Predicting the productivity of a young hybrid poplar clone under intensive plantation management in northern Alberta, Canada using soil and site characteristics

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Abstract

Site productivity of the hybrid poplar clone Brooks6 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. Percent sand (R^2=0.352, p=0.001) was the best single predictor of hybrid poplar productivity, showing a curved relationship. Soil pH also showed a curved but weaker relationship with hybrid poplar productivity (R^2=0.133, p=0.100). Maximum tree productivity occurred at sand contents between 55-70% and pH values near 6. Other variables, including foliar nutrient concentrations, foliar $\delta^{13}C$, electrical conductivity, depth of the A horizon and total chemistry of the soil, were also related to hybrid poplar productivity at the local and microsite scales. However, all of these variables were correlated to either soil texture (percent sand) or pH. At the microsite scale within plantations, percent sand was the most important predictor of tree productivity and explained more than 50% of the variability within plantations, although the relationship varied by plantation. In plantations with fine textures, sandier microsites were associated with increased growth while in sandy plantations, finer textured microsites were more productive. As a whole, the growth of the hybrid poplar clone Brooks6 appears to be mostly influenced by a combination of soil water and nutrient availability, the former being impacted by soil texture and the latter being governed by soil pH.

Keywords: Brooks6 , afforestation, soil water availability, soil nutrient availability, foliar nutrients, tree productivity, hybrid poplar, plantation

Introduction

Establishing plantations of fast-growing tree species is currently being advanced around the world as a means of meeting the timber needs of the forest industry as well as other goals such as increasing biodiversity and sequestering carbon (Sedjo 1999; McKenney et al. 2004). In western Canada, these plantations are generally being established on marginal agricultural land in transitional areas between Prairies to the south and forests to the north. This management system is being employed by a large forest management company in north-eastern Alberta with the expectation of producing 12% of its fibre requirements from 25,000 ha of intensively managed plantations. This is a practical application of the TRIAD approach in which land is divided into three categories (Messier et al. 2003): 1) a fully protected or benchmark 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 extensively 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 and 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 shelterbelt trees in agricultural areas and are now being used in industrial plantations. 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 and disease resistance, show various levels of resistance to stress,

e.g. cold temperatures and dry conditions, and have different resource requirements (van Oosten 2006; DesRochers et al. 2007).

In order for these intensively managed timber plantations to be as productive as possible, they must be established on the best growing sites available since the trees on these high productivity sites will respond more favorably 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 water vapour deficit, is well known to have a major impact on tree growth (e.g. Ung et al. 2001; Hogg et al. 2005). 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 that management decisions are made about establishing tree plantations. At this scale, there is little climatic variation and differences in tree growth are more 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 (Pinno and Bélanger 2009). The objective of this study was to identify the soil and site factors responsible for controlling productivity of the HP clone Brooks6 in plantations established on agricultural land in Alberta in order to predict the best growing sites for future HP plantations in the area.

Methods

Study Area and Field Sampling

Six four-year-old HP plantations, established in 2004 on former agricultural crop land in north-east Alberta (Canada) near the communities of Athabasca (54º43'N, 113º17'W) and Lac La Biche (54º46'N, 111º59'W), were selected for the study. Clone Brooks6 (*Populus deltoides x P.x petrowskyana*), which was also popularized as Green Giant, was the clone used in all plantations. The study area is in the boreal transition ecoregion which has a relatively dry climate 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, each of which was at least 20 ha in size, six plots were established at a minimum distance of 50 m from each other. Each plot consisted 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.

During the 2007 growing season, soil samples (approximately 500 ml in size) were taken from the A, B and C horizons from one soil pit in the middle of each plot. Other soil and site information recorded included depth of A horizon, depth to mottling (or signs of gleying), topographic position, geographic location, and elevation. 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). Individual tree volumes were calculated using diameter at breast height (DBH) and total height of the tree based on the volume equation for HP developed in Ontario (Ontario Ministry of Natural Resources 1991). Plantation volumes (m^3 ha^{-1}) were then calculated based on 1100 trees ha^{-1}.

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 from a sub-sample using the Horiba Partica LA-950 Laser Particle Analyzer. The A horizon samples were treated with NaOCl because of the high C levels and presence of aggregates. Sodium hexametaphosphate (4 mg per sample cell) and sonication for 1 minute at level 7 were used on all samples for particle dispersion before measurement. Electrical conductivity and pH were measured in water for the A horizons using a 1 to 5 soil to water ratio. 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 Analyzer at 1100ºC. Elemental composition (Ca, Mg, K, Na, P, Si, Al, Fe, Mn and Ti) 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). The results were recalculated as oxides in weight percent.

From each tree, the 25-leaf bulked sample was oven-dried at 40ºC until it was at constant weight and then finely ground in a ball mill prior to C and N determination using the Leco CNS-2000 Analyzer. For Ca, Mg, K and P, the leaf samples were digested in a 15 N 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. Base nutrient concentrations were determined using atomic absorption/emission, whereas P concentrations were analyzed colourimetrically (molybdenum blue) with a Technicon Auto-Analyzer. The same procedure as that for base nutrients was used for determining Cu and Mn levels in leaves, except that only one tree per plot was analyzed. 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 growing season (Stewart et al. 1995, McNulty and Swank 1995) in seasonally dry climates where variation in other environmental factors is minimal (Warren et al. 2001). Our study meets these assumptions since it is located in a region where precipitation does not exceed potential evapotranspiration and differences in other environmental factors are reduced through common silvicultural treatments at all sites, including the use of an identical clone and plots under the same hydroclimatological conditions. Therefore, the

major factor controlling $\delta^{13}C$ foliar concentration should be soil water availability as affected by soil and site properties. Although foliar estimates of $\delta^{13}C$ reflect only the current growing season, the 2007 growing season had similar precipitation (400 mm) as the previous three years and was slightly less than the normal of 500 mm.

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) using correlation and multiple regression analysis. Other measures of tree productivity, i.e. diameter, volume and height growth, were also tested using linear models, resulting in very similar relationships between site properties and tree productivity. However, the relationships with tree height resulted in slightly better R^2 values and were therefore used throughout the study as the best measure of productivity. 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 using plot means (n=6 for five of the plantations and n=5 for the other). Correlation along with simple linear and quadratic non-linear regressions were used to determine the suite of variables most closely related to tree productivity at both the local and microsite scales. All statistics were completed using SPSS version 15.0 (SPSS Inc., Chicago, Illinois).

Results

General Site Properties

Average tree productivity values along with foliar and soil properties are presented in Table 1 for each of the six sites. After 4 years of growth, plantation average tree height ranged from 279 to 398 cm. This range was greater, i.e. 187 to 498 cm, when using the means of all 35 plots. Leaf P concentrations ranged between 0.65 and 1.14 g kg^{-1}, whereas leaf N ranged 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.

Local Scale Analysis

Climate differences between plantations were not a major controlling factor of HP productivity in this region given that the climatic proxies of northing ($p=0.456$) and elevation ($p=0.912$) were not correlated with HP productivity, thereby placing the focus on the soil and site properties impacting tree growth in our models. Significant linear relationships between soil properties, foliar nutrient status and tree height using all 35 plots and the six plantation averages are presented in Table 2 and Figures 1 and 2. The strongest relationships were with $\delta^{13}C$ which was negatively related to tree height and foliar P concentration, depth of the A horizon and MnO content in the B horizon which were all positively related to tree height. It also appears that there is a distinct threshold value for electrical conductivity of approximately150 µS cm^{-1}, above which tree height decreases. Foliar Cu concentration and total CaO in the B horizon were positively related to HP productivity, while foliar Mn concentration was negatively related.

Two other variables were related to tree growth but showed curved relationships (Figure 3). 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% ($p=0.001$ for the 35 plots and $p=0.081$ for the six plantation averages). A horizon pH also showed a quadratic relationship to tree height with an optimal pH of about 6 ($p=0.100$ for the 35 plots and $p=0.113$ for the six plantation averages). All of the variables mentioned above that were related to tree productivity were also correlated with either the amount of sand in the B horizon or the pH of the A horizon (Table 3). For example, foliar P concentration ($p=0.040$) and electrical conductivity ($p<0.001$) were non-linearly related to pH. Also, foliar Cu concentration ($p=0.002$) was negatively related to pH, while MnO in the B horizon ($p=0.049$) was non-linearly related to the amount of sand in that same horizon.

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, sand content was the most highly correlated variable to tree size, whereas the remaining site had no measured soil or site variables related to productivity (Table 4). However, the influence of sand content on tree productivity differed between sites. For example, at sites 1, 5 and 6, increasing sand was negatively related to tree productivity, while at sites 2 and 4, increasing sand was positively related to tree productivity. Other soil, site and foliar variables were not related to tree productivity (e.g., pH, electrical conductivity and foliar nutrients) even though some of these variables were significant at the local scale. Foliar Mn and Cu concentrations 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, nor did elemental soil chemical compositions show consistent relationships with tree growth or foliar nutrient status.

Discussion

Tree growth is related to the amount of resources the tree can acquire. Within a local area, the largest difference between sites is often the soil and site properties which strongly influence the amount of water and nutrients available for tree growth (Carmean 1975). In this study, it appears that two relatively simple variables, pH of the A horizon and the amount of sand in the B horizon were reliable indicators of water and nutrient availability for the whole area. Other variables, such as total soil chemistry and foliar nutrient concentrations were related to percent sand and pH and did not explain more of the variability in tree productivity. Depth of the A horizon is another relatively simple variable that was positively related to HP productivity. This likely represents the amount of quality rooting space available for trees and has previously been shown to be an important factor in determining HP productivity on the Canadian Prairies (Schroeder et al. 2003). This is also similar to the depth to root restricting layer which has been related to trembling aspen productivity in northern Ontario (Carmean 1996). Particle size distribution and acid-base status of the parent material partly influences A horizon development and thus, it would not be surprising that A horizon depth is also related to soil pH and/or texture in combination with factors such as topography and site history. In fact, a quadratic relationship was found between A horizon depth and sand content, but it is beyond the scope of the paper to elucidate these relationships. For management

decisions, which are generally made at the local scale, percent sand and pH thus seem the best criteria to use to predict the best growing sites in this area, especially that they are easily and rapidly measured soil variables.

Moisture Availability

Soil texture (percent sand), 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, Pinno and Bélanger (2009) found that soil texture was the best predictor of HP growth in central Saskatchewan with soils with more silt and clay producing better growth. For trembling aspen, Paré et al. (2001) in Quebec and Martin and Gower (2006) in Manitoba also found that aspen trees were taller on clayey soils as opposed to coarser textured soils, presumably because of the greater water holding capacity of the clay soils.

In our study however, Brooks6 productivity was not linearly related to percent sand. Rather, there appears to be an optimal sand content range and productivity decreases outside of this range. In sites with high sand contents, productivity is favored by increasing amounts of silt and clay, likely leading to more available moisture for plant growth. On finer textured sites, productivity is promoted by increasing sand content perhaps because this favors better soil aeration and drainage.

This relationship between soil water and HP productivity is supported by $\delta^{13}C$ data with more negative values suggesting more available water during the growing season.

The negative relationship between HP growth and foliar $\delta^{13}C$ indicates that available soil moisture was positively related to HP productivity. However, at the microsite scale, it appears that this particular clone is quite sensitive to excess soil water as shown by the poor growth of the trees in depressional / poor drainage microsites (personal observation). This has also been found with a balsam poplar clone in Germany which grew better on well drained soils compared to sites with evidence of stagnant water (Hofmann-Schielle et al. 1999). Even though the hybrid poplar clone used in our study has been identified as having higher water use efficiency than other clones (DesRochers et al. 2007), it is still sensitive to extremes in available soil moisture.

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 appeared to access nearly all the N required for maximum growth based on optimal foliar concentrations of 33 g N kg^{-1} as 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) and in central Saskatchewan (Pinno and Bélanger 2009). 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 production of N-fixing legume crops.

Foliar P was the nutritional variable most related to HP productivity. Foliar P values (mean = 0.88 g P kg^{-1}) were much lower than the optimal value of 3.3 g P kg^{-1} proposed by Hansen (1994), indicating that any increase in P nutrition should improve growth. These low foliar P levels and strong positive relation to growth has also been found for another study of HP plantations in central Saskatchewan (Pinno and Bélanger 2009). 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, than any further increases in N availability/uptake could result in P imbalances in HP (DesRochers et al. 2006).

Soil pH is often used as a general indication of nutrient availability. Soil P availability, for example, is usually at its highest at a pH ranging from 6 to 7 (Brady and Weil 1996). In this study, the A horizon pH of the sites ranged from about 4.9 to 7.8. Both high (≥7.0) and low (≤6.0) pH values resulted in reduced HP growth and foliar P concentrations. The optimum pH value for growth and P nutrition of Brooks6 appeared to be between 6.0 and 6.5. For this particular clone, Desrochers et al. (2007) also found in a greenhouse study that at pH 7 compared to pH 5, stomatal conductance and N and P uptake were all reduced. At higher pH, P is known to become less available due to its bonding with the abundant Ca in the soils. At lower pH levels, Al and P also form complexes and precipitate, again making the P unavailable for plants (Havlin et al. 2005). For the sites studied here, soil pH and P availability thus seem to be interacting and influencing, at least in part, the P nutrition and growth of the HP clone Brooks6. Soil total P levels at many of the Alberta sites were high at pH values of low P availabilities.

Total P in soil was therefore a poor predictor of soil P availability and was not as well related to HP growth or foliar P.

Total CaO in the B horizon was also positively related to HP productivity. This seems reasonable given that base nutrients, in particular Ca, are very important for the 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). However, many of the soils in the area have a petrography acquired through the glacial transport of the quartzitic rocks (metamorphosed SiO_2 rich sandstone) that abound in the surrounding area. In fact, many of soils exhibited a SiO_2 content greater than 85%. Therefore, in the absence of a relationship with foliar Ca, we believe the positive relationship between HP growth and soil CaO content is indicative of trees doing generally better on better buffered soils. This is further supported by the positive relationship between soil pH and CaO content.

Foliar Cu concentrations were positively related to HP productivity. Interestingly, this area is known for its Cu deficiencies in small grain crops growing on sandy soils (Havlin et al. 2005). Also, micronutrient deficiencies in short rotation intensive forestry plantations are known to be more common than in natural forests due to the fast growth rates and high resource demands of the trees (Ericsson et al. 1992). Soil Cu availability is usually at its highest at a pH ranging between 5 and 6 and decreases above or below these pH values (Brady and Weil 1996). The plots in our study generally have a soil pH between 5 and 6.5, giving an inconvenient spectrum for testing the effects of soil pH on soil Cu availability and uptake in trees. Our field design and sampling, however, captured two plots with soil pH values above 7.2 which appear to be driving the negative

relationship between soil pH and foliar Cu. If these two plots are removed, then the relationship disappears. Our data thus offer only weak evidence that Cu availability in these HP plantations is suppressed at soil pH starting around 7. Moreover, the soil elemental Cu was not related to tree growth or foliar Cu concentration because total soil Cu is a poor predictor of Cu availability to trees outside its optimum pH range. To determine if Cu is deficient for Brooks6 in this area, it would be necessary to conduct fertilization trials where more sites fall below and above the optimum pH range for Cu availability.

Foliar Mn concentration was negatively related to HP productivity. Similar relationships between foliar Mn and tree growth have been observed in Eastern North American sugar maple stands growing on acidified soils (Houle et al., 2007; Horsley et al., 2000). The optimum Mn bioavailability is generally at pH below 5.0 and decreases progressively until neutral or slightly alkaline conditions (Havlin et al. 2005). In this case, as opposed to Cu, our plots were better situated along the decreasing Mn availability spectrum. The effects of soil pH on Mn availability and uptake in trees were therefore clearly demonstrated from the negative relationship between foliar Mn and soil pH. The negative relationship was maintained even when removing the two sites with pH above 7.2, suggesting also a significant decreasing gradient in soil Mn availability from pH 5 to 6.5. Therefore, the relationship between foliar Mn and tree growth is again likely governed in part by soil pH. Houle et al. (2007) could not confirm that the high Mn levels in leaves were a cause of the poor health of sugar maple stands rather than a symptom, but they speculated that soil acidification and the associated release of Mn in soil solution could play a large role in sugar maple decline. In this study, however, it is

difficult to suggest that Mn is negatively impacting the growth of HP trees due to the following : (1) Mn levels in HP leaves are one order of magnitude lower (0.03 to 0.11 mg g^{-1}) than sugar maple Mn levels in leaves (0.5 to 2.3 mg g^{-1}) reported by Houle et al. (2007); (2) the Alberta soils are lower in Mn with the average total B horizon MnO level (0.34 mg g^{-1}) being less than half that found in Boreal Shield BC horizons of Quebec (0.88 mg g^{-1}) (Bélanger, unpublished data); and (3) Mn availability to trees in Boreal Shield soils is likely greater than in Alberta soils because of more acidic conditions, increasing Mn solubility. The low MnO contents coupled with the higher soil pH in the Alberta soils compared to eastern Shield soils likely explain the differences in foliar Mn levels between HP and sugar maple trees. The high dominance of quartzite in the soils of the Athabasca region is proposed to be the cause for this low MnO content compared to other soils. It is also believe that the Alberta soils with the highest MnO contents have resulted from the glacial mixing of quarzite and complementary geologies (with greater amounts of base cations, P, Al, Mn, Fe and trace metals) in the surrounding area, thus yielding a positive relationship between MnO and HP growth. The latter relationship is no indication, however, of Mn availability to trees as it is mostly influenced by soil pH.

Conclusion

It appears possible to predict and identify the best growing sites/microsites for this particular HP clone based on simple soil and site factors, those being pH and texture (or sand content). The choice of scale, local or microsite, depends on the desired use of the information. 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 these different clones. For example, the clone Brooks6 appears to be best adapted to specific sand content and pH ranges. Other clones are likely adapted to texture and pH ranges above and below that of Brooks6, thereby increasing the precision with which plantation management decisions can be made.

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Table 1: Average tree and soil characteristics for each plantation. DBH is the diameter at breast height (1.3 m). Total soil chemistry data are from the B horizon.

Site	Tree height	DBH	Volume	Leader growth	Foliar N	Foliar P	Foliar K	Foliar Ca	Foliar Mg	Foliar Mn	Foliar Cu	Foliar $\delta^{13}C$
	(cm)		($m^3 ha^{-1}$)	(cm)	($mg\ g^{-1}$)							(‰)
1	279	2.1	1.8	109.4	36.2	0.77	13.8	10.7	3.54	0.099	0.012	-25.09
2	299	2.2	1.9	101.6	32.1	0.65	10.5	9.8	4.69	0.088	0.011	-25.62
3	306	2.7	3.1	102.5	29.3	0.96	16.5	11.6	3.53	0.061	0.008	-26.16
4	360	3.0	3.3	94.5	29.2	0.88	11.0	9.3	4.37	0.073	0.010	-25.54
5	373	3.7	4.8	118.6	25.3	0.89	12.3	11.7	4.62	0.047	0.016	-26.67
6	398	3.7	4.6	146.3	35.7	1.14	16.0	11.4	2.72	0.075	0.016	-27.30

Site	A hor. sand	B hor. sand	C hor. clay	A hor. pH	Electrical conduc.	A hor. depth	Mottle depth	A hor. N	A hor. C	MgO	K_2O	CaO	P_2O_5
	(%)				($\mu S\ cm^{-1}$)	(cm)		($mg\ g^{-1}$)		(%)			
1	75	77	10	5.7	93.8	14.8	43.0	2.1	20.1	0.46	1.18	0.568	0.062
2	55	34	28	5.6	88.2	15.7	29.7	2.5	23.6	1.22	1.88	0.412	0.114
3	70	77	10	6.7	118.7	20.8	51.5	2.3	23.7	0.54	1.51	0.725	0.089
4	63	61	9	6.0	42.9	17.8	21.3	1.7	15.3	0.83	1.45	0.612	0.083
5	56	57	15	6.1	135.8	19.0	20.2	2.3	24.9	1.00	1.58	0.782	0.098
6	73	66	5	6.1	49.6	25.0	38.7	1.8	16.5	0.73	1.65	0.715	0.116

Note: Total soil chemistry data is for the B horizon.

Table 2: Local scale correlation analysis (r) and associated p-values using all plots (n=35) and plantation averages (n=6). Correlation coefficients are given for all relationships with p<0.15.

	All plots (n=35)		Plantation averages (n=6)	
	p	r	p	r
Foliar N	0.308	-	0.627	-
Foliar P	0.111	0.274	0.096	0.736
Foliar K	0.949	-	0.838	-
Foliar Ca	0.978	-	0.656	-
Foliar Mg	0.449	-	0.729	-
Foliar Mn	0.055	-0.327	0.229	
Foliar Cu	0.052	0.332	0.818	
Foliar $\delta^{13}C$	0.002	-0.505	0.053	-0.807
A horizon sand content	0.400	-	0.823	-
B horizon sand content	0.693	-	0.921	-
C horizon clay content	0.251	-	0.423	-
A horizon pH	0.915	-	0.615	-
A horizon electrical conductivity	0.118	-0.270	0.520	-
A horizon depth	0.056	0.326	0.090	0.743
Depth to mottling	0.613	-	0.355	-
A horizon N content	0.218	-	0.253	-
A horizon C content	0.204	-	0.424	-
MgO	0.251	-	0.674	-
K_2O	0.197	-	0.601	-
CaO	0.003	0.488	0.200	-
P_2O_5	0.086	0.295	0.297	-
MnO	0.001	0.564	0.001	0.977
SiO_2	0.202	-	0.619	-

Note: r values are reported for all relationships with p<0.15; total chemistry data is for the B horizon.

Table 3: Relationships between all variables correlated with HP productivity and the general soil characteristics of percent sand content and pH.

	B horizon sand content			A horizon pH		
	Form	p	R^2	Form	p	R^2
All 35 Plots						
Foliar P	Quadratic	0.006	0.272	Quadratic	0.04	0.214
Foliar Mn		-		Linear	0.001	0.337
Foliar Cu		-		Linear	0.002	0.249
Foliar $\delta^{13}C$		-		Linear	0.038	0.123
A horizon electrical conductivity		-		Quadratic	0.001	0.589
A horizon depth	Quadratic	0.034	0.233		-	
CaO	Quadratic	0.001	0.448	Quadratic	0.001	0.404
P_2O_5	Linear	0.008	0.192		-	
MnO	Quadratic	0.001	0.434		-	
Plantation Averages						
Foliar P		-		Quadratic	0.144	0.726
Foliar $\delta^{13}C$		-			-	
A horizon depth		-			-	
MnO	Quadratic	0.049	0.874	Quadratic	0.049	0.867

Note: Total chemistry data is for the B horizon.

Table 4: Microsite scale correlation analysis (r) and associated p-values for the single most highly correlated soil variable with HP productivity for each plantation. Correlation coefficients are given for all relationships with $p<0.15$.

Site	Variable	r	p
1	B horizon sand content	-0.855	0.030
2	B horizon sand content	0.803	0.054
3	No significant relationship	-	-
4	A horizon sand content	0.729	0.087
5	A horizon sand content	-0.802	0.048
6	B horizon sand content	-0.775	0.070

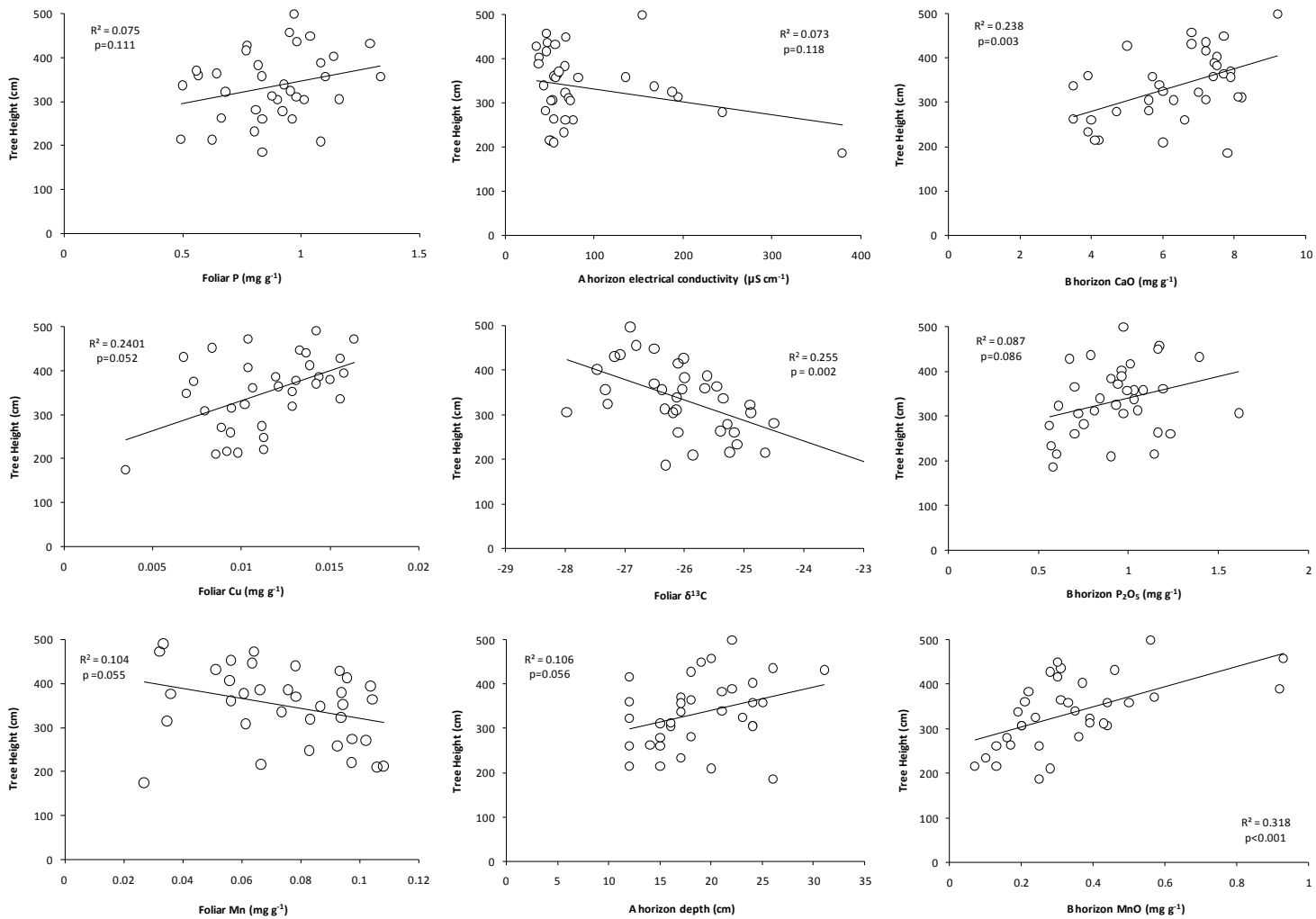

Figure 1: All significant local scale relationships between HP productivity and soil and site properties using all 35 plots.

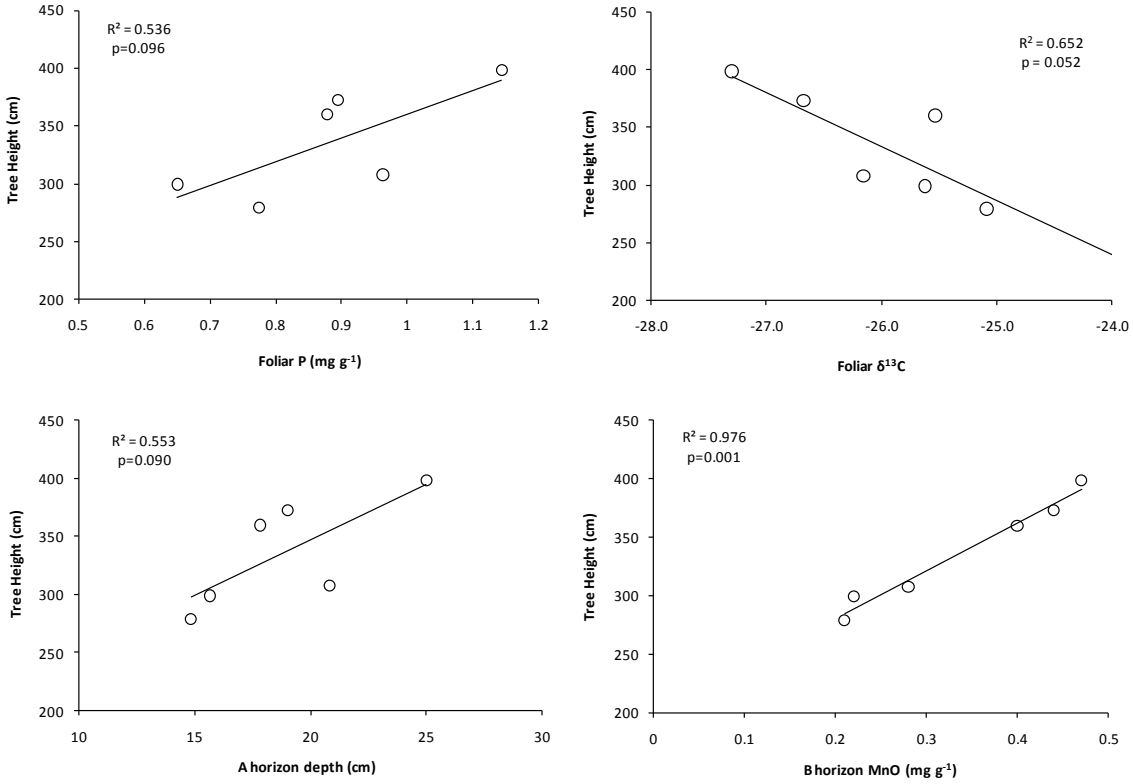

Figure 2: All significant local scale linear or quadratic relationships between HP productivity and soil and site properties using plantation averages (n=6).

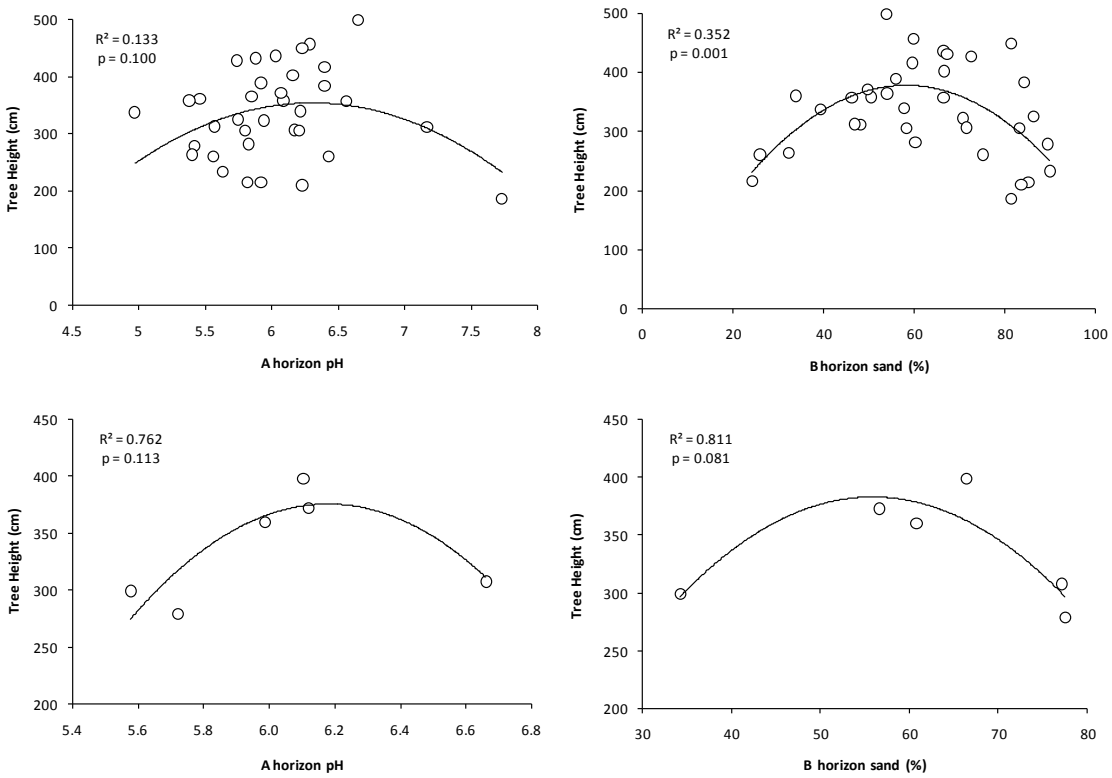

Figure 3: Quadratic relationships between A horizon pH, B horizon percent sand content and HP productivity using all 35 plots and plantation averages.

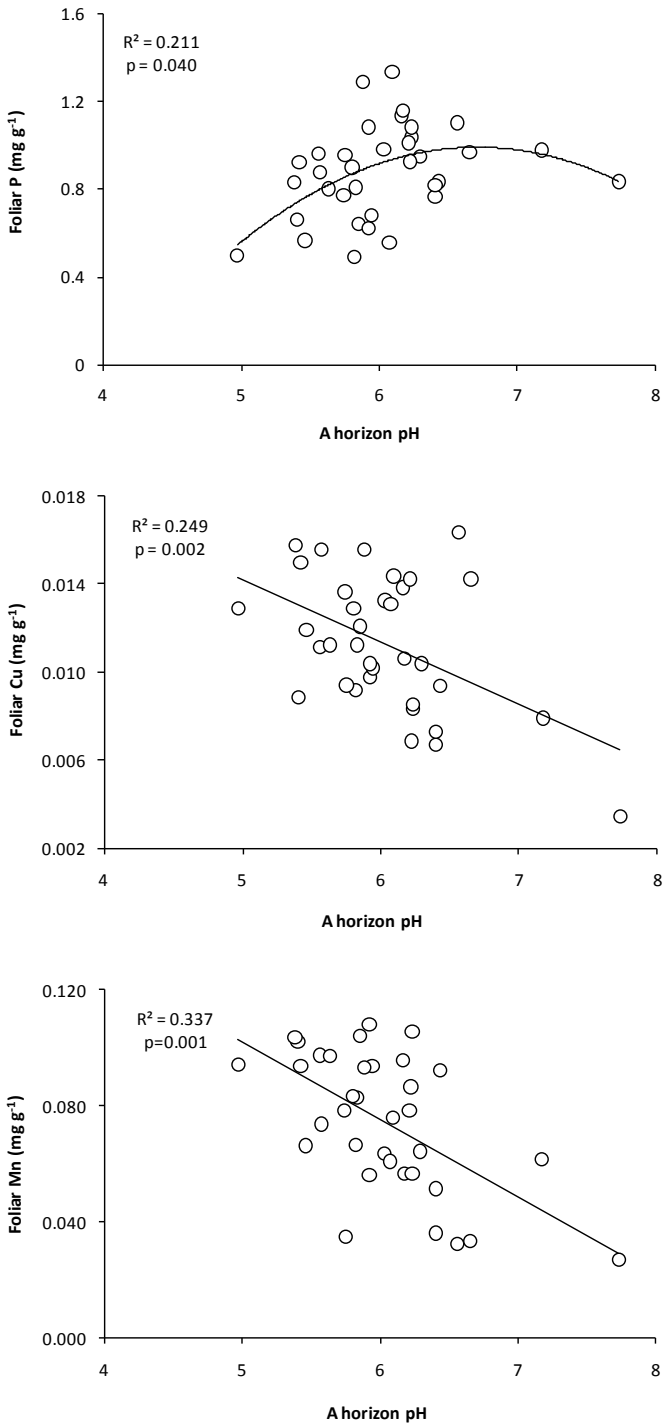

Figure 4: Relationships between foliar nutrients and soil pH.