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**EFFECTS OF EDAPHIC CONDITIONS ON SITE QUALITY
FOR *SALIX PURPUREA* 'HOTEL' PLANTATIONS ACROSS A
LARGE CLIMATIC GRADIENT IN CANADA**

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Abstract

Willow has been identified as a possible species for supplying large quantities of biomass for bioenergy and wood fibers in Canada. However, before site selection occurs, there is a need to know how the soils and climate of the prairies and central regions affect willow productivity. Soil, foliar, and climatic variables were therefore measured along with yields at nine “first rotation” *Salix purpurea* ‘Hotel’ plantations from central Alberta to southern Ontario. Correlation analysis was used to identify those parameters having the most influence on yields. Relationships between soil and climate and growth were established by regression analysis. The acid-base status of the soil as dictated by bulk elemental composition, in particular the presence of Ca, was found to be the dominant factor affecting productivity ($r^2 = 0.967$, $P < 0.001$ total Ca vs. yields) despite large regional differences in climate. From a nutritional standpoint, total soil N ($r = 0.743$, $P < 0.048$) and foliar K ($r^2 = 0.938$, $P < 0.009$ for sites with adequate moisture) were positively correlated with growth. *S. purpurea* ‘Hotel’ yields were found to be primarily limited by water availability at the two lowest productivity prairie sites. Soil total Ca concentration, pH and total organic C concentration were all generally correlated with higher yields. Additional deficiencies appeared in the following order of importance: water > N and K > Mg. As a whole, soil properties were the dominant predictors of ‘Hotel’ growth in this study, which suggests that, even at the regional scale, growth was governed in large part by the capacity of soils to retain water and/or nutrients. Climate played a lesser role, except perhaps at two sites which appeared to receive inadequate moisture.

Keywords: Biomass energy; Short rotation intensive culture; Fast growth; Yields; Soil nutrient availability; Foliar nutrition; Calcium; Nitrogen; Potassium.

Introduction

There is expanding interest in the use of fast growing tree species for both wood fiber and fuel. Using fast growing species in dedicated plantations reduces pressures on natural forests and can substantially reduce transportation costs. The Canadian prairies could provide an extensive land base for growing trees in a plantation setting. However, there are challenges for tree growth as this region is characterized by short and dry growing seasons and harsh cold winters (Padbury et al. 2002). As such, native tree growth is often limited to depressions, north facing slopes and more northern regions where evapotranspiration rates are decreased by cooler temperatures (Richards and Fung 1969; Padbury et al. 2002).

Despite being water demanding, *Populus* and *Salix* can return economically viable yields under various environmental conditions and plantation designs (Cardias Williams and Thomas 2006; Devine et al. 2010; Cao et al. 2011; Nelson et al. 2012). *Populus* and *Salix* spp. have been widely used in the Canadian prairies in shelterbelts to prevent soil erosion and conserve soil moisture (Schroeder 1988) and have been identified as having reasonable juvenile plantation yields despite the unfavorable conditions (DesRochers and Thomas 2003; Pinno et al. 2010).. Tree yields are greater in British Columbia, Ontario and Quebec than in the prairie provinces, but the prairies offer a larger and less expensive land base (McKenney et al. 2004). *Salix* spp. (later referred to as 'willow' for simplicity) are relatively new to agroforestry use in Canada but they do offer some advantages. For one, there is tremendous natural diversity of willow, with over 450 species worldwide having been identified (Argus 1997), which provides opportunity for breeding programs, using native species and/or non-native species, to tailor hybrids for specific needs (Kopp et al., 2001a). Willow regrows vegetatively and responds well to coppicing (Volk et al. 2004). Depending on planting and management style, rotation lengths can be short (typically 3–5

years) and the trees will stay vigorous for several rotations (Mitchell et al. 1999; Volk et al. 2004). This addresses the need for producers to recover costs as soon as possible. It also enables a producer to harvest stems damaged by pests and extreme weather and restore vigor to the plant in the process. Thus, willow is well suited to short rotation intensive culture (SRIC) on the Canadian prairies.

If willow is to be planted as SRIC in Canada, then knowledge of how it will respond to varying soil and climate conditions, in terms of productivity, needs to be examined to ensure that plantations are established in appropriate locations and productivity can be maintained well into the future without overuse of irrigation and nutrient amendments that would unnecessarily increase the water and energy demands of the system (Bhardwaj et al. 2011). Site quality index, which is the height of the dominant trees for a given location and management regime at a chosen base age is the most commonly used estimate of productivity in forestry (Ung et al. 2001). For high density willow plantations, this system could be adapted by substituting measures of biomass for height to closer reflect maximum biomass production as the desired outcome. Even so, because plantations are to be established in the context of afforestation, there are no pre-existing willow trees to measure site quality index for most sites before planting. Therefore, it is necessary to examine the underlying soil and climatic factors controlling site productivity for willow grown under a wide range of Canadian soil and climatic conditions. Specific limiting factors must be identified, after which the relationships between these variables and willow growth can be used to assess the quality of a site without directly measuring the traditional site quality index.

Research thus far has concluded that willow grows best in loamy soils with a well developed structure and a rooting depth of 45 cm or more (Abrahamson et al. 2002). Ledin and

Willebrand (1995) concluded that, in general, SRIC requires a soil with a minimum depth of 1 m. Willow has been found to establish slowly on soils with high clay content but it has been suggested that productivity may be greater in these soils in successive rotations (Abrahamson et al. 2002). Clayey soils are difficult to penetrate for young roots but have a much larger exchange capacity, thereby maintaining better nutrition of rapidly growing trees. Excessively well or poorly drained soils or soils with a pH lower than 5.5 or higher than 8.0 have been shown to limit productivity (Mitchell et al. 1999; Abrahamson et al. 2002).

Willow yields in Canada are on average lower than that achieved in the United States and parts of Europe owing in large part to a limited growing season (Mitchell et al. 1999). Moreover, the fast growing nature of willow requires a steady supply of water and nutrients for optimal growth. Although Lindroth and Cienciala (1996) reported a relatively high water use efficiency (WUE) for *S. viminalis* (6.3 g kg^{-1}), a moderate value for annual precipitation on the Canadian prairies of 430 mm would produce a maximum of only $10 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. Thus, the low amount of precipitation in the Canadian prairies has been expected to greatly hinder willow growth such that the importance of fertility is diminished. Additionally, Guidi et al. (2008) concluded that increasing the available nutrients for willow also increases transpiration. In a water limited region, this would translate to underutilization of already limited moisture.

Willow has frequently been shown to respond favorably to fertilization, particularly with N (Adegbidi et al. 2003), both from synthetic and organic amendments (Labrecque et al. 1998). However, when planted on fertile arable land response to fertilizers may be minimal early in the plantation life-cycle (i.e. <10 years) (Mitchell et al. 1999). As such, amendments should be applied only where there is a need and should not be a common prescription for every site. What needs further examination (notably in Canada) is the potential for willow growth given soil and

climatic factors at a variety of sites and an estimate of the ability of these sites to achieve optimal nutrient status before adding amendments.

There are many factors including soil pH and ionic concentrations of other nutrients that affect the ability of a plant to take up essential nutrients. Adebidi et al. (2003) found that although willow initially responded similarly to a single input of either N-fertilizer or organic amendments (sewage sludge or manure), the increase in growth associated with the organic amendments continued over a longer period of time. Maintaining a continual supply of the required nutrients for willow growth depends upon the nutrients present within the soil and its capacity to store and exchange ions and water. Thus, soil C and organic matter are critical for maintaining beneficial soil properties. It is therefore important to examine both the response in willow growth to soil and climate variables as well as how different soils are meeting the nutritional needs of willow by examining foliar nutrient levels.

Simon et al. (1990) described foliar nutrient levels of willow spp. leaves, stems and whole plants grown with no nutrient limitations by employing a nutrient solution maintained at optimum levels for the species. Although there was considerable variation, particularly with N, this does provide a useful reference for willow nutrition at its optimum. Foliar N, P, and K concentrations were respectively 28.4, 1.8, and 19.0 mg g⁻¹ for *S. eriocephala*, 35.4, 2.3 and 22.0 mg g⁻¹ for *S. exigua*, and 28.0, 1.9, and 23.4 mg g⁻¹ of dry weight for *S. lucida*. Similarly, Kopinga and van den Burg (1995) reported optimal foliar nutrient concentrations for willow at N > 22, P > 2.1, K > 19, and Mg > 3.0 mg g⁻¹. These values are much lower than those reported by Cornelissen et al. (1997) who found *S. caprea* to have the highest N (43.0 mg g⁻¹), P (6.53 mg g⁻¹), and K (32.4 mg g⁻¹) foliar concentrations of 34 temperate deciduous and coniferous trees species. The N and K requirements of willow spp. identified by Simon et al. (1990) and Kopinga

and van den Burg (1995) would similarly be at the high end of nutrient levels in Cornelissen et al. (1997) (N ranges from 13.1-32.9 mg g⁻¹ and K from 6.1-21.7 mg g⁻¹ excluding *S. caprea*), though P concentrations were more moderate (1.08-5.71 mg g⁻¹, excluding *S. caprea*). Calcium, which is the final nutrient examined in this study, can exhibit considerable variation in concentrations in leaves with species and with development stages (Jones 1998). The higher demand for nutrients of willow (Simon et al. 1990; Mitchell et al. 1999) compared to many other temperate tree species (Cornelissen et al. 1997; Alriksson and Eriksson 1998) may mean that productivity is controlled more by soils than by climate unlike other temperate species (Post and Curtis 1970; Chen et al. 1998; Ung et al. 2001; Hogg et al. 2005). It is therefore hypothesized that site quality will be dependent primarily on soil factors and that climate will be responsible for less of the variability in production observed between sites. This pattern could be influenced by geographic scale. For example, regional-scale studies (Ung et al. 2001; Hogg et al. 2005), having large climatic gradients, place more importance on the impact of climate on tree growth, whereas local-scale studies (Pinno et al. 2009; Pinno and Bélanger 2011), having small climate gradients, place more emphasis on the effects of soils—in particular those factors that dictate nutrient availability—on tree productivity.

Despite increasing interest in willow as a SRIC crop in the Canadian prairies, there is little available data for determining suitable site quality. The objective was therefore to measure soil and climate variables as well as productivity and nutrition across a broad range of sites in Canada to determine which set of conditions are conducive to greater growth. It was hypothesized that, due to willow's high nutrient demand and the broad range of soil present in Canada, soil, and in particular nutrient status, will be dominant over climate in controlling

willow productivity. In testing this hypothesis, high and low site quality for willow production were characterized.

Materials and Methods

There is a broad range of climate conditions across the Canadian prairies and southern Ontario and as such this was expected to have an impact on willow growth. Included in this study were nine sites following a transect from the northwestern to southeastern boundaries of the Canadian prairies and extending into southern Ontario (Table 1). Much of the climate diversity of the prairie region was included in this study, with the exception of the driest regions of southern Alberta and Saskatchewan. As a generalization, there are longer and warmer growing seasons and more precipitation towards the southeast. At the northern bounds of the Canadian prairies, evapotranspiration decreases and in turn so does the water deficit, leading to the growth of native forests despite only modest gains in precipitation compared to the southern prairies.

Climate data for the years in which the trees grew were modeled using the BioSIM model (Régnière 1996), which typically yields a coefficient >0.98 between measured and modeled values (Régnière and Bolstad 1994). The BioSIM model used real data collected from surrounding Environment Canada weather stations to model site specific conditions where weather stations did not exist. Total annual precipitation, summer precipitation, vapor pressure deficit, potential evapotranspiration and aridity index were all modeled in this way. Degree days were calculated at both the 5°C and 10°C bases from the results of the BioSIM model.

At each site, the 'Hotel' clone of *Salix purpurea* was planted in triple rows with 60 cm spacing between trees and 200 cm between rows. This clone was selected largely for logistical reasons, as planting stock (unrooted cuttings) was readily available. Expected *S. purpurea*

‘Hotel’ yields were moderate to low when compared to other clones bred as bioenergy feedstock. However, this clone has been relatively resistant to cold, herbivore and disease damage. Soil and foliar samples were collected during the third year of the first rotation from five plots at each plantation. Plots were 3.2 m × 1.8 m and contained nine trees according to the original planting as well as a proportional representation of in row and between row area. There were several rows of buffer trees of *S. purpurea* ‘Hotel’ around each plot.

Soil and leaf samples were collected at all sites. However, two of the nine sites included in this study for nutritional analysis, i.e. ELL and BIR, were coppiced a year before sampling. This left only seven sites that had accumulated three years of growth, which is the general rotation length. GUE had been coppiced after the first year of growth but was allowed to still accumulate biomass for three years afterwards. While coppicing is typically implemented with the purpose of increasing biomass production via promoting branching to form multiple stems, *S. purpurea* ‘Hotel’ branches readily and, as such, there were no strong morphological differences between GUE and other sites. GUE willow did have an advantage in that the root system had an extra year of growth compared to other sites but it was deemed that this difference was within the variability associated with variance in management across the large scale of this study. Thus, for the sake of studying the factors regulating aboveground biomass production, only sites with three years of aboveground biomass accumulation were considered (n=7), whereas all sites (n=9) were included for linking soil fertility to foliar nutrition.

Within each plot, soils were sampled at 0-20 cm and 20-40 cm increments (3 subsamples). Soils were analyzed for total organic C, total N, inorganic N forms (NO₃ and NH₄), bulk elemental composition (e.g. total Ca, total K and total Al), acid leachable P, exchangeable K, Ca, Mg, Na, Fe and Al, pH, sand, silt, and clay. Soil C and N were determined by combustion

at 800°C and infrared detection on a LECO CNS-2000 (LECO Corporation, St. Joseph, MI). Nitrate and NH_4 were extracted using 2.0 M KCl and analyzed on a Technicon Auto-Analyzer (Technicon Instruments Corporation, Tarrytown, NY). Acid leachable P was extracted from the soil with concentrated H_2SO_4 and measured with a SmartChem Instrument (Mandel Scientific Company Inc., Guelph, ON). Exchangeable K, Ca, Mg, Na, Fe, and Al were extracted using a 0.1 M BaCl_2 solution (Hendershot et al. 2007) and analyzed by atomic emission (K, Na) and absorption (Ca, Mg, Fe, Al) (SpectraAA 220, Varian Analytical Instruments). Soil pH was measured in a 2:1 water to soil suspension. Particle size distribution (soil texture) was analyzed on a Horiba Partica LA-950 laser particle analyzer (Horiba Instruments, Irvine, CA) and corrected for clay content using the pipette method (Kroetsch and Wang 2008). The bulk elemental composition of the upper 20 cm of soil was determined by X-ray fluorescence spectroscopy following the procedure described in Bélanger et al. (2004).

Fifty upper canopy leaves were randomly collected from within each plot in early August of the year harvested (i.e. 2007 and 2008), weighed, dried and ground in bulk for foliar analysis. Stems were harvested and weighed in the field for fresh weight once leaves had senesced. In the event that total leaf fall had not yet occurred, leaves were first removed manually before harvesting stems. Fresh weight of the stems was measured in the field. A 1-2 kg subsample, incorporating whole stems, was dried and reweighed to convert fresh weight to dry weight. Leaves were analyzed for concentrations of C, N, P, K, Ca, Mg, and Na. Carbon and N of leaves were determined by infrared detection on a LECO CNS-2000 at 800°C. Phosphorus, K, Ca, and Mg concentrations of leaves were determined from a concentrated H_2SO_4 - H_2O_2 digest (Kalra and Maynard 1999). Concentrations of PO_4 were measured with a SmartChem Instrument.

Potassium, Ca, Mg, Na were determined by atomic absorption (Ca, Mg, Fe, Al) and emission (K, Na) spectroscopy.

After weighing, the stems were chipped (5-10 mm) and mixed to ensure homogeneity. Two samples (per plot) of approximately 40 g were then prepared by grinding in stages to produce a very fine homogeneous powder (<60 µm). The two samples were prepared as a mix such that percentage from any one year was proportional to the growth increment that year (i.e. first year of growth is small relative to the third year). A 1.0±0.15 mg subsample of that powder was analyzed for ¹³C/¹²C ratio using a continuous flow isotope ratio mass spectrometer interfaced with a RoboPrep Sample Converter (Europa Scientific, Crewe, UK). The working standard for δ¹³C determination was lentil (*Lens culinaris*) straw with a δ¹³C of -27.6‰ relative to the PeeDee belemnite standard. The δ¹³C of the sample was calculated as followed:

$$\delta^{13}\text{C} = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{sample}}} \times 1,000$$

where R_{sample} and R_{standard} are the ratios of ¹³C/¹²C in the sample and standard, respectively. The δ¹³C signature was used as an indicator of water stress. It is an integrative measure of WUE (whole growing season) in arid regions where minimal variation is observed for other environmental factors (McNulty et al. 1995; Stewart et al. 1995). Some of our study sites located in the semi-arid prairies have potential evapotranspiration exceeding precipitation. Also, the use of an identical willow clone and management practices at all sites reduced the variability among other environmental factors. Therefore, the major factor controlling foliar δ¹³C values should be soil water availability as affected by site and soil properties.

Relationships between harvested biomass and each soil, plant nutrient or climate variable were determined using the Pearson product-moment correlation. However, many of the relationships were non-linear in which case non-linear regression was used. Stepwise and

forward multiple linear regression were used to determine which measured parameters would work best together to predict yields at the 7 study sites. The maximum number of variables selected in the multiple regression analysis was set at three in the interest of achieving parsimonious relationships while still utilizing the predictive capability of the analyses (Pinno and Bélanger 2011). Relationships at $P = 0.05$ were considered significant. Statistical analyses were carried out with CoStat (CoHort Software, Monterey, CA).

Results

Across sites, soils were highly varied from acidic sandy loams (pH = 5.1) to slightly alkaline heavy clays (pH = 8.3) (Table 1). Nutrient content of soil was similarly wide-ranging (total N = 1.75-3.03 mg g⁻¹; acid leachable P = 0.35-1.15 mg g⁻¹; and exchangeable K = 0.09-1.33 cmol_c kg⁻¹). The large geographic scale of this study also meant climate and weather were also very diverse (mean annual precipitation = 382-971 mm; and degree days base 5°C = 1330-2300 °C day) (Table 1). Therefore, it is unsurprising that there was a large range in productivity (5.3-22.8 Mg ha⁻¹) present across sites in response to the diversity of site characteristics (Table 1). In general, the 'Hotel' clone with the greatest yields tended to be on sites receiving adequate moisture (see summer precipitation in Table 2) with calcareous (Figure 2) medium textured soils (Figure 3). Sites with sandy soils, very low precipitation or a combination of both produced the lowest yields.

Few climate variables were correlated with yields of the 'Hotel' clone (Table 2). There was no relationship between yields and annual or summer precipitation over the course of three years. There was, however, a positive correlation between summer precipitation in the first two years of growth ($r = 0.752$, $P < 0.051$).

Different plant species have unique $\delta^{13}\text{C}$ signatures based on their intrinsic WUE and photosynthetic pathway (i.e., C_3 vs. C_4 plants). This means that there is no absolute baseline $\delta^{13}\text{C}$ signature indicating water stress; rather that as the $\delta^{13}\text{C}$ increases (becomes less negative), WUE increases in response to water scarcity and plants are likely more water stressed than others of the same species. Examination of $\delta^{13}\text{C}$ values of the 'Hotel' stems confirms that there is no simple relationship between productivity and water stress across all sites (Figure 1). Rather, there are two distinct groups: SMO and UOS were the only two sites where moisture limitations crossed a threshold severe enough to limit productivity and caused these sites to have the highest $\delta^{13}\text{C}$ values. At the other sites, $\delta^{13}\text{C}$ values were positively correlated with harvestable biomass, indicating that factors other than water stress were more limiting for at least a number of these sites.

Site quality of the 'Hotel' clone was strongly correlated with bulk soil chemical composition (Table 3). Total Ca (Figure 2a) was the strongest single indicator of 'Hotel' yields as were soil pH (Figure 2b) and $(\Sigma\text{Total Ca+Mg})/(\Sigma\text{Total Si+Al+Fe})$ (Figure 2c). The latter variable is an indicator of the acid-base status of the soil (Birkeland 1999). Soil organic C was another general indicator of productivity (Table 3). Additionally, soil texture influenced productivity as the 'Hotel' clone grew best on medium textured soils with adequate drainage (Figure 3).

Foliar N was related to total soil N (Figure 4b), foliar K was related to soil exchangeable K (Figure 5c), and foliar P was related to soil leachable P (Figure 6b). However, foliar Mg and Ca were not related to soil (total or exchangeable) Mg and Ca (results not shown). When considering all seven sites for which we have yield data for three years, no significant positive correlations between foliar concentrations and yields of the 'Hotel' clone were found (Table 4). However, with the water stressed SMO and UOS sites removed from the dataset, the analyses

revealed a statistically significant positive correlation coefficient between foliar K and willow yields (Table 4, Figure 5) and a marginally significant positive correlation coefficient between foliar N and yields (Table 4, Figure 4). After removing SMO and UOS from the foliar dataset, soil total N was still more strongly correlated with yields (greater P value) than was foliar N (Tables 3 and 4, respectively). Foliar Mg was only positively correlated with productivity at LAK, POR and PIC sites (Table 4).

None of the multiple linear regression models calculated via stepwise and forward regression were able to exceed the strength of the relationship described by a second order polynomial with total Ca (Figure 2a). Several models could be created by combining different variables with total Ca but these yielded slightly lower coefficients of determination (results not shown). In terms of secondary predictors, there is both a high degree of covariance among variables and relatively little room for improvement of the models such that multiple linear regressions, both stepwise and forward, were not able to adequately identify the most important nutritional or climatic requirements of willow.

Discussion

Degree days are useful in estimating the potential for plant productivity from a temperature standpoint (Wang 1960) and have been shown to be positively correlated ($r^2 > 0.95$) with willow growth (Kopp et al. 2001b). Because of the large climatic gradient created in this study, it was therefore expected that greater annual precipitation and a longer growing season as reflected by degree days would have been somewhat important for determining productivity of the 'Hotel' clone. However, degree days did not explain the variability in average site yields. This is at odds with studies examining the growth of other tree species at the regional scale (Post and

Curtis 1970; Lindroth and Båth 1999; Ung et al. 2001; Hamel et al. 2004; Hogg et al. 2005) and may be related to the high water and nutrient requirements of *S. purpurea* 'Hotel' or a possible effect of photoperiod across the range in latitude that was beyond the scope of this study.

Likewise, other climate variables had poor correlations with growth. Vapor pressure deficit, which is the difference between the actual water content of the air and the potential content of the air at a relative humidity of 100%, is a good measure of the atmospheric control on transpiration. Potential evapotranspiration is similarly reflective of potential plant activity as it increases with increasing available solar radiation but can cause water stress if precipitation cannot meet demands. Aridity index, which is based on the ratio of precipitation to potential evapotranspiration, takes into consideration both the supply and use of water. However, none of these variables satisfactorily explained the variability in biomass production.

Soil properties were the dominant predictors of *S. purpurea* 'Hotel' growth in this study, which suggests that, even at the regional scale, growth was governed in large part by the capacity of soils to retain water and/or nutrients. Climate played a lesser role, except perhaps at two sites (i.e. SMO and UOS) which appeared to receive inadequate moisture. Site selection based on soil quality can thus result in minimizing the need for inputs such as irrigation and fertilizers (Bhardwaj et al. 2011), thereby keeping the water and energy footprints to a minimum and maximizing the environmental benefits of willow biomass production. The rationale for a large control from soils on the growth of the 'Hotel' clone is discussed in details below.

Water availability

The $\delta^{13}\text{C}$ signatures of the 'Hotel' stems were correlated with total precipitation over three years across the sites ($r = -0.789$, $P = 0.028$, Table 4) but not summer precipitation over the first

two years of growth ($r = -0.472$, $P = 0.276$, Table 2). This is despite that summer precipitation over the first two years of growth and harvested biomass were correlated ($r = 0.752$, $P = 0.051$). There was clearly more radial growth in the third year than the first two years and consequently, there was a higher percentage of wood from that third year in the sample compared with years 1 and 2. This means that the $\delta^{13}\text{C}$ values were biased towards the third year. It also suggests that the critical first two years may be underrepresented relative to their importance in determining productivity.

Figure 1 indicates that, with the exception of SMO and UOS, as productivity rose from other factors (e.g. due to improved nutrition), photosynthetic rates increased. Higher rates of carbon gain increases WUE. In turn, faster growing plants in moisture limited regions may have exerted more pressure on dwindling moisture supplies, thus also increasing WUE (Moukouri et al. 2012). Both of these conditions may have contributed to the positive correlation between $\delta^{13}\text{C}$ and harvested biomass across the majority of sites. However, unless we measure gas exchange or water potential, it is not possible to determine whether carbon gain or water loss or both are responsible for the relationship between $\delta^{13}\text{C}$ and yields.

The two sites with the lowest productivity (SMO and UOS) were those with the greatest $\delta^{13}\text{C}$ values, though in this case they were probably negatively affected by severe water stress. The growth of 'Hotel' at SMO is supported by a soil with a very coarse texture and received an annual average of 432 mm of precipitation over the three year growing period. Further, although UOS is a clay soil, it experienced extended periods without rain, particularly in July 2007 [16.4 mm of precipitation in July as compared to a 30 yr-normal of 60.1 mm (Environment Canada, 2011)]. It is therefore reasonable to conclude that the poor yields at these two sites are primarily

a result of water stress due respectively to soil type and summer precipitation. Thus, while these two sites were limited by water stress, other sites were at least partially limited by other factors.

Soil texture and topography can have a large impact on water availability for plants. Coarse soils allow water to quickly drain such that even soils that receive adequate precipitation may not be able to retain moisture long enough to support high rates of plant growth, as per SMO. Likewise, topography can affect moisture availability by affecting water redistribution. However, this was likely not a factor as the study sites were mostly flat.

Productivity of willow plantations early in their establishment stage has been reported as greatest in medium textured soils (Mitchell et al. 1999; Abrahamson et al. 2002). Similarly in this study, medium textured soil produced the highest yields for the 'Hotel' clone (Figure 3). Negative correlations with sand content and positive correlations with silt content at 0-20 cm were found (Table 3). Mitchell et al. (1999) explained that willow requires soils with good drainage and that stagnating water will result in a decline in productivity. However, the stagnating water argument is improbable at this site, due to low precipitation and rather the $\delta^{13}\text{C}$ data indicates the opposite, that it is related to a lack of moisture. In moisture limited regions, medium textured soils still produced the highest yield at 3 years presumably because sandy soils do not efficiently retain the water and nutrients required for willow growth, and heavier clay soils are likely too difficult for young roots to penetrate when dry.

Drought is common on the Canadian prairies but it is not the only weather associated limiting factor. Extreme cold in winter months is particularly hard on young shoots and some winter kill was noted at the UOS site, and nearly caused plantation failure at the BIR site. At the latter site, extreme cold during the winter (minimum daily temperatures $<-40^{\circ}\text{C}$) was blamed for killing most of the aboveground biomass. To restore plant health, the *S. purpurea* shrubs were

coppiced to encourage growth from the still healthy base of the plants. This made it impossible to compare the rates of productivity at the BIR site with other plantations but it does highlight the potential of extreme weather to limit the productivity of a plantation. Therefore, while it is still important to look at typical rates of precipitation and the length of growing season, it may be more important to look at the probability of extreme weather when evaluating the suitability of a site for willow production.

Soil chemical composition

Soil chemistry was a strong indicator for the productivity of the 'Hotel' clone. While soil texture appeared to have an impact on *S. purpurea* growth due to its influence on water retention, it seems that the acid-base status of the soil had a much greater control over yields. The elemental composition of the soil can be grouped into categories of elements that co-vary and thus are similarly associated with productivity. As a whole, total Ca and Mg were indicators of high growth rates, while total Si was related to poor productivity (Table 3). This indicates that soils containing calcite and dolomite were more conducive to willow growth than base-poor and acidic soils containing dominantly felsic minerals.

Dolomite and calcite weather faster than most Ca-rich minerals contained in felsic rocks (e.g. plagioclase, amphibole). In a young landscape that was “recently” glaciated, a soil that contains Ca and Mg bearing minerals that are easily dissolved (and thus leads to more available Ca and Mg) will therefore be likely more productive. While we are unaware of studies showing such a relationship between total Ca and tree growth, a few studies with sugar maple indicated the benefits of total Ca-rich soils on growth variables, notably seedling survival and positive correlations with arbuscular mycorrhizal fungi (Kobe et al. 1995; Juice et al. 2006). Our results

suggest that total chemistry of the soil, which is not a common soil analysis, can be a reliable indicator of tree growth, possibly providing different information than the most commonly tested exchangeable cations (Thiffault et al. 2006).

Calcium and Mg-rich soils also create an environment that has an appropriate pH level which, in turn, is generally a good indicator for the suitability of a soil for plant growth as it affects cation exchange capacity of soils, soil microbial activity and nutrient availability for plants (Havlin et al. 2005). Soil pH was strongly (positively) correlated to total Ca ($r = 0.938$, $p < 0.001$) and total Mg ($r = 0.967$, $p = 0.002$) (results not shown). *S. purpurea* 'Hotel' grew best in soils with a pH of approximately 8.3 but growth declined sharply below 7.0. Anything below a pH of 6.0 showed very poor productivity. This is higher than the site recommendations for willow spp. by Abrahamson et al. (2002) of between pH of 5.5 and 8.0 and by Mitchell et al. (1999) of between pH of 6.0 and 7.0.

Soil C, due to its role in increasing soil fertility and moisture retention (Havlin et al. 2005), was positively correlated to *S. purpurea* 'Hotel' yields (Table 3). Higher soil C is generally associated with higher rates of primary productivity and, as such, would suggest that the soils most capable of supporting high rates of willow biomass production will also be the same soils producing the greatest yields for agriculture [i.e. soils high in total C (Christensen and Johnston 1997)]. However, the strong affinity for total Ca and pH >8.0 exhibited by *S. purpurea* 'Hotel' may provide an exploitable niche from within agricultural regions. This study confirms that the growth of *S. purpurea* 'Hotel' (and likely other willow clones) in degraded soils or those low in soil C will exhibit lower yields. Ens et al. (2013) found that at 3 years from plantation establishment, soil C was depleted in Canadian SRIC of willow. However, should tillage decrease with establishment of perennial willow, soil C would be expected to increase [as was

the case in Arevalo et al. (2011) in hybrid poplar plantations in Alberta, Canada, with net accumulation after 7 years] leading to a positive feedback of increased willow productivity and soil C over time.

Willow Foliar Nutrition

Although the ultimate goal of this study was to determine site quality from soils, foliar nutrition is a more direct measure of the status of the plants—thus, it was also used for determining site quality. When examining the effects of nutritional concentration of *S. purpurea* 'Hotel' as a predictor for productivity, it is important to consider that two sites were limited by water availability. With water stress, the potential effect of nutrient deficiencies on growth is masked. Thus, these sites were excluded from the dataset when trying to link foliar nutrients to tree growth. This assumes that water stress is not affecting any other site and that any nutrient deficiency has negligible effects on those plants experiencing water stress, no matter how severe the deficiency.

The two nutrients that had the strongest relationship with the growth of the 'Hotel' clone were N and K, not Ca and Mg (Figures 4 and 5, Table 4). It is for this reason that the acid-base status of the soil is suspected to be a proxy for nutrient availability as a whole, not just for Ca and Mg. Total soil N was positively correlated with yield as well as foliar N (Table 3, Figure 4). The highest foliar N concentrations in the dataset were approximately 30 mg N g⁻¹, which falls in the range of optimum concentrations (22 to 35 mg g⁻¹, depending on species) reported by Simon et al. (1990) and Kopinga and van den Burg (1995) (Figure 4). That foliar concentrations are approaching or are at optimum levels for LAK, POR and PIC may explain why there was no definite linear relationship between foliar N and productivity (Figure 4a). However, that GUE

and SSM are both below ideal concentrations and experiencing low growth may well be due to the high N requirements of *S. purpurea* 'Hotel' for maximum growth.

The vast majority of soil total N is organic N, but the inorganic N is the readily available fraction for plant uptake. Ens et al. (2013) observed a depletion of soil inorganic N under *S. purpurea* 'Hotel' relative to reference plots which served as a proxy for conditions before 'Hotel' was planted. The loss in soil inorganic N was attributed to faster growth of *S. purpurea* 'Hotel' and in turn, faster rates of uptake. The same effect was observed by Moukoui et al. (2012) in pure willow plantations in Saskatchewan as well as intercroppings with the N-fixing caragana shrub.

The effect of K nutrition on *S. purpurea* 'Hotel' yields is shown by the strong relationship with foliar K and harvested biomass as well as soil exchangeable K and harvested biomass (Figure 5a,b). Below a leaf concentration of between 8.0 and 10.0 mg K g⁻¹, growth was severely impaired. This corresponds well with the threshold value for K deficiencies reported in the literature (Mengel 2007). Above a foliar concentration of 10.0 mg K g⁻¹, *S. purpurea* 'Hotel' responded strongly to increasing concentrations of foliar K. Potassium also appeared sufficient to avoid severe deficiencies at soil exchangeable concentrations of 0.5 cmol_c kg⁻¹ both in terms of yield and foliar concentration (Figure 7b,c). No upper bound where excess K was taken up was detected in this study.

From 0.4–1.2 mg g⁻¹ H₂SO₄ leached soil P, covering much of the range seen in this study, the foliar P concentration remained relatively stable near 2.0 mg P g⁻¹ (Figure 6b). This is the optimum nutrition of willow leaves as reported by Simon et al. (1990). Concentrations of foliar P varied from the optimum only where leachable soil P was at the extremes of the range of concentrations. This suggests that willow was able to effectively regulate P uptake within the

range of conditions experienced in this study and as such, there was no discernible growth response of added P within this range (Figure 6a). Interestingly, the relationship between soil P and foliar P suggest that the acid leach is a good proxy for available soil P in SRIC of willow (Figure 6c). As such, should H₂SO₄ leached soil P at other sites be outside of 0.4–1.2 mg g⁻¹, P uptake and nutrition will likely differ from the optimum.

Any possible effects of foliar Mg on willow growth were masked by acute water stress, N deficiencies or K deficiencies (Table 4). Foliar concentrations of Mg at high producing sites (LAK, POR, PIC) were as high as 4.0 mg g⁻¹, which suggests the >3.0 mg g⁻¹ value for optimal nutrition reported by Kopinga and van den Burg (1995) is possibly low for *S. purpurea* ‘Hotel’. Thus, Mg may increase in importance as deficiencies in water, N and K are alleviated. However, due to the low number of sites with adequate moisture, N and K, there was no clear relationship between exchangeable soil Mg or foliar Mg and productivity, making prediction of Mg soil requirements for willow difficult.

Similarly, foliar Ca was also found to be correlated with the yields of *S. purpurea* ‘Hotel’ but its effects as a nutrient is inseparable from its effect as the key buffer for pH—therefore, it is difficult to discern Ca nutrition from soil analyses (Figure 2). Foliar Ca was not correlated with harvested biomass at sites not experiencing acute water stress, N deficiencies or K deficiencies (Table 4). While the full causation of soil Ca on productivity is unclear, the low productivity below 30-35 mg g⁻¹ of total Ca seen in Figure 2 indicates caution should be given to establishing willow on sites with low surface soil exchangeable Ca.

Conclusions

It appears that soil properties are the most important for estimating *S. purpurea* 'Hotel' yields from the Canadian prairies to southern Ontario. Prediction of site quality is possible given mainly soil data despite a large climatic gradient. Characteristics which affect water retention and nutrient availability are the most useful for predicting yields of *S. purpurea* 'Hotel'. The acid-base status of the soil as dictated by bulk elemental composition, in particular the presence of Ca, was found to be the dominant control. From a nutritional standpoint, sites with total soil N and foliar K (for sites with adequate moisture) also had greater growth. Water availability was found to be primarily limiting yields the two lowest productivity prairie sites where moisture deficiencies overshadowed nutritional deficiencies. Thus, each site experienced its own unique combination of limiting factors: severe water stress > N and K deficiencies > Mg and P deficiencies. It is expected that as one limitation is removed through selection of optimal sites, another will become dominantly important. Therefore, yields of *S. purpurea* 'Hotel' can be explained by Liebig's Law of Minimum as stated by Taylor (1934) such that growth is limited largely by soil variables but that extreme environmental conditions can become limiting even though climate is not.

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Table 1 Site names, locations, history, soil texture, soil pH, bulk density, precipitation and harvested biomass summary data for the nine studied *S. purpurea* ‘Hotel’ plantations

Site (ID)	Geographic Coordinates	Site History	Soil Texture	Soil pH (SE)	Bulk Density (SE)	Mean Annual Precipitation (SE)†		Year Planted/ Harvested	Harvested Biomass (SE)
						30 Year Mean (SE)	Year Planted to Year Harvested (SE)		
						mm			
Ellerslie Research Station, AB (ELL)	53°25'N 113°31'W	Cereal crops	Silty Clay Loam	6.0 (0.1)	1.09 (0.01)	444 (14)	404 (43)	2005/2007	N/A¶
Smoky Lake, AB (SMO)	54°07'N 112°24'W	Tree nursery‡	Sandy Loam	5.1 (0.1)	1.51 (0.02)	432 (13)	412 (27)	2005/2007	5.4 (0.1)
Lakeshore Tree Nursery, SK (LAK)	52°00'N 106°45'W	Pasture	Silty Clay Loam	8.3 (0.0)	1.24 (0.02)	349 (16)	454 (53)	2005/2007	18.4 (1.2)
University of Saskatchewan, SK (UOS)	52°07'N 106°36'W	Cereal crops	Clay	6.6 (0.1)	1.24 (0.02)	364 (17)	382 (74)	2006/2008	5.3 (0.8)
Portage la Prairie, MB (POR)	49°57'N 98°10'W	Vegetables	Silt Loam	8.3 (0.0)	1.09 (0.01)	537 (17)	523 (88)	2005/2007	22.8 (3.2)
Bird's Hill, MB (BIR)	50°00'N 97°00'W	Pasture	Heavy Clay	8.3 (0.1)	1.18 (0.01)	560 (21)	538 (91)	2005/2007	N/A¶
Sault Ste Marie, ON (SSM)	46°32'N 84°24'W	Managed forest	Sandy Clay Loam	5.4 (0.1)	1.39 (0.02)	914 (26)	826 (56)	2006/2008	6.1 (0.3)
Guelph, ON (GUE)	43°33'N 80°13'W	Turf grass	Clay Loam	6.9 (0.0)	1.29 (0.03)	894 (26)	971 (143)	2005§/2008	9.5 (2.5)
Pickering, ON (PIC)	44°00'N 79°01'W	Idle / Failed plantation	Clay	6.8 (0.2)	1.22 (0.03)	887 (18)	948 (131)	2006/2008	14.0 (2.1)

† Modeled using BioSIM

‡ Unable to find ideal optimal match to previous land use; used surrounding forest

§ Coppiced after first year; three years of aboveground biomass

¶ Harvested previously such that comparable data is unavailable

Table 2 Pearson product-moment correlations for climate variables modeled with BioSIM and harvested biomass for seven *S. purpurea* ‘Hotel’ plantations (SMO, LAK, UOS, POR, SSM, GUE, PIC)

	r	P
Degree days (base 5°C)	0.398	0.377
Degree days (base 10°C)	0.425	0.341
Annual precipitation	-0.058	0.902
Summer precipitation (3 years)	0.256	0.579
Summer precipitation (First 2 years)	0.752	0.051
Thornwaite potential evapotranspiration	0.543	0.208
Standard Thornwaite potential evapotranspiration	0.343	0.452
Vapor pressure deficit	-0.080	0.865
Aridity index	0.236	0.446

Table 3 Pearson product-moment correlations for measured soil variables and harvested biomass for seven *S. purpurea* ‘Hotel’ plantations (SMO, LAK, UOS, POR, SSM, GUE, PIC)

	0 - 20 cm		20 - 40 cm	
	r	P	r	P
pH	0.886	0.005	0.804	0.023
Organic C	0.882	0.006	0.897	0.004
Total N	0.743	0.048	0.380	0.394
C:N ratio	0.259	0.570	0.497	0.073
H ₂ SO ₄ extractable P	0.479	0.268	0.414	0.349
Bulk chemistry				
Total Ca	0.967	0.000	--†	--
Total Mg	0.925	0.002	--	--
Total Al	0.385	0.387	--	--
Total Fe	0.403	0.363	--	--
Total Si	-0.785	0.030	--	--
Total K	0.340	0.449	--	--
Total P	0.637	0.114	--	--
Exchangeable Cations				
K	0.473	0.276	0.132	0.777
Ca	0.891	0.005	0.858	0.004
Mg	-0.426	0.333	-0.412	0.352
Na	-0.412	0.351	-0.403	0.362
Fe	-0.492	0.253	-0.506	0.238
Al	-0.548	0.193	-0.412	0.351
Sand content	-0.698	0.072	-0.164	0.723
Silt content	0.922	0.002	0.793	0.027
Clay content	0.144	0.755	-0.377	0.398

† not included in analyses

Table 4 Pearson product-moment correlations for measured foliar variables and harvested biomass for seven *S. purpurea* ‘Hotel’ plantations (SMO, LAK, UOS, POR, SSM, GUE, PIC)

	All sites (SMO, LAK, UOS, POR, SSM, GUE, PIC)		Water stressed sites excluded (LAK, POR, SSM, GUE, PIC)		Water, N, K stressed sites excluded (LAK, POR, PIC)	
	r	P	r	P	r	P
Stems						
$\delta^{13}\text{C}$	-0.288	0.526				
Leaves						
Nitrogen	0.103	0.825	0.811	0.075		
Potassium	0.621	0.127	0.938	0.009		
Calcium	0.444	0.311	-0.245	0.684	-0.705	0.425
Magnesium	-0.457	0.294	-0.544	0.324	0.928	0.130
Phosphorus	-0.063	0.893	0.070	0.910	-0.764	0.358

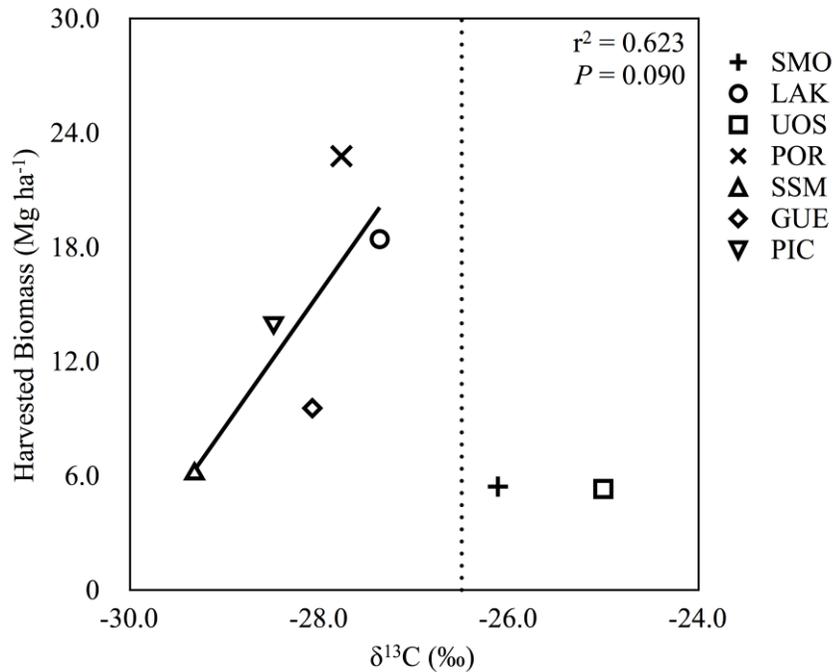


Fig. 1 Relationship between $\delta^{13}\text{C}$ of stems vs. harvested biomass for seven *S. purpurea* ‘Hotel’ plantations (SMO, LAK, UOS, POR, SSM, GUE, PIC). Less negative $\delta^{13}\text{C}$ values (towards right) indicate increasing water use efficiency and/or water stress. Dashed line represents approximate threshold for acute water stress. Regression excludes SMO and UOS as these sites are beyond the threshold for acute water stress and therefore are a distinct population from the remaining dataset.

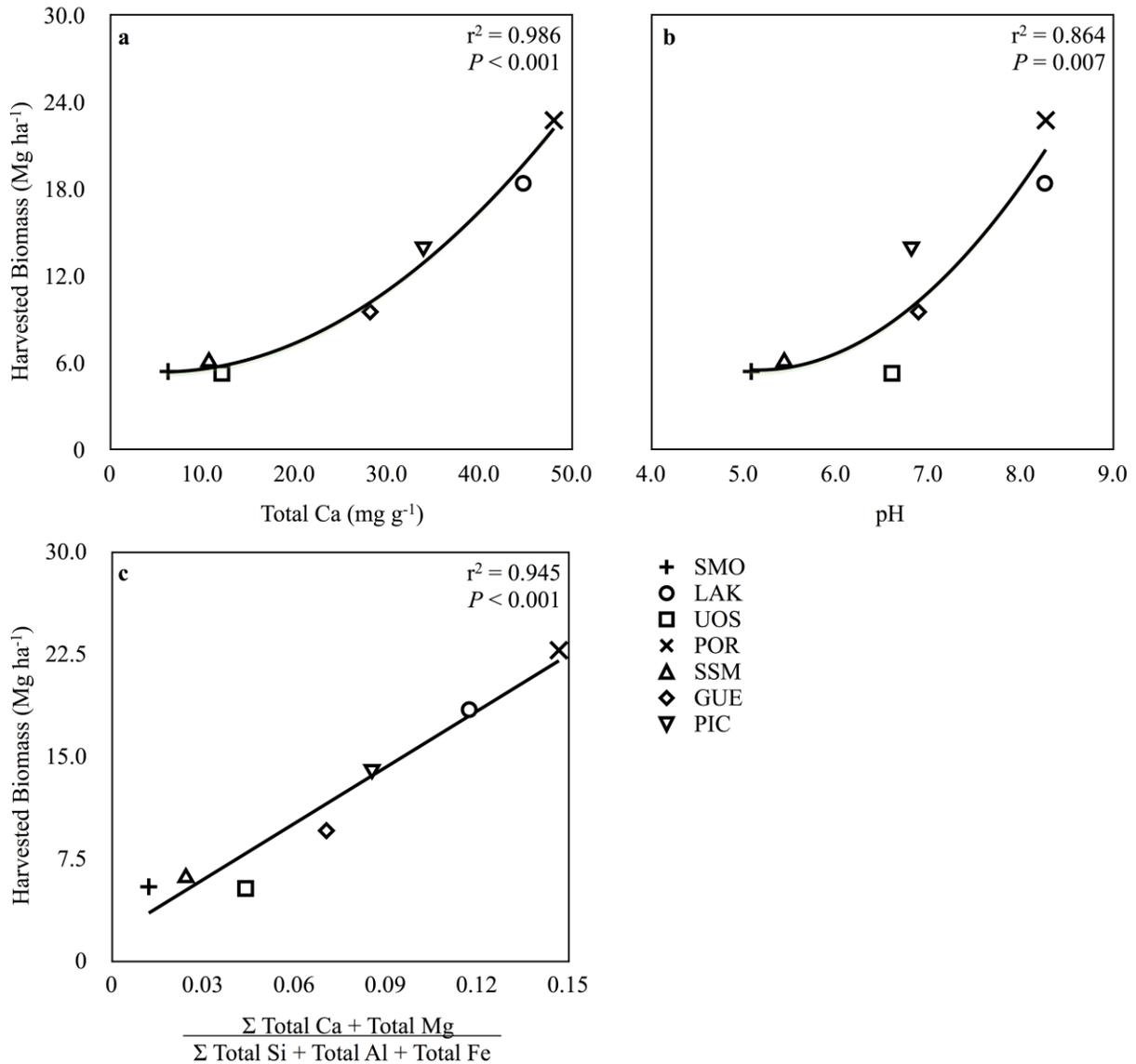


Fig. 2 Relationship between total Ca (a) pH (b) and $\Sigma \text{ Total Ca} + \text{Total Mg} / \Sigma \text{ Total Si} + \text{Total Al} + \text{Total Fe}$ (c) of top 0-20 cm of soil vs. harvested biomass for seven *S. purpurea* ‘Hotel’ plantations (SMO, LAK, UOS, POR, SSM, GUE, PIC).

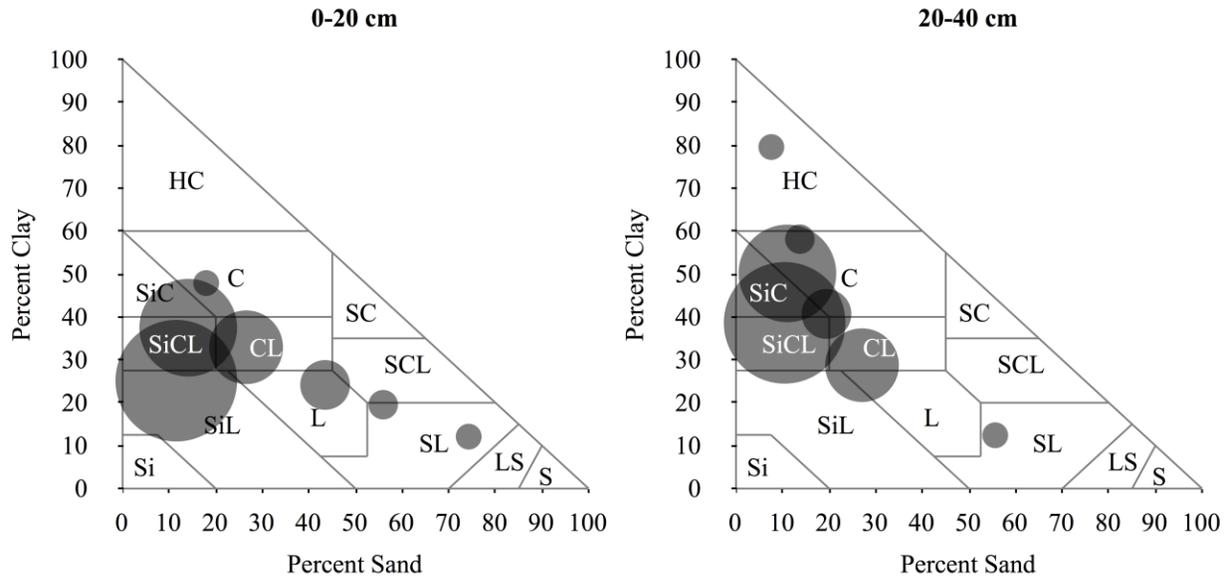


Fig. 3 Soil texture (Soil Classification Working Group 1998) in relation to harvested biomass for seven *S. purpurea* ‘Hotel’ plantations (SMO, LAK, UOS, POR, SSM, GUE, PIC). Larger circles indicate higher harvested biomass.

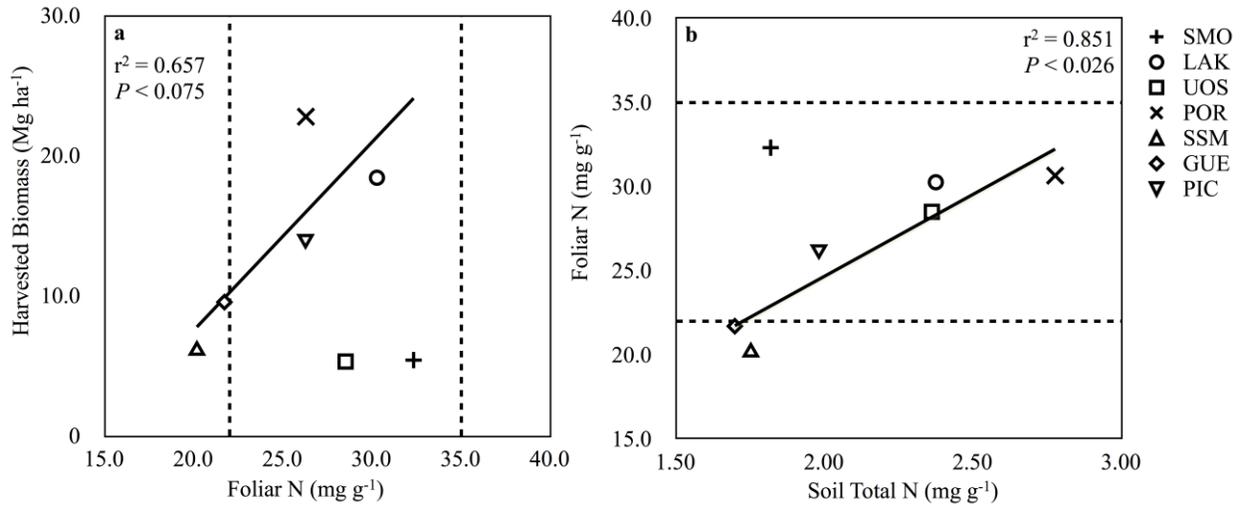


Fig. 4 Relationship between N availability and productivity expressed as foliar N (a) vs. harvested biomass for seven *S. purpurea* ‘Hotel’ plantations (SMO, LAK, UOS, POR, SSM, GUE, PIC), and soil total N vs. foliar N in the upper 20 cm of soil (b) for all nine plantations (adding ELL and BIR). Due to water stress, UOS and SMO sites do not share benefit from increasing N uptake and, as such, are excluded from the regression dataset. Dashed lines represent low and high of range of optimal concentrations of foliar N for other *Salix* species (22-35 mg g⁻¹) as reported by Simon et al. (1990) and Kopinga and van den Burg (1995).

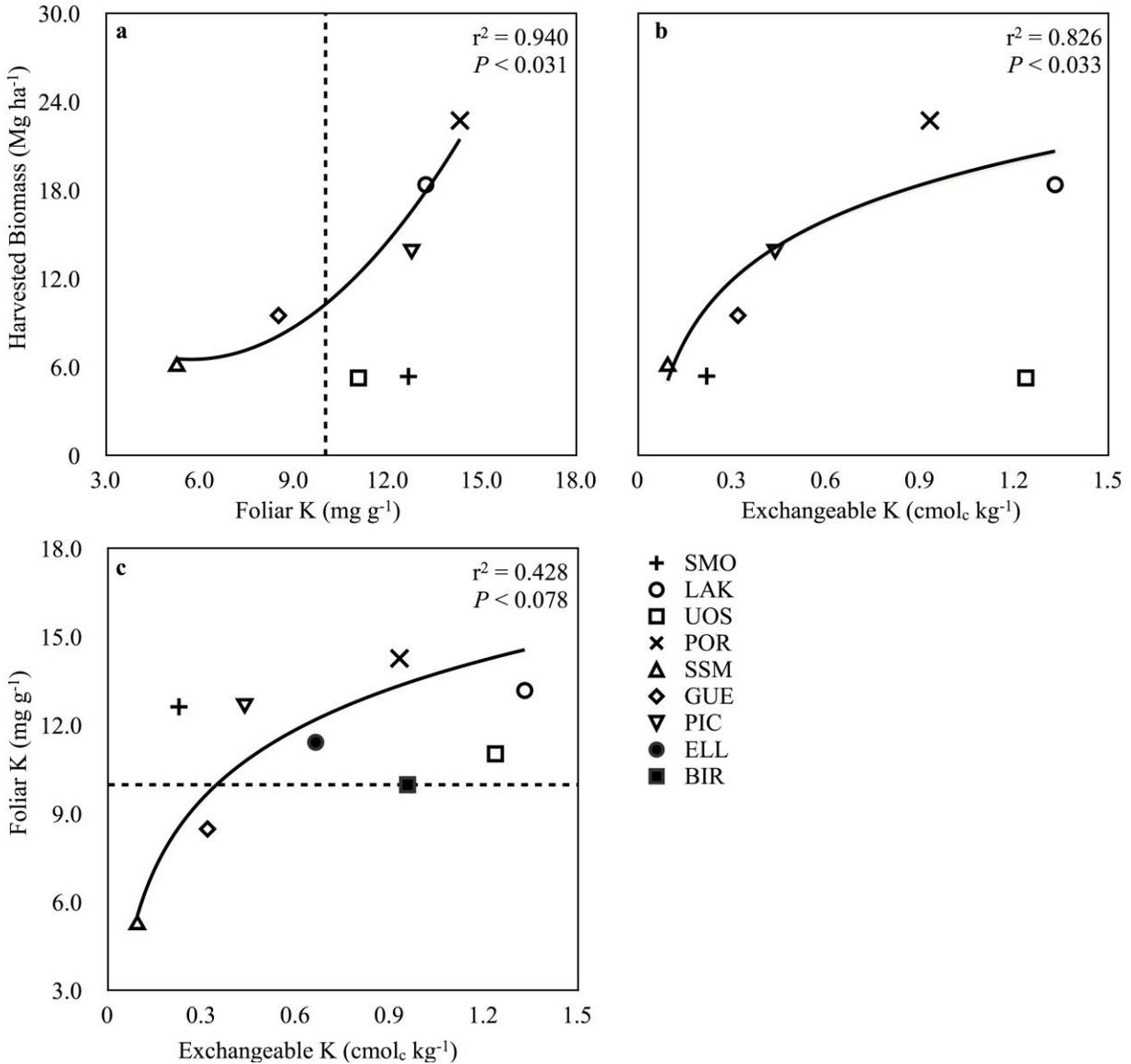


Fig. 5 Relationship between K availability and productivity expressed as foliar K (a) and soil exchangeable K (0-20 cm) (b) vs. harvested biomass for seven *S. purpurea* ‘Hotel’ plantations (SMO, LAK, UOS, POR, SSM, GUE, PIC), and soil exchangeable K (0-20 cm) vs. foliar K (c) for all nine plantations (adding ELL and BIR). Due to water stress, UOS and SMO sites do not share benefit from increasing K uptake and, as such, are excluded from the regression datasets (a,b). Minimum threshold for foliar K (10 mg g^{-1}) is indicated by dashed lines (Mengel 2007).

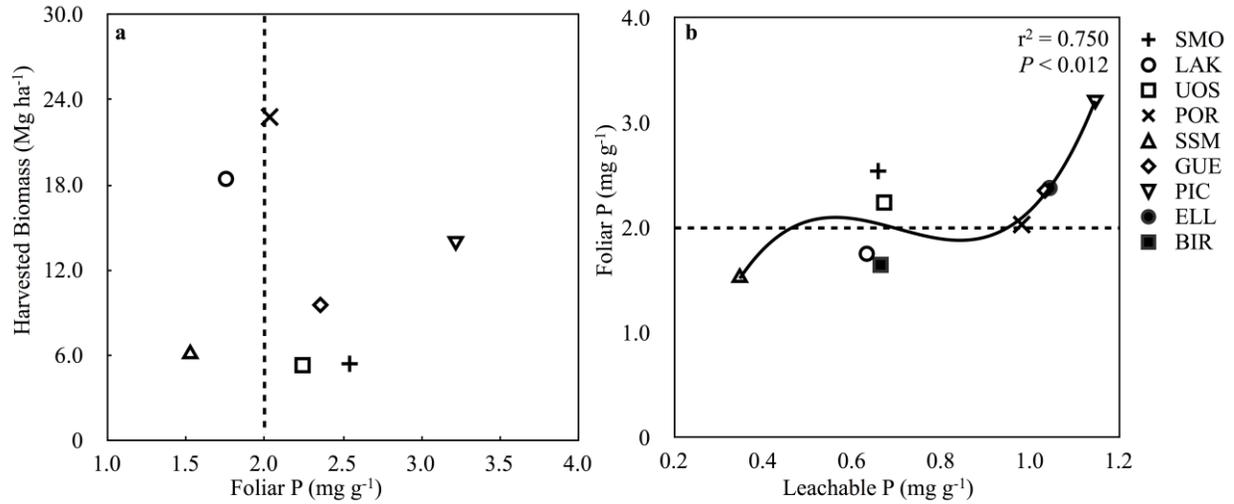


Fig. 6 Relationship between P availability and productivity expressed as foliar P vs. harvested biomass for seven *S. purpurea* 'Hotel' plantations (SMO, LAK, UOS, POR, SSM, GUE, PIC) (a), and leachable soil P (0-20 cm) vs. foliar P (b) for all nine plantations (adding ELL and BIR). Dashed line represents apparent approximate sufficiency for P (Simon et al. 1990).