284 | 5925457 | well | 0 | 54 | 6.5 | 0.06 | 10 | 17.5 | 91.7 | 0.109 | Waitville | 3 |
| 18.1 | 522383 | 5827203 | well | 28 | 27 | 6.5 | 1.21 | 2 | 26.8 | 5.7 | 0.000 | Waitville | 3 |
| 18.2 | 527770 | 5839267 | well | 11 | 39 | 6.3 | 0.44 | 6 | 18.2 | 8.4 | 0.499 | Pathlow | 2 |
| 19.1 | 547315 | 5832164 | well | 23 | 9 | 6.1 | 0.32 | 6 | 28.8 | 27.9 | 0.257 | Waitville | 5 |
| 20 | 516766 | 5832125 | well | 31 | 7 | 7.2 | 1.86 | 7 | 26.7 | 21.8 | 0.169 | Waitville | 3 |
| 21 | 527754 | 5839576 | well | 20 | 30 | 6.5 | 0.33 | 10 | 14.8 | 12.3 | 0.116 | Pathlow | 3 |
| 21.9 | 604287 | 5925591 | well | 38 | 25 | 6.6 | 0.17 | 10 | 25.2 | 96.7 | 0.119 | Waitville | 3 |

**Table A.6**: Location of plots for the AlPac site quality study (Chapter 6).

| Site | Zone | Northing | Easting | Elevation (m) |
|---|---|---|---|---|
| 1 | 12 | 435571 | 5989055 | 678 |
| 2 | 12 | 414082 | 6075040 | 624 |
| 3 | 12 | 339951 | 6033585 | 663 |
| 4 | 12 | 408345 | 6117701 | 597 |
| 5 | 12 | 433205 | 5988106 | 661 |
| 6 | 12 | 364288 | 6040110 | 676 |

**Table A.7**: Location and slope position of plots in the hybrid poplar competition study (Chapter 7).

| Plot | Site | Latitude | Longitude | Slope Position | Hybrid Poplar Clone |
|---|---|---|---|---|---|
| 1 | Dundurn | 51°49'N | 106°30'W | Upper | Walker |
| 2 | Dundurn | 51°49'N | 106°30'W | Lower | Walker |
| 3 | Osler | 52°22'N | 106°32'W | Upper | Walker |
| 4 | Osler | 52°22'N | 106°32'W | Lower | Walker |
| 5 | Duck Lake | 52°49'N | 106°14'W | Upper | Assiniboine |
| 6 | Duck Lake | 52°49'N | 106°14'W | Lower | Assiniboine |
| 7 | Holbein | 53°14'N | 106°12'W | Lower | Hill |
| 8 | Holbein | 53°14'N | 106°12'W | Upper | Hill |

# APPENDIX B

Comparison of elemental chemistry data from XRF analysis and digested samples analyzed with atomic absorption / emission

**Table B.1**: Comparison of soil elemental composition from XRF analysis and digests of soil / lithium tetraborate beads with subsequent analysis using atomic aborption / emission.

| | Al mg/g | | Fe mg/g | | P mg/g | | Ca mg/g | | Mg mg/g | | K mg/g | | Na mg/g | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | XRF | Digest | XRF | Digest | XRF | Digest | XRF | Digest | XRF | Digest | XRF | Digest | XRF | Digest |
| Basalt | 72.9 | 58.7 | 51.7 | 50.1 | 0.6 | 0.1 | 25.5 | 18.3 | 18.5 | 18.7 | 5.4 | 6.2 | 39.4 | 33.9 |
| Quebec Fluvial BC | 78.0 | 58.1 | 33.3 | 31.0 | 1.1 | 0.6 | 24.0 | 17.1 | 7.9 | 7.8 | 22.6 | 24.6 | 33.2 | 28.0 |
| Quebec Till BC | 74.3 | 59.1 | 43.8 | 47.5 | 1.0 | 0.5 | 24.0 | 18.4 | 8.9 | 11.9 | 18.7 | 21.9 | 29.5 | 25.4 |
| Saskatchewan Lacustrine | 66.4 | 54.3 | 31.3 | 29.5 | 0.6 | 0.2 | 25.2 | 21.1 | 14.7 | 15.6 | 17.3 | 20.1 | 12.0 | 10.3 |
| Saskatchewan Till | 52.8 | 44.0 | 29.1 | 30.0 | 0.6 | 0.2 | 22.3 | 20.8 | 11.9 | 14.5 | 15.6 | 17.0 | 13.6 | 10.4 |
| Alberta A | 30.4 | 27.2 | 9.9 | 9.1 | 0.5 | 0.1 | 5.0 | 2.7 | 2.4 | 1.9 | 11.0 | 11.9 | 10.5 | 7.9 |
| Alberta B | 44.3 | 36.6 | 19.2 | 16.9 | 0.7 | 0.2 | 4.9 | 2.9 | 3.8 | 3.4 | 14.1 | 15.5 | 11.4 | 8.8 |
| % Recovery | 81.7 | | 96.6 | | 33.4 | | 72.8 | | 104.6 | | 111.9 | | 81.6 | |

Note: % Recovery is the average per centage recovery of each element using the digest method relative to the XRF method.

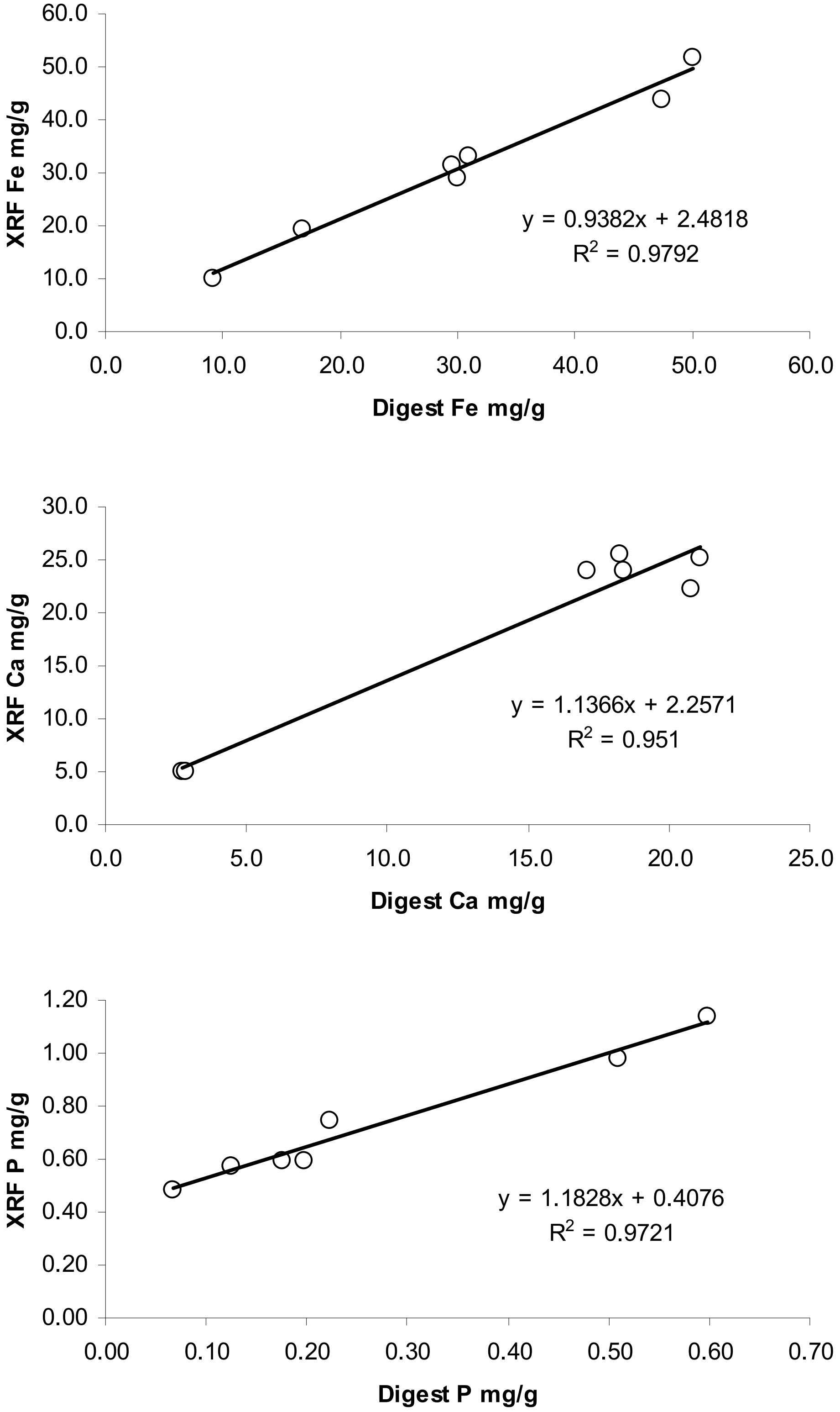

**Figure B.1**: Relationship between the elemental composition from digested samples and XRF analysis for a) Fe, b) Ca and c) P.

# APPENDIX C

Bulk chemistry and nitrogen mineralization data for the site quality studies.

Table C.1: Bulk chemistry of the BC horizon for the Quebec site quality study determined from XRF analysis. Values are in per cent.

| Easting | Northing | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 714691 | 5316629 | 69.16 | 0.757 | 13.61 | 4.34 | 0.076 | 0.81 | 2.46 | 3.82 | 3.04 | 0.195 |
| 669895 | 5288252 | 73.61 | 0.450 | 12.75 | 2.81 | 0.044 | 0.61 | 2.07 | 3.84 | 3.03 | 0.076 |
| 669856 | 5288238 | 67.63 | 0.722 | 14.00 | 4.35 | 0.072 | 1.12 | 2.60 | 3.98 | 3.06 | 0.165 |
| 669919 | 5288247 | 73.84 | 0.401 | 12.67 | 2.66 | 0.048 | 0.62 | 2.10 | 3.87 | 3.09 | 0.082 |
| 669945 | 5288257 | 70.91 | 0.582 | 12.72 | 3.12 | 0.058 | 0.60 | 2.00 | 3.64 | 3.05 | 0.140 |
| 658840 | 5290456 | 69.57 | 0.765 | 12.92 | 4.65 | 0.076 | 1.26 | 2.94 | 3.92 | 2.70 | 0.193 |
| 658887 | 5290463 | 65.90 | 0.703 | 14.40 | 4.75 | 0.082 | 1.37 | 3.61 | 4.50 | 2.11 | 0.258 |
| 656831 | 5288839 | 51.32 | 1.207 | 16.19 | 11.74 | 0.124 | 2.47 | 4.36 | 4.47 | 1.04 | 0.245 |
| 659016 | 5291395 | 58.37 | 1.580 | 14.81 | 8.33 | 0.146 | 2.33 | 4.21 | 3.93 | 2.26 | 0.370 |
| 659027 | 5291366 | 54.57 | 2.071 | 14.54 | 10.74 | 0.128 | 3.22 | 4.99 | 3.69 | 1.91 | 0.496 |
| 661853 | 5287849 | 62.22 | 0.918 | 14.87 | 6.00 | 0.087 | 1.67 | 3.54 | 3.84 | 2.44 | 0.274 |
| 661875 | 5287889 | 63.55 | 0.844 | 14.52 | 5.45 | 0.084 | 1.51 | 3.60 | 3.98 | 2.55 | 0.290 |
| 661949 | 5287942 | 64.97 | 0.843 | 14.25 | 5.51 | 0.089 | 1.65 | 3.78 | 3.98 | 2.52 | 0.284 |
| 618717 | 5282208 | 64.53 | 0.855 | 15.26 | 5.02 | 0.086 | 1.40 | 3.36 | 4.33 | 3.33 | 0.297 |
| 618986 | 5282560 | 65.40 | 1.546 | 13.64 | 6.74 | 0.125 | 1.72 | 3.29 | 3.93 | 2.93 | 0.217 |
| 711590 | 5290092 | 43.19 | 0.444 | 8.65 | 2.55 | 0.045 | 0.56 | 1.81 | 2.37 | 1.90 | 0.134 |
| 711649 | 5289952 | 52.50 | 0.722 | 11.52 | 3.95 | 0.042 | 0.39 | 1.25 | 2.14 | 2.07 | 0.092 |
| 708923 | 5286355 | 62.07 | 0.782 | 14.38 | 5.12 | 0.069 | 1.27 | 2.64 | 3.51 | 2.44 | 0.171 |
| 708938 | 5286338 | 65.83 | 0.866 | 13.59 | 4.66 | 0.074 | 1.19 | 2.66 | 3.63 | 2.56 | 0.137 |
| 715532 | 5317094 | 72.87 | 0.345 | 13.32 | 2.13 | 0.045 | 0.62 | 2.20 | 3.92 | 3.20 | 0.138 |
| 715508 | 5317077 | 68.50 | 0.784 | 13.28 | 3.40 | 0.063 | 0.87 | 2.48 | 3.89 | 3.19 | 0.209 |
| 714641 | 5316692 | 65.95 | 0.862 | 13.69 | 4.71 | 0.077 | 0.88 | 2.56 | 3.69 | 2.75 | 0.246 |
| 714660 | 5316829 | 69.27 | 0.705 | 13.35 | 3.75 | 0.067 | 0.70 | 2.50 | 3.99 | 3.02 | 0.207 |
| 662860 | 5283282 | 64.49 | 0.922 | 14.43 | 5.68 | 0.082 | 1.44 | 3.37 | 3.92 | 2.51 | 0.243 |
| 662799 | 5283318 | 65.87 | 0.844 | 14.11 | 5.59 | 0.083 | 1.52 | 3.69 | 4.01 | 2.44 | 0.258 |
| 663806 | 5283796 | 62.23 | 0.736 | 14.10 | 5.53 | 0.083 | 2.55 | 3.70 | 3.65 | 2.27 | 0.241 |
| 663845 | 5283860 | 63.37 | 0.826 | 14.02 | 5.26 | 0.076 | 1.70 | 3.42 | 3.83 | 2.49 | 0.244 |
| 679487 | 5281389 | 55.11 | 1.371 | 14.40 | 7.13 | 0.139 | 4.87 | 4.73 | 3.51 | 4.00 | 0.583 |
| 679589 | 5281171 | 60.34 | 1.132 | 14.26 | 7.18 | 0.080 | 1.58 | 3.01 | 3.79 | 3.10 | 0.275 |
| 659311 | 5252582 | 59.01 | 1.061 | 14.21 | 7.03 | 0.098 | 1.88 | 3.79 | 3.66 | 2.27 | 0.312 |
| 659168 | 5252564 | 68.28 | 1.067 | 13.15 | 5.54 | 0.092 | 1.18 | 3.04 | 3.89 | 2.67 | 0.205 |
| 656823 | 5252521 | 58.63 | 0.973 | 13.80 | 6.44 | 0.094 | 1.52 | 2.86 | 3.49 | 2.43 | 0.176 |
| 703063 | 5282475 | 64.06 | 1.040 | 13.98 | 5.98 | 0.092 | 2.08 | 3.49 | 3.78 | 2.81 | 0.219 |
| 712591 | 5314065 | 59.15 | 1.240 | 12.72 | 7.15 | 0.099 | 1.26 | 2.49 | 3.26 | 2.58 | 0.276 |
| 714654 | 5316685 | 68.37 | 0.822 | 13.42 | 4.31 | 0.068 | 0.84 | 2.47 | 3.92 | 2.94 | 0.195 |
| 682307 | 5283233 | 58.27 | 3.152 | 12.59 | 12.87 | 0.192 | 1.54 | 3.01 | 3.47 | 2.68 | 0.224 |
| 682060 | 5283220 | 51.17 | 1.207 | 14.80 | 8.37 | 0.126 | 1.04 | 2.83 | 3.19 | 2.24 | 0.770 |
| 682110 | 5283193 | 61.82 | 0.946 | 15.11 | 5.88 | 0.099 | 1.32 | 3.11 | 3.83 | 2.73 | 0.373 |
| 682102 | 5283145 | 62.48 | 0.960 | 14.80 | 6.18 | 0.093 | 1.33 | 3.29 | 3.90 | 2.79 | 0.310 |
| 678904 | 5278491 | 61.78 | 1.239 | 14.29 | 6.84 | 0.096 | 1.28 | 3.01 | 4.05 | 3.22 | 0.324 |
| 678896 | 5278509 | 65.52 | 0.912 | 14.46 | 5.36 | 0.091 | 1.28 | 3.29 | 4.34 | 3.44 | 0.317 |
| 667632 | 5259781 | 65.10 | 0.809 | 15.15 | 5.01 | 0.081 | 1.35 | 3.51 | 4.53 | 2.96 | 0.287 |
| 667676 | 5259883 | 73.45 | 0.284 | 13.29 | 2.23 | 0.047 | 0.56 | 1.76 | 3.92 | 3.86 | 0.070 |
| 669249 | 5258899 | 66.19 | 0.734 | 15.63 | 4.03 | 0.061 | 0.90 | 3.30 | 4.30 | 3.09 | 0.150 |
| 663851 | 5259800 | 67.05 | 0.814 | 13.83 | 5.28 | 0.084 | 1.40 | 3.52 | 4.10 | 2.20 | 0.219 |
| 666607 | 5263801 | 66.93 | 1.084 | 13.66 | 5.78 | 0.103 | 1.47 | 3.55 | 4.23 | 2.43 | 0.268 |
| 666539 | 5263727 | 65.16 | 0.718 | 14.94 | 4.73 | 0.091 | 1.32 | 3.53 | 4.52 | 2.83 | 0.298 |
| 666436 | 5263789 | 53.77 | 0.894 | 15.08 | 6.71 | 0.097 | 1.17 | 2.78 | 3.53 | 2.26 | 0.347 |
| 663746 | 5258761 | 61.43 | 0.768 | 13.28 | 6.78 | 0.075 | 1.18 | 2.99 | 3.70 | 2.35 | 0.248 |
| 663746 | 5258708 | 69.67 | 0.630 | 13.64 | 3.39 | 0.066 | 1.29 | 3.28 | 4.10 | 2.44 | 0.173 |

Table C.2: Total elemental chemistry of the Saskatchewan BC horizons determined from digests of soil-lithium tetraborate fused beads with subsequent analysis using atomic aborption / emission. Values are mg/g.

| Easting | Northing | Ca | Mg | Na | K | Fe | Al | $PO_4$ |
|---|---|---|---|---|---|---|---|---|
| 514367 | 5830515 | 5.3 | 6.4 | 10.0 | 17.1 | 26.3 | 44.2 | 0.168 |
| 514236 | 5826672 | 54.7 | 10.8 | 8.9 | 14.1 | 17.8 | 33.3 | 0.141 |
| 516766 | 5832125 | 21.8 | 11.1 | 10.1 | 15.3 | 17.7 | 37.3 | 0.169 |
| 542819 | 5890542 | 5.5 | 2.7 | 11.8 | 15.2 | 12.1 | 35.9 | 0.000 |
| 549302 | 5900417 | 12.9 | 2.7 | 10.9 | 13.9 | 12.0 | 29.4 | 0.000 |
| 531317 | 5835262 | 53.6 | 16.4 | 9.7 | 14.1 | 19.1 | 28.7 | 0.125 |
| 528494 | 5836540 | 7.4 | 4.8 | 10.8 | 17.3 | 21.0 | 41.9 | 0.016 |
| 522383 | 5827203 | 5.7 | 5.8 | 11.1 | 19.7 | 26.0 | 46.6 | 0.000 |
| 527073 | 5825684 | 67.3 | 21.1 | 11.6 | 17.8 | 18.9 | 37.9 | 0.144 |
| 527135 | 5825754 | 22.4 | 12.4 | 10.4 | 19.3 | 34.4 | 47.7 | 0.117 |
| 529177 | 5890410 | 7.5 | 3.7 | 11.8 | 17.2 | 16.6 | 43.7 | 0.118 |
| 529180 | 5890482 | 4.7 | 3.9 | 11.3 | 17.2 | 19.3 | 42.5 | 0.191 |
| 528877 | 5891449 | 5.0 | 2.7 | 11.8 | 15.7 | 14.3 | 37.4 | 0.046 |
| 528829 | 5891473 | 5.0 | 4.7 | 10.6 | 17.7 | 22.0 | 45.7 | 0.137 |
| 547022 | 5872627 | 19.8 | 11.4 | 7.5 | 18.8 | 29.3 | 54.1 | 0.183 |
| 547315 | 5832164 | 27.9 | 20.8 | 10.8 | 18.1 | 31.1 | 41.2 | 0.257 |
| 573105 | 5851400 | 7.6 | 9.0 | 10.9 | 22.6 | 31.3 | 55.1 | 0.148 |
| 573065 | 5851489 | 8.0 | 9.7 | 11.1 | 23.6 | 36.7 | 59.6 | 0.048 |
| 574876 | 5848115 | 6.2 | 7.7 | 9.9 | 20.5 | 31.4 | 57.3 | 0.076 |
| 574947 | 5848125 | 6.7 | 8.5 | 10.6 | 22.5 | 33.5 | 57.7 | 0.104 |
| 592409 | 5909753 | 28.6 | 6.6 | 12.5 | 14.3 | 8.9 | 31.3 | 0.069 |
| 592319 | 5909723 | 7.4 | 2.3 | 14.0 | 16.7 | 11.6 | 40.4 | 0.000 |
| 527709 | 5839198 | 6.5 | 2.9 | 14.1 | 18.2 | 17.6 | 41.8 | 0.133 |
| 527770 | 5839267 | 8.4 | 6.7 | 13.4 | 21.4 | 32.4 | 48.5 | 0.499 |
| 527754 | 5839576 | 12.3 | 7.6 | 13.1 | 20.7 | 25.3 | 49.7 | 0.116 |
| 527745 | 5839479 | 7.9 | 7.8 | 10.4 | 21.8 | 31.8 | 56.2 | 0.000 |
| 533439 | 5832105 | 25.4 | 10.2 | 11.4 | 16.3 | 20.3 | 38.1 | 0.035 |
| 540322 | 5822637 | 69.4 | 23.8 | 8.8 | 15.6 | 22.3 | 33.9 | 0.163 |
| 540394 | 5822659 | 11.3 | 8.4 | 12.3 | 18.3 | 27.5 | 46.6 | 0.036 |
| 604284 | 5925457 | 91.7 | 29.6 | 13.2 | 14.6 | 18.3 | 35.4 | 0.109 |
| 604270 | 5925438 | 27.7 | 23.5 | 11.1 | 21.6 | 30.4 | 55.2 | 0.155 |
| 604287 | 5925591 | 96.7 | 29.5 | 14.5 | 15.9 | 25.6 | 36.2 | 0.119 |
| 604296 | 5925413 | 34.8 | 27.6 | 12.6 | 20.8 | 30.2 | 53.8 | 0.156 |
| 602550 | 5920422 | 67.8 | 37.6 | 13.8 | 16.9 | 20.0 | 37.5 | 0.065 |
| 602524 | 5920465 | 66.8 | 37.4 | 13.9 | 17.9 | 21.9 | 40.1 | 0.111 |
| 604429 | 5915102 | 20.3 | 18.7 | 7.4 | 22.2 | 38.4 | 62.2 | 0.193 |
| 604448 | 5915149 | 17.8 | 16.6 | 10.5 | 20.9 | 32.6 | 55.5 | 0.185 |
| 595245 | 5833038 | 6.2 | 3.0 | 13.0 | 16.6 | 14.2 | 35.1 | 0.000 |
| 595205 | 5833128 | 10.2 | 6.2 | 13.8 | 17.3 | 22.5 | 37.7 | 0.122 |
| 594485 | 5832932 | 5.8 | 2.7 | 12.2 | 15.7 | 13.5 | 34.6 | 0.000 |
| 594445 | 5832929 | 4.7 | 9.2 | 7.2 | 21.0 | 32.8 | 57.5 | 0.068 |
| 587245 | 5874785 | 7.4 | 7.4 | 11.1 | 20.4 | 29.2 | 48.1 | 0.050 |
| 587286 | 5874774 | 14.7 | 10.6 | 11.1 | 16.4 | 24.8 | 40.2 | 0.041 |
| 588018 | 5886986 | 8.3 | 11.7 | 5.7 | 23.7 | 40.8 | 65.4 | 0.279 |
| 588021 | 5886958 | 5.3 | 11.1 | 5.8 | 23.2 | 41.3 | 69.2 | 0.270 |
| 575371 | 5861690 | 4.8 | 13.8 | 5.6 | 24.0 | 45.6 | 74.0 | 0.152 |
| 575366 | 5861766 | 6.1 | 10.7 | 7.8 | 23.9 | 37.7 | 66.5 | 0.134 |
| 608444 | 5832126 | 9.0 | 8.5 | 12.5 | 19.3 | 30.0 | 47.7 | 0.007 |
| 608418 | 5832081 | 5.4 | 3.4 | 12.2 | 16.6 | 17.1 | 37.4 | 0.099 |
| 605104 | 5834339 | 6.0 | 5.8 | 12.4 | 20.3 | 28.7 | 49.3 | 0.081 |

Table C.3: Elemental composition of the A horizons for the Alberta site quality study determined from XRF analysis. Values are in per cent.

| Plot | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1-a | 81.78 | 0.404 | 6.52 | 1.58 | 0.078 | 0.44 | 0.77 | 1.16 | 1.50 | 0.099 |
| 1-b | 86.20 | 0.274 | 4.48 | 1.15 | 0.044 | 0.33 | 0.60 | 1.19 | 1.09 | 0.087 |
| 1-c | 81.19 | 0.383 | 6.38 | 1.81 | 0.059 | 0.49 | 0.85 | 1.49 | 1.43 | 0.101 |
| 1-d | 83.78 | 0.355 | 5.59 | 1.44 | 0.074 | 0.39 | 0.70 | 1.01 | 1.23 | 0.097 |
| 1-e | 86.80 | 0.260 | 4.30 | 1.03 | 0.047 | 0.28 | 0.58 | 0.82 | 0.98 | 0.094 |
| 1-f | 82.23 | 0.410 | 6.21 | 1.26 | 0.031 | 0.41 | 0.75 | 1.10 | 1.48 | 0.108 |
| 2-a | 78.61 | 0.517 | 7.36 | 2.26 | 0.121 | 0.55 | 0.59 | 0.98 | 1.53 | 0.135 |
| 2-b | 78.79 | 0.562 | 7.46 | 2.48 | 0.140 | 0.56 | 0.56 | 0.97 | 1.50 | 0.134 |
| 2-c | 77.76 | 0.558 | 7.66 | 2.44 | 0.110 | 0.56 | 0.59 | 1.00 | 1.57 | 0.148 |
| 2-d | 75.51 | 0.564 | 8.40 | 2.75 | 0.154 | 0.69 | 0.74 | 0.90 | 1.69 | 0.198 |
| 2-e | 77.37 | 0.529 | 7.80 | 2.51 | 0.125 | 0.60 | 0.64 | 1.04 | 1.65 | 0.172 |
| 2-f | 78.17 | 0.566 | 7.96 | 2.45 | 0.134 | 0.63 | 0.63 | 0.99 | 1.65 | 0.144 |
| 3-a | 81.09 | 0.464 | 7.32 | 1.96 | 0.103 | 0.48 | 0.70 | 1.23 | 1.58 | 0.158 |
| 3-b | 77.27 | 0.552 | 8.68 | 2.39 | 0.049 | 0.59 | 0.70 | 1.22 | 1.85 | 0.414 |
| 3-c | 81.53 | 0.408 | 6.93 | 1.94 | 0.073 | 0.46 | 0.73 | 1.16 | 1.52 | 0.125 |
| 3-d | 81.38 | 0.415 | 6.94 | 1.99 | 0.073 | 0.46 | 0.70 | 1.15 | 1.52 | 0.172 |
| 3-e | 82.17 | 0.391 | 6.91 | 1.80 | 0.071 | 0.44 | 0.69 | 1.19 | 1.55 | 0.120 |
| 3-f | 78.03 | 0.501 | 8.40 | 2.55 | 0.086 | 0.60 | 0.70 | 1.20 | 1.71 | 0.206 |
| 4-a | 80.65 | 0.567 | 6.96 | 2.06 | 0.152 | 0.47 | 0.71 | 1.06 | 1.63 | 0.238 |
| 4-b | 81.57 | 0.577 | 6.79 | 1.87 | 0.105 | 0.45 | 0.64 | 1.07 | 1.62 | 0.152 |
| 4-c | 82.33 | 0.578 | 6.83 | 1.77 | 0.094 | 0.46 | 0.65 | 1.07 | 1.61 | 0.128 |
| 4-d | 81.84 | 0.575 | 6.79 | 1.65 | 0.073 | 0.45 | 0.66 | 1.07 | 1.61 | 0.142 |
| 4-e | 81.14 | 0.538 | 6.91 | 2.35 | 0.082 | 0.49 | 0.68 | 1.34 | 1.57 | 0.120 |
| 4-f | 82.79 | 0.562 | 6.70 | 1.74 | 0.074 | 0.44 | 0.59 | 1.03 | 1.52 | 0.099 |
| 5-a | 77.54 | 0.421 | 7.62 | 2.68 | 0.072 | 0.57 | 0.94 | 1.46 | 1.57 | 0.127 |
| 5-b | 79.35 | 0.428 | 7.58 | 2.54 | 0.072 | 0.53 | 0.83 | 1.47 | 1.58 | 0.124 |
| 5-c | 70.00 | 0.206 | 5.61 | 1.85 | 0.096 | 0.53 | 5.68 | 1.26 | 1.23 | 0.149 |
| 5-d | 79.11 | 0.411 | 8.55 | 2.83 | 0.052 | 0.68 | 0.79 | 1.37 | 1.66 | 0.091 |
| 5-e | 82.54 | 0.343 | 6.50 | 2.01 | 0.076 | 0.41 | 0.74 | 1.46 | 1.51 | 0.141 |
| 5-f | 79.23 | 0.444 | 7.28 | 2.38 | 0.089 | 0.50 | 0.87 | 1.53 | 1.57 | 0.122 |
| 6-a | 78.56 | 0.538 | 7.98 | 2.62 | 0.069 | 0.60 | 0.64 | 1.43 | 1.59 | 0.093 |
| 6-b | 76.63 | 0.492 | 8.40 | 2.91 | 0.046 | 0.71 | 0.76 | 1.37 | 1.55 | 0.083 |
| 6-c | 72.56 | 0.496 | 8.72 | 3.04 | 0.068 | 0.73 | 1.04 | 1.41 | 1.50 | 0.110 |
| 6-d | 79.06 | 0.499 | 7.72 | 2.65 | 0.058 | 0.58 | 0.66 | 1.40 | 1.57 | 0.103 |
| 6-e | 76.97 | 0.463 | 7.44 | 2.41 | 0.040 | 0.51 | 0.76 | 1.40 | 1.50 | 0.124 |

Table C.4: Elemental composition of the B horizons for the Alberta site quality study determined from XRF analysis. Values are in per cent.

| Plot | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1-a | 76.91 | 0.398 | 9.71 | 3.05 | 0.031 | 0.84 | 0.77 | 1.32 | 1.75 | 0.070 |
| 1-b | 92.83 | 0.132 | 2.97 | 0.67 | 0.007 | 0.23 | 0.42 | 0.98 | 0.75 | 0.060 |
| 1-c | 80.98 | 0.335 | 7.80 | 2.82 | 0.039 | 0.78 | 0.70 | 0.80 | 1.48 | 0.061 |
| 1-d | 86.41 | 0.385 | 6.21 | 1.46 | 0.025 | 0.42 | 0.66 | 1.21 | 1.46 | 0.070 |
| 1-e | 93.23 | 0.128 | 2.87 | 0.70 | 0.010 | 0.21 | 0.39 | 0.92 | 0.71 | 0.057 |
| 1-f | 91.40 | 0.198 | 3.74 | 0.89 | 0.016 | 0.26 | 0.47 | 1.10 | 0.95 | 0.056 |
| 2-a | 66.20 | 0.649 | 13.91 | 5.05 | 0.017 | 1.34 | 0.35 | 0.85 | 1.86 | 0.116 |
| 2-b | 67.02 | 0.623 | 13.40 | 5.29 | 0.021 | 1.32 | 0.39 | 0.55 | 1.86 | 0.119 |
| 2-c | 69.08 | 0.622 | 12.91 | 4.73 | 0.019 | 1.21 | 0.35 | 0.56 | 1.84 | 0.103 |
| 2-d | 66.78 | 0.689 | 13.81 | 4.70 | 0.013 | 1.29 | 0.40 | 0.77 | 2.23 | 0.123 |
| 2-e | 78.26 | 0.468 | 8.74 | 3.86 | 0.050 | 0.85 | 0.57 | 0.74 | 1.47 | 0.108 |
| 2-f | 68.63 | 0.686 | 13.51 | 4.41 | 0.013 | 1.32 | 0.41 | 0.78 | 2.03 | 0.114 |
| 3-a | 79.30 | 0.395 | 8.87 | 2.94 | 0.037 | 0.73 | 0.75 | 1.38 | 1.60 | 0.096 |
| 3-b | 81.10 | 0.381 | 8.18 | 2.74 | 0.044 | 0.66 | 0.72 | 1.07 | 1.61 | 0.161 |
| 3-c | 78.54 | 0.517 | 9.41 | 3.02 | 0.093 | 0.75 | 0.68 | 1.15 | 1.85 | 0.117 |
| 3-d | 79.72 | 0.396 | 8.55 | 3.07 | 0.033 | 0.72 | 0.74 | 1.34 | 1.60 | 0.103 |
| 3-e | 79.68 | 0.378 | 8.78 | 3.00 | 0.031 | 0.71 | 0.72 | 1.01 | 1.49 | 0.079 |
| 3-f | 77.20 | 0.472 | 9.66 | 3.41 | 0.046 | 0.80 | 0.68 | 1.16 | 1.73 | 0.139 |
| 4-a | 78.42 | 0.447 | 8.77 | 3.31 | 0.035 | 0.82 | 0.59 | 1.06 | 1.50 | 0.084 |
| 4-b | 83.78 | 0.350 | 6.82 | 2.54 | 0.028 | 0.58 | 0.50 | 1.09 | 1.27 | 0.067 |
| 4-c | 76.45 | 0.441 | 9.44 | 3.79 | 0.036 | 0.91 | 0.56 | 0.70 | 1.44 | 0.075 |
| 4-d | 75.57 | 0.412 | 9.59 | 4.58 | 0.092 | 1.00 | 0.74 | 0.97 | 1.36 | 0.096 |
| 4-e | 75.55 | 0.536 | 9.88 | 3.77 | 0.030 | 0.87 | 0.72 | 0.86 | 1.72 | 0.101 |
| 4-f | 77.58 | 0.425 | 9.37 | 3.19 | 0.020 | 0.81 | 0.56 | 0.65 | 1.43 | 0.072 |
| 5-a | 84.04 | 0.309 | 7.11 | 2.11 | 0.022 | 0.49 | 0.75 | 1.52 | 1.48 | 0.090 |
| 5-b | 82.16 | 0.346 | 7.77 | 2.52 | 0.030 | 0.58 | 0.77 | 1.46 | 1.51 | 0.116 |
| 5-c | 84.77 | 0.239 | 6.58 | 2.00 | 0.025 | 0.46 | 0.78 | 1.53 | 1.46 | 0.058 |
| 5-d | 76.29 | 0.439 | 10.05 | 3.57 | 0.043 | 0.93 | 0.82 | 1.60 | 1.78 | 0.081 |
| 5-e | 87.08 | 0.133 | 5.78 | 1.76 | 0.028 | 0.32 | 0.60 | 1.51 | 1.53 | 0.090 |
| 5-f | 85.56 | 0.257 | 6.33 | 2.04 | 0.020 | 0.46 | 0.63 | 1.31 | 1.30 | 0.097 |
| 6-a | 67.67 | 0.721 | 12.93 | 5.34 | 0.057 | 1.32 | 0.79 | 1.04 | 1.69 | 0.094 |
| 6-b | 72.13 | 0.496 | 11.14 | 4.27 | 0.044 | 1.18 | 0.79 | 1.36 | 1.58 | 0.099 |
| 6-c | 75.29 | 0.480 | 10.19 | 3.70 | 0.056 | 1.00 | 0.92 | 1.39 | 1.69 | 0.097 |
| 6-d | 73.02 | 0.488 | 10.76 | 3.97 | 0.039 | 1.01 | 0.81 | 1.35 | 1.59 | 0.105 |
| 6-e | 85.31 | 0.245 | 6.48 | 1.80 | 0.024 | 0.47 | 0.60 | 1.48 | 1.34 | 0.093 |

Table C.5: Elemental composition of the C horizons for the Alberta site quality study determined using XRF analysis. Values are in per cent.

| Plot | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1-a | 92.69 | 0.145 | 3.16 | 0.71 | 0.014 | 0.22 | 0.40 | 0.99 | 0.82 | 0.039 |
| 1-b | 87.73 | 0.222 | 4.97 | 1.66 | 0.024 | 0.51 | 0.52 | 0.94 | 1.07 | 0.047 |
| 1-c | 81.35 | 0.326 | 7.55 | 2.62 | 0.029 | 0.73 | 0.72 | 1.14 | 1.40 | 0.069 |
| 1-d | 90.57 | 0.183 | 4.00 | 1.06 | 0.019 | 0.34 | 0.45 | 1.04 | 0.96 | 0.044 |
| 1-e | 91.75 | 0.166 | 3.50 | 0.87 | 0.011 | 0.29 | 0.42 | 0.94 | 0.92 | 0.045 |
| 1-f | 77.94 | 0.409 | 9.36 | 3.32 | 0.041 | 0.88 | 0.70 | 0.87 | 1.71 | 0.075 |
| 2-a | 67.65 | 0.628 | 13.15 | 5.78 | 0.027 | 1.28 | 0.52 | 0.60 | 1.94 | 0.211 |
| 2-b | 70.39 | 0.586 | 12.62 | 4.61 | 0.039 | 1.28 | 0.49 | 0.62 | 1.91 | 0.157 |
| 2-c | 69.67 | 0.592 | 12.40 | 5.02 | 0.017 | 1.21 | 0.39 | 0.57 | 1.79 | 0.137 |
| 2-d | 69.87 | 0.616 | 12.84 | 4.59 | 0.017 | 1.20 | 0.49 | 0.63 | 2.01 | 0.142 |
| 2-e | 70.06 | 0.594 | 12.64 | 4.58 | 0.032 | 1.26 | 0.61 | 0.60 | 1.86 | 0.144 |
| 2-f | 67.18 | 0.701 | 13.63 | 4.95 | 0.012 | 1.34 | 0.35 | 0.83 | 2.04 | 0.139 |
| 3-a | 78.59 | 0.417 | 9.07 | 3.10 | 0.043 | 0.75 | 0.79 | 1.16 | 1.61 | 0.102 |
| 3-b | 81.07 | 0.375 | 8.16 | 2.64 | 0.041 | 0.63 | 0.72 | 1.14 | 1.68 | 0.124 |
| 3-c | 84.28 | 0.325 | 6.51 | 2.49 | 0.041 | 0.50 | 0.66 | 1.42 | 1.34 | 0.079 |
| 3-d | 81.52 | 0.378 | 7.90 | 2.76 | 0.037 | 0.66 | 0.73 | 1.38 | 1.54 | 0.091 |
| 3-e | 79.78 | 0.377 | 8.40 | 2.92 | 0.035 | 0.68 | 0.75 | 1.10 | 1.50 | 0.092 |
| 3-f | 90.49 | 0.150 | 4.18 | 1.08 | 0.018 | 0.25 | 0.45 | 1.19 | 1.05 | 0.057 |
| 4-a | 80.12 | 0.421 | 8.40 | 3.28 | 0.042 | 0.79 | 0.63 | 1.11 | 1.46 | 0.083 |
| 4-b | 79.39 | 0.435 | 8.66 | 3.31 | 0.050 | 0.83 | 0.62 | 1.07 | 1.43 | 0.073 |
| 4-c | 78.00 | 0.440 | 9.12 | 3.65 | 0.026 | 0.89 | 0.61 | 1.09 | 1.40 | 0.076 |
| 4-d | 79.67 | 0.405 | 8.45 | 3.32 | 0.026 | 0.78 | 0.51 | 1.07 | 1.36 | 0.080 |
| 4-e | 81.82 | 0.341 | 7.23 | 3.57 | 0.033 | 0.62 | 0.69 | 1.28 | 1.39 | 0.101 |
| 4-f | 78.85 | 0.431 | 8.87 | 3.35 | 0.039 | 0.78 | 0.65 | 1.20 | 1.49 | 0.103 |
| 5-a | 77.39 | 0.467 | 9.67 | 3.52 | 0.045 | 0.94 | 0.78 | 1.20 | 1.79 | 0.091 |
| 5-b | 83.36 | 0.322 | 7.34 | 2.30 | 0.040 | 0.55 | 0.80 | 1.57 | 1.51 | 0.115 |
| 5-c | 84.92 | 0.185 | 6.97 | 1.89 | 0.022 | 0.49 | 0.98 | 1.91 | 1.51 | 0.077 |
| 5-d | 82.39 | 0.305 | 7.61 | 2.59 | 0.033 | 0.63 | 0.70 | 1.33 | 1.46 | 0.066 |
| 5-e | 78.88 | 0.434 | 9.20 | 3.16 | 0.039 | 0.80 | 0.81 | 1.43 | 1.81 | 0.120 |
| 5-f | 84.66 | 0.284 | 6.82 | 2.14 | 0.026 | 0.49 | 0.68 | 1.42 | 1.43 | 0.096 |
| 6-a | 61.55 | 0.932 | 15.28 | 5.74 | 0.105 | 1.66 | 1.01 | 1.14 | 2.23 | 0.194 |
| 6-b | 72.76 | 0.509 | 10.10 | 3.70 | 0.050 | 1.34 | 1.57 | 1.41 | 1.66 | 0.143 |
| 6-c | 71.35 | 0.500 | 10.10 | 3.56 | 0.048 | 1.34 | 2.43 | 1.40 | 1.66 | 0.139 |
| 6-d | 75.01 | 0.505 | 10.38 | 3.92 | 0.049 | 0.99 | 0.83 | 1.32 | 1.65 | 0.117 |
| 6-e | 89.93 | 0.164 | 4.32 | 1.53 | 0.021 | 0.28 | 0.44 | 1.15 | 1.03 | 0.060 |

Table C.6: Mineralizable nitrogen values for the Saskatchewan site quality study determined after 28 day incubations. Values are in mg/g.

| Easting | Northing | FH NH$_4$ | FH NO$_3$ | Ah NH$_4$ | Ah NO$_3$ |
|---|---|---|---|---|---|
| 514367 | 5830515 | 3.70 | 10.49 | 1.80 | 4.00 |
| 514236 | 5826672 | 0.97 | 8.28 | 0.37 | 7.19 |
| 516766 | 5832125 | 0.83 | 9.44 | 0.30 | 32.95 |
| 542819 | 5890542 | 0.87 | 7.30 | 0.90 | 6.03 |
| 549302 | 5900417 | 0.15 | 7.75 | 0.18 | 9.68 |
| 531317 | 5835262 | 0.31 | 0.78 | -0.18 | 3.34 |
| 528494 | 5836540 | 0.13 | 4.86 | -0.14 | 4.46 |
| 522383 | 5827203 | 0.15 | 3.38 | 0.41 | 0.71 |
| 527073 | 5825684 | 0.20 | 8.42 | -0.13 | 2.59 |
| 527135 | 5825754 | -0.12 | 8.34 | 0.33 | 3.50 |
| 529177 | 5890410 | -0.14 | 2.92 | 1.40 | 1.95 |
| 529180 | 5890482 | 8.70 | 1.66 | 8.10 | 3.64 |
| 528877 | 5891449 | 0.07 | -0.28 | 2.40 | 0.92 |
| 528829 | 5891473 | 0.30 | 8.26 | 0.00 | 3.20 |
| 547022 | 5872627 | -0.22 | 8.80 | 0.57 | 10.77 |
| 547315 | 5832164 | 0.09 | 8.92 | -0.14 | 5.34 |
| 573105 | 5851400 | 0.60 | 7.02 | -0.09 | 7.06 |
| 573065 | 5851489 | -0.14 | 8.49 | -0.14 | 3.21 |
| 574876 | 5848115 | -0.04 | 9.16 | -0.08 | 3.19 |
| 574947 | 5848125 | -0.05 | 4.71 | -0.14 | 3.01 |
| 592409 | 5909753 | -0.08 | 6.72 | -0.06 | 13.26 |
| 592319 | 5909723 | 0.91 | 2.83 | 0.70 | 1.09 |
| 527709 | 5839198 | -0.06 | 4.24 | -0.06 | 4.26 |
| 527770 | 5839267 | -0.26 | 5.12 | -0.09 | 7.60 |
| 527754 | 5839576 | 0.00 | 1.00 | 0.95 | 5.57 |
| 527745 | 5839479 | -0.02 | 0.45 | 0.10 | 3.03 |
| 533439 | 5832105 | 0.07 | 4.84 | -0.16 | 5.66 |
| 540322 | 5822637 | 0.01 | 5.15 | -0.10 | 3.76 |
| 540394 | 5822659 | -0.16 | 2.16 | 0.66 | 13.51 |
| 604284 | 5925457 | -0.15 | 0.93 | 0.25 | 0.16 |
| 604270 | 5925438 | 0.11 | 6.76 | -0.11 | 3.63 |
| 604287 | 5925591 | 0.36 | 0.59 | -0.06 | 3.09 |
| 604296 | 5925413 | 4.90 | -0.52 | 0.24 | -0.62 |
| 602550 | 5920422 | 0.02 | 4.93 | -0.06 | 1.98 |
| 602524 | 5920465 | -0.01 | 1.78 | 0.14 | 1.81 |
| 604429 | 5915102 | -0.07 | 2.28 | 0.06 | 2.64 |
| 604448 | 5915149 | -0.02 | 3.26 | 0.02 | 1.55 |
| 595245 | 5833038 | 0.24 | 4.24 | 2.40 | 0.28 |
| 595205 | 5833128 | -0.03 | -0.11 | 0.94 | 1.53 |
| 594485 | 5832932 | 2.40 | 6.58 | 1.00 | 2.32 |
| 594445 | 5832929 | 0.40 | 8.14 | 0.56 | 2.51 |
| 587245 | 5874785 | 1.30 | 8.28 | 1.20 | 4.76 |
| 587286 | 5874774 | 0.36 | 6.73 | 1.20 | 0.63 |
| 588018 | 5886986 | -0.20 | 5.62 | -0.01 | 1.43 |
| 588021 | 5886958 | -0.05 | 4.88 | 0.14 | 0.71 |
| 575371 | 5861690 | -0.19 | 9.10 | 0.06 | 6.34 |
| 575366 | 5861766 | -0.20 | 0.59 | 0.03 | 3.18 |
| 608444 | 5832126 | -0.16 | -0.33 | 0.00 | 2.62 |
| 608418 | 5832081 | -0.07 | 2.63 | 0.24 | 2.49 |
| 605104 | 5834339 | -0.17 | 3.02 | 1.30 | 0.14 |

Table C.7: Mineralizable nitrogen values for the Quebec site quality study determined after 28 day incubations. Values are in mg/g.

| Easting | Northing | FH NH4 | FH NO3 | Bf1 NH4 | Bf1 NO3 |
|---|---|---|---|---|---|
| 714691 | 5316629 | 19.0 | -0.15 | 2.30 | -0.09 |
| 669895 | 5288252 | 11.0 | -0.19 | 0.61 | -0.11 |
| 669856 | 5288238 | 0.6 | 2.35 | 0.35 | -0.11 |
| 669919 | 5288247 | 4.1 | -0.16 | 1.80 | -0.10 |
| 669945 | 5288257 | 11.0 | -0.17 | 1.80 | -0.09 |
| 658840 | 5290456 | 0.1 | 1.72 | 0.38 | 2.70 |
| 658887 | 5290463 | 4.1 | 1.83 | 4.10 | 0.01 |
| 656831 | 5288839 | 0.5 | 8.02 | 6.50 | 0.45 |
| 659016 | 5291395 | 0.1 | -0.10 | 1.10 | -0.08 |
| 659027 | 5291366 | 2.7 | -0.14 | 2.60 | -0.04 |
| 661853 | 5287849 | 13.0 | -0.10 | 0.67 | 2.91 |
| 661875 | 5287889 | 12.0 | -0.16 | 3.30 | 0.66 |
| 661949 | 5287942 | 20.0 | -0.11 | 6.60 | 1.06 |
| 618717 | 5282208 | 13.0 | -0.18 | 0.74 | -0.08 |
| 618986 | 5282560 | 17.0 | -0.15 | 2.30 | -0.11 |
| 711590 | 5290092 | 13.0 | -0.15 | 3.90 | -0.14 |
| 711649 | 5289952 | 13.0 | -0.16 | 7.30 | -0.08 |
| 708923 | 5286355 | 21.0 | -0.15 | 5.90 | 0.22 |
| 708938 | 5286338 | 15.0 | -0.16 | 6.20 | 0.19 |
| 715532 | 5317094 | 13.0 | -0.16 | 3.20 | -0.09 |
| 715508 | 5317077 | 8.10 | -0.14 | 0.97 | -0.08 |
| 714641 | 5316692 | 9.20 | -0.18 | 8.30 | 0.04 |
| 714660 | 5316829 | 24.0 | -0.17 | 4.00 | 0.04 |
| 662860 | 5283282 | 37.0 | -0.15 | 3.00 | 0.16 |
| 662799 | 5283318 | 23.0 | -0.15 | 7.80 | -0.10 |
| 663806 | 5283796 | 22.0 | -0.15 | 7.40 | -0.08 |
| 663845 | 5283860 | 27.0 | -0.72 | 3.80 | -0.07 |
| 679487 | 5281389 | 3.8 | 6.78 | 3.00 | -0.05 |
| 679589 | 5281171 | 13.0 | -0.34 | 1.90 | -0.08 |
| 659311 | 5252582 | 9.0 | -0.57 | 4.90 | 0.06 |
| 659168 | 5252564 | 12.0 | -0.60 | 4.10 | 0.12 |
| 656823 | 5252521 | 11.0 | -0.60 | 6.80 | 0.22 |
| 703063 | 5282475 | 15.0 | -0.61 | 1.60 | -0.09 |
| 712591 | 5314065 | 19.0 | -0.61 | 2.20 | 3.45 |
| 714654 | 5316685 | 20.0 | -0.63 | 5.80 | -0.08 |
| 682307 | 5283233 | 3.6 | -0.63 | 2.80 | 0.04 |
| 682060 | 5283220 | 16.0 | -0.63 | 7.60 | -0.02 |
| 682110 | 5283193 | 5.5 | -0.64 | 6.20 | -0.08 |
| 682102 | 5283145 | 8.9 | -0.64 | 4.00 | -0.07 |
| 678904 | 5278491 | 9.1 | 0.38 | 5.30 | 0.13 |
| 678896 | 5278509 | 17.0 | -0.63 | 3.30 | 0.05 |
| 667632 | 5259781 | 7.1 | -0.63 | 1.50 | 0.00 |
| 667676 | 5259883 | 3.7 | -0.61 | 0.39 | 1.05 |
| 669249 | 5258899 | 6.7 | -0.64 | 2.40 | -0.02 |
| 663851 | 5259800 | 13.0 | -0.59 | 3.30 | 0.02 |
| 666607 | 5263801 | 2.1 | -0.63 | 3.10 | 0.08 |
| 666539 | 5263727 | 2.3 | 7.57 | 2.60 | 0.97 |
| 666436 | 5263789 | 1.4 | -0.32 | 5.30 | 0.22 |
| 663746 | 5258761 | 21.0 | -0.50 | 3.50 | 0.07 |
| 663746 | 5258708 | 29.0 | -0.59 | 2.40 | 0.00 |