Determining Soil Nutrient Requirements For Growing Hybrid Poplar

R.D. Hangs[1], K.J. Greer[2], K.C.J. Van Rees[1], and W.R. Schroeder[3]

[1]Department of Soil Science, University of Saskatchewan, Saskatoon, SK S7N 5A2, [2]Western Ag Innovations, 3 - 411 Downey Road, Saskatoon, SK S7N 4L8, [3]W.R. Schroeder, Prairie Farm Rehabilitation Administration, Agriculture and Agri-Food Canada, Shelterbelt Centre, Indian Head, SK S0G 2K0.

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Abstract

Under conditions of adequate soil moisture, reductions in the early growth of tree seedlings mainly are attributable to soil nutrient limitations. Monitoring soil nutrient availability, therefore, is important for ensuring optimal tree nutrition and promoting successful seedling establishment and growth. Notwithstanding the importance of routine soil testing practices in supporting annual crop production, less than 10 % of the fields in western Canada currently are managed based on annual soil testing practices. Consequently, producers see limited utility in the fertilizer recommendations provided to them based on conventional soil tests. The objective of this three-year study was to measure nutrient supply rates at several hybrid poplar plantations in northern Saskatchewan, using *in situ* burials of ion-exchange membrane (Plant Root Simulator™-probes), and relate these data to plantation productivity during the early establishment phase. Determining the relationship between soil nutrient supply rates and seedling growth should help to support effective management strategies, in terms of proper site selection and elucidating possible fertilizer requirements.

Introduction

In Saskatchewan, there is a large amount of current agricultural land that is suitable for growing perennial woody species, such as hybrid poplar. Consequently, the Saskatchewan government in 2005 proposed an ambitious 1.6 million-hectare (i.e., 10 per cent of the province's arable land) 20-year afforestation initiative, with the intention of addressing not only the expected increased demand for woody biomass as differential markets develop, but also to mitigate the increasingly unfavourable agricultural sector within the province. The establishment of short-rotation hybrid poplar plantations, therefore, represents a legitimate option for diversifying farmers trying to maintain an economically viable operation in the face of historically decreasing commodity prices, along with increasing input and transportation costs, especially in the northern regions where annual crops are grown on marginal agricultural soils.

Before there is widespread adoption of agroforestry practices in Saskatchewan, however, a clear economic advantage for producers to grow hybrid poplar must become apparent. In order to achieve this goal, there needs to be adequate survival and growth of planted seedlings, especially within the first few years. Under conditions of adequate soil moisture, reductions in the early growth of tree seedlings mainly are attributable to soil nutrient limitations. Monitoring soil nutrient availability, therefore, is important for ensuring optimal tree nutrition and promoting successful seedling establishment and growth. Notwithstanding the importance of routine soil testing practices in supporting annual crop production, less than 10 % of the fields in western Canada currently are managed based on annual soil testing practices (Karamanos, 2001). Since the inception of soil testing, grower adoption of annual soil testing has been minimal, with a peak occurring in 1968 followed by a large decline until the late 70's/early 80's, where it has since stabilized (Jones and Kalra, 1992). Such statistics clearly indicate that producers see limited utility in the fertilizer recommendations provided to them based on traditional soil tests (Green et al., 2000). Although the crop may be different, producers growing hybrid poplar have similar biases towards conventional soil testing, therefore, requiring the development of an alternative soil testing technology. Unlike conventional soil extractions, *in situ* burials of ion-exchange resin integrates all of the principal edaphic factors affecting nutrient uptake by plants (Yang et al., 1991; Qian et al., 1992; van Raij, 1998; Qian and Schoenau, 2002).

The objective of this three-year study, therefore, was to measure soil nutrient supply rates at several hybrid poplar plantations in northern Saskatchewan, using *in situ* burials of ion-exchange membrane (Plant Root Simulator (PRS)™-probes; Western Ag Innovations Inc., Saskatoon, SK), and relate these data to plantation productivity during the early establishment phase. Measuring soil nutrient supply rates for three years is necessary to properly correlate baseline fertility data with plantation productivity during the early establishment phase. Diversifying producers can use PRS™-probes and the database generated from this study as a decision support tool for making effective management decisions related to agroforestry practices. Specifically, they will form the basis of *a priori* site assessments for the selection of suitable afforestation sites and determine the fertility requirements needed to promote successful seedling establishment and growth.

Materials and Methods

Study sites

The data for this study were collected from four hybrid poplar plantations in northern Saskatchewan. Two sites are located approximately 25 km southwest of Meadow Lake, Saskatchewan (Cubbon: NW 22 58 19 W3; Culbert: SW 31 57 19 W3). The other two sites are located near Star City and Arborfield (NW 36 45 17 W2 and NE 4 46 12 W2, respectively). Although the topography of all sites is very gently undulating (i.e., slopes less than two percent), the soil and site characteristics are diverse (Table 1).

Experimental design

At the two Meadow Lake sites, the experimental design was a 3 x 2 x 2 factorial, randomized complete block and replicated three times. The treatments include: stock type (cuttings, rooted cuttings, and container seedlings), pruning (pruned lower branches and unpruned), and fertilization split-plots. For the fertilization treatment, half of the treatment plots within each block were control plots and the others designated fertilizer plots. Within the fertilizer plots, each plot was split in half (i.e., split-plot design) with one half receiving a broadcast application of NH_4NO_3 fertilizer (100 kg N/ha) on June 4, 2003 (year two of the plantation; Figure 1a), while the second half received a similar fertilizer N application along with and additional application of $(NH_4)H_2PO_4$ fertilizer (25 kg P/ha) on June 9, 2005 during the

Table 1. Selected Characteristics of Four Hybrid Poplar (HP) Study Sites Located in Northern Saskatchewan.

Site	Soil Characteristics					Site Characteristics			Vegetation Management Practices			
									Pre-planting		Post-planting	
	Association	Soil Type	Texture	pH	EC (mS/cm)	Prior Crop (year HP planted)	ACC[*]	Rainfall[†] (mm)	Mechanical	Chemical	Mechanical	Chemical
Cubbon[‡]	Loon River	Orthic Gray Luvisol	sandy-loam to loam	6.5	0.8	alfalfa (2002)	3-4	190 (2003) 308 (2004) 371 (2005)	- Deep till - Light cultivation	- Glyphosate (2.5 L/ha) - Linuron (4 kg/ha)	-Tandem disc -Mowing	- Glyphosate (2.5 L/ha) - Linuron (4 kg/ha)
Culbert[‡]	Bittern Lake	Brunisolic Gray Luvisol	sandy-loam to loam	5.4	0.7	pasture (2002)	4-5	190 (2003) 334 (2004) 412 (2005)	Deep till (x2)	- Glyphosate (2.5 L/ha) - Linuron (4 kg/ha)	Tandem disc	- Glyphosate (2.5 L/ha) - Linuron (4 kg/ha)
Star City[§]	Melfort-Hoey	Orthic Black Chernozem	clay-loam to loam	5.1	0.8	canola (2002)	1	250 (2003) 429 (2004) 320 (2005)	Tandem disc (x 2)	- Treflan (5 L/ha) - Sencor (395 g/ha)	-Tandem disc -Mowing	- Glyphosate (2.5 L/ha) - Linuron (4 kg/ha)
Arborfield[¶]	Eldersley	Orthic Gray Luvisol	clay-loam to loam	6.3	0.6	wheat (2003)	2	350 (2003) 496 (2004) 393 (2005)	Tandem disc (x 2)	- Treflan (5 L/ha) - Sencor (395 g/ha)	-Tandem disc -Mowing	- Glyphosate (2.5 L/ha) - Linuron (4 kg/ha)

[*] Agriculture capability classification (Class 1: no significant limitations; Class 2: moderate limitations; Class 3: moderately severe limitations; Class 4: severe limitations; Class 5: very severe limitations).

[†] During the period of PRS™-probe burials.

[‡] For a complete description (i.e., map unit, parent material, stoniness, drainage, etc.) see SCSR (1995).

[§] For a complete description see SCSR (1989).

[¶] For a complete description see Stonehouse and Ellis (1983).

Figure 1. Broadcast application of NH_4NO_3 fertilizer (100 kg/ha) on June 4, 2003 (a) and NH_4NO_3 (100 kg N/ha) and $(NH_4)H_2PO_4$ (25 kg P/ha) fertilizers on June 9, 2005 (b).

fourth growing season (Figure 1b). The remaining two sites had no imposed treatments, but instead were simply clonal studies set-up in a randomized complete block design (12 and 18 different hybrid poplar clones planted at the Star City and Arborfield sites, respectively) and replicated three times. The Meadow Lake and Star City sites were established in the spring of 2002, while the Arborfield site was planted in June 2003.

Soil nutrient analysis

Plant Root Simulator (PRS)™-probes were used to measure soil nutrient availability at each site. Plant Root Simulator™-probes provide a basis for determining fertilizer recommendations for different cereal, oil seed, pulse, and forage crops in western Canada (Qian and Schoenau, 2002) and have been used to study forest soil nutrient dynamics in both undisturbed and disturbed sites (Huang and Schoenau, 1996;1997; Johnson et al., 2001; Duarte, 2002; Hangs et al., 2004). The PRS™-probe consists of either cation- or anion-exchange resin membrane encased in a plastic holding device and is inserted into soil to measure nutrient supply rates *in situ* with minimal disturbance (Figure 2).

At the Meadow Lake sites, four pairs of PRS™-probes (i.e., four cation- and four anion-exchange) were installed within each treatment plot, for a total of 288 PRS™-probes (i.e., 12 treatment plots x 3 reps x 4 PRS™-probes x 2 types) per burial period at each site. At the other two sites, two pairs of PRS™-probes were installed within each clone plot, for a total of 144 (i.e., 12 clone plots x 3 reps x 2 PRS™-probes x 2 types) and 216 (18 clone plots x 3 reps x 2 PRS™-probes x 2 types) PRS™-probes per burial period at the Star City and Arborfield sites, respectively. The PRS™-probes were inserted vertically into the Ap horizon (Figure 2); thereby having the IEM effectively measure soil nutrient supply rates in the zone having the largest concentration of hybrid poplar roots (Block, 2004). The PRS™-probes were left in the soil for five weeks and then replaced with fresh PRS™-probes twice more during the growing season for

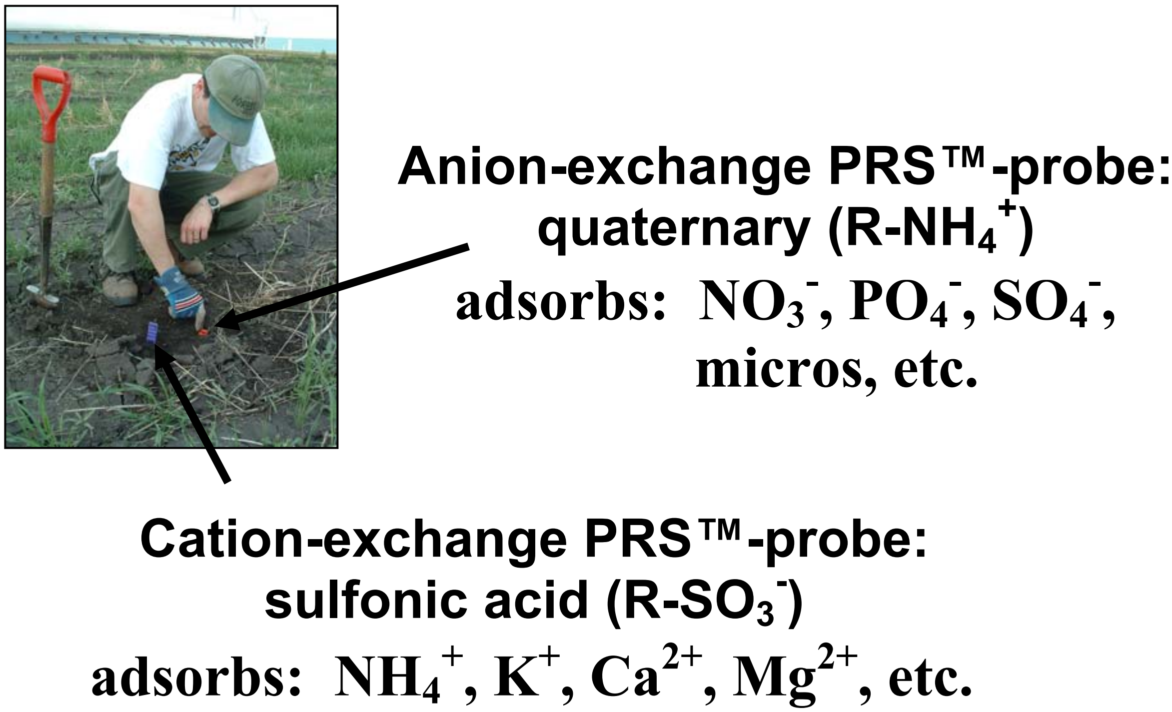

Figure 2. PRS™-probes used to measure soil nutrient availability *in situ*.

a total of 15 weeks in 2003, 2004, and 2005 (only the 2005 data is reported). Replacing fresh PRS™-probes in the same soil slot provides a true *in situ* measure of temporal nutrient availability and yields the most accurate index of nutrient availability to correlate with seedling growth. Consequently, continuously measuring soil solution nutrient availability should provide a basis for accurately predicting nutrient supply-limited uptake or growth, because it is an integral part of the mechanisms governing nutrient supply and uptake (Lajtha et al., 1999; Smethurst, 2000).

Although the PRS™-probes greatly simplify the use of ion-exchange resin technology *in situ*, a few fundamental principles still need to be considered in order to ensure the accuracy and precision of the nutrient supply rate data. Primarily, when burying the PRS™-probes for extended periods, it is imperative to account for any other below-ground competing sinks, such as plant roots (Figure 3a). When placed among plant roots, the PRS™-probes will provide a *net nutrient supply rate* (i.e., measuring the difference between total soil nutrient supply and plant uptake); therefore, yielding a measure of *nutrient surpluses* rather than *net mineralization* over the burial period. Depending on the research objective this may be desirable (Huang and Schoenau, 1997; Hangs et al., 2004); however, if the goal is to measure the effects of net mineralization on nutrient supply (which is the case in this study), then the confounding effects of below-ground competition from plant roots is undesirable and the use of a root exclusion cylinder (i.e., PVC pipe) is required (Figure 3b). The use of a PVC cylinder does not significantly affect soil temperature and moisture and, therefore, soil N supply to the PRS™-probes compared with bulk soil (Adams et al., 1989; Hart and Firestone, 1991; Huang and Schoenau, 1997). Throughout the growing season any plants growing within the cylinder were removed.

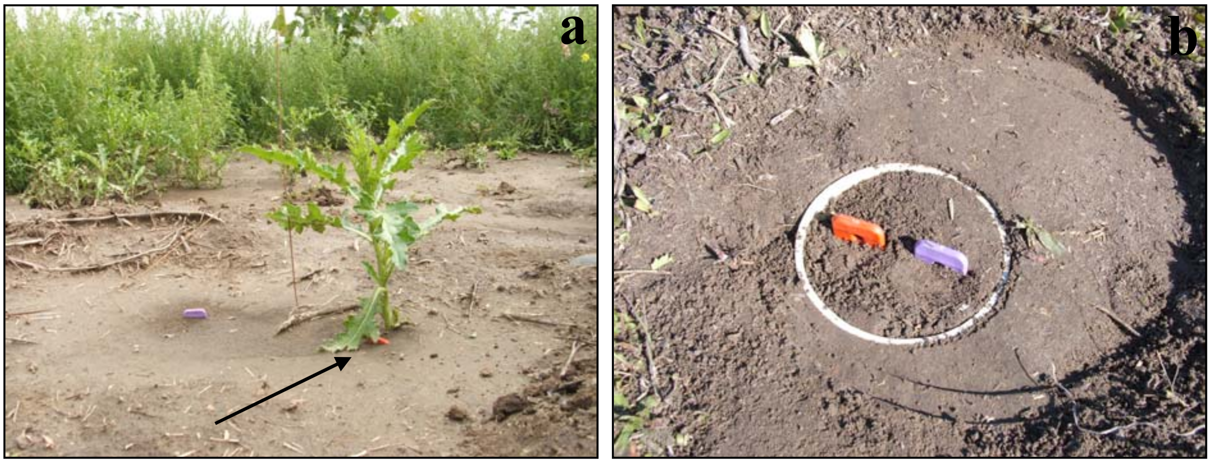

Figure 3. Below-ground competition for soil nutrients between *in situ* burials of PRS™-probes (arrow) and non-crop vegetation (a) and the use of a root exclusion cylinder (i.e., PVC pipe) to minimize the confounding effects of root competition (b).

After removal, the PRS™-probes were washed free of soil and then thoroughly scrubbed and re-washed back in the lab prior to the analysis to ensure complete removal of any residual soil. The PRS™-probes within each treatment plot were combined for analysis, much like a composite soil sample, and this helped to account for any microscale variability. The PRS™-probes were analyzed according to Hangs et al. (2004). Briefly, after elution with 0.5N HCl, the inorganic N as ammonium (NH_4^+-N) and nitrate (NO_3^--N) in the eluate was determined colourimetrically and the remaining nutrients (P, K, S, Ca, Mg, Cu, Zn, Mn, Al, Fe, B, and Pb) were measured using inductively-coupled plasma spectrometry. Unused PRS™-probe method blanks also were analysed to test for contamination during the regeneration and handling steps.

Seedling survival and growth

At the end of each growing season, seedling establishment and growth were assessed at each site by measuring seedling survival, ground-line diameter (GLD), and height. Determining the relationship between soil nutrient supply rate at both time of planting and throughout each growing season and subsequent seedling growth should help support effective management strategies, in terms of proper site selection and effectively managing fertilizer requirements.

Statistical analyses

The soil nutrient availability and seedling growth data were analysed independently by site using the GLM procedure in SAS (Version 8.0, SAS Institute Inc. Cary, NC). Mean comparisons were performed using least significant differences (LSD) at a significance level of 0.05. The LSD option was used to carry out pair-wise *t* tests (equivalent to Fisher's protected LSD) of the different means between treatments and clones. All data were tested for homogeneity of variances and normality. Simple linear regressions were performed using the REG procedure in SAS (Version 8.0, SAS Institute Inc. Cary, NC) using pooled data (i.e., all sites) to quantify the relationship between the nutrient supply rate data during the 2003, 2004, and 2005 growing seasons and growth of hybrid poplar seedlings over that same period. Residuals from the analyses were examined to the test the assumptions of equal variance and no data transformations were necessary.

Results and Discussion

Nutrient availability among sites

Similar with the two previous years, there was relatively little variability in nutrient supply rate within each site during 2005 for most nutrients (i.e., CV < 35%; data not shown), which is not surprising considering that agricultural soils historically have less microscale variability compared with forest soils (Pritchett and Fisher, 1987). As with the first two years, NO_3^--N was the predominant inorganic N source available for seedling uptake at all sites and is expected considering that NH_4^+-N often is rapidly nitrified in agricultural soils (Brady, 1990). The total N supply rates (i.e., NH_4^+-N + NO_3^--N) varied among the sites with Star City and Arborfield having the largest values. The class 1 and 2 soils at these sites clearly have greater N fertility compared with the coarser-textured Luvisols at the Meadow Lake sites. The important role of past management practices on subsequent soil fertility is illustrated at Cubbon when looking at the differences in P supply rates among the sites in that Cubbon being one of the least fertile soils in this study, had the greatest P availability (Table 2). Although initially difficult to explain given the similarity in soil pH and moisture conditions among the sites, according to the landowner, apparently this site has had a long history of fertilizer applications, especially high levels of fertilizer P applied. Looking at the differences in both potassium (K) and sulphur (S) supply rates among the four sites, again these can be primarily attributed to differences in soil type, with the coarse-textured glacial till-derived soils at Meadow Lake having more K-bearing minerals than the finer-textured glacial-lacustrine-derived soils at Star City and Arborfield and, therefore, larger supply rates. Conversely with S, the finer-textured soils at Star City and Arborfield have larger amounts of organic matter and sulfate minerals than the coarse-textured soils at the Meadow Lake sites.

In terms of the remaining macro- and micro-nutrients, there was a wide range in supply rates among the four sites in this study (Table 2) and this can be attributed to a number of factors, including differences in soil type, past management practices (i.e., recently broken pasture, prior crops, fertilization, site preparation technique, etc.), and growing season conditions. Such variability in nutrient variability among these different sites is essential, for subsequently relating them to seedling growth, if accurate recommendations are to be made across a large inference space. The extremely large Mn supply rate measured at the Cubbon site in 2003 and 2004 continued in 2005, but was less pronounced (Table 2). As previously discussed, one possible mechanism for this could have been the mixing of the acidic subsoil with the calcareous topsoil, during the deep tillage of this site prior to planting, which would have lowered the soil pH and increased manganese availability. Typically, with decreased soil pH and increased Mn availability, there is a concomitant decrease in Mg availability (Havlin et al., 1999), and this was measured using PRS™-probes (Table 2). In addition, while in sustained forage production this field had a balanced fertility package applied annually with both macro- and micro-nutrients, including Mn (Dave Cubbon, personal communication), which also helps to explain the larger Mn supply rates at the Cubbon site. The only other anomaly continuing since 2003 is the very large Fe supply rate at Star City and given the expected soil pH and good soil drainage, there must have been simply an abundance of Fe-bearing minerals at this site relative to the others.

Table 2. Mean cumulative nutrient supply rates, measured using *in situ* burials of PRS™-probes, at four hybrid poplar sites in northern Saskatchewan from early May to late August, 2005.

Site	N	NH_4^+	NO_3^-	Total N	P	K	S	Ca	Mg	Cu	Zn	Mn	Al	Fe	B	Pb
		μg/10cm²/15 weeks														
Cubbon	36	32a*	952b	983b	32.6a	1338a	221c	4177d	402d	0.6d	3.8c	81.8a	96.3a	81.1c	3.3c	0.6c
Culbert	36	16b	1166b	1183b	18.6b	1034b	200c	5195c	884c	1.3c	4.8c	39.4c	65.8b	118.5bc	3.6bc	1.5b
Star City	36	7c	1636a	1644a	21.0b	163c	1207a	5714b	2137a	3.6a	13.5a	57.3b	100.6a	360.6a	4.5a	3.0a
Arborfield	54	9c	1604a	1614a	15.5b	75c	591b	7753a	1290b	2.7b	8.3b	24.8d	58.5b	139.6b	4.0b	3.0a

* Means within a column followed by the same letter are not significantly different (P >0.05) using LSD.

Nutrient availability following fertilizer application in the 2nd and 4th growing seasons

At both Meadow Lake sites two years after fertilizer N application, there was no residual effect on NH_4^+-N, NO_3^--N, and total N supply rates over the growing season, relative to plots without fertilizer N added (Table 3), even when expressed on a per-burial basis (Figure 4). As expected, the added fertilizer N in 2005 resulted in larger total N supply rates with a minimal effect on the supply rates of other nutrients except for S. This is to be expected with these low organic matter content soils having inherently small S supply rates, due to increased microbial immobilization of S as soil microbes metabolize the added fertilizer N in order to maintain an N:S required for their metabolic processes. The lack of increase in P supply rate following fertilizer P addition was unexpected though given the sensitivity of the PRS™-probes to treatment effects. However, 25kg P/ha is not a lot of added P when broadcasted across the surface. In addition, given the relatively low solubility of $(NH_4)H_2PO_4$ fertilizer, not all of the added P would be available in the season of application.

Relationship between soil nutrient availability and hybrid poplar seedling growth

Over the three years of this study and across all sites, the total N supply rate often was better correlated with seedling height, GLD, and stem volume growth than other nutrients (data not shown). The total N supply rate had a stronger correlation (R^2 0.40 to 0.94, P <0.01) with seedling growth when calculated on an individual treatment combination basis instead of using pooled data including more than one stock type, pruning method, fertilizer rate, and clone. This is not surprising considering that each treatment has a varied influence on seedling growth rate and form, cold hardiness, mortality, etc. and adds considerable variability to the seedling growth data and, therefore, weakens the resultant correlation with the PRS™-probe nutrient supply rate data. Indeed, such variability is not representative of typical operational practices. Figure 5 illustrates the strong relationship between total N supply rate measured during the 2005 growing season and the stem volume growth increment (i.e., believed to be the most accurate indicator of overall seedling vigour and growth) of outplanted seedlings each year from a single hybrid poplar clone (var. Walker), planted as rooted cuttings with no fertilizer N applied or pruning treatment and ranging in age from 2-4 years depending on the site. Due to high seedling mortality of the Walker poplar at the Arborfield site in 2003, these seedlings were replaced in 2004. Consequently, these seedlings had stem volume growth increments a magnitude smaller than the other sites during 2005 and as a result, these data greatly influenced the correlation analysis with the PRS™-probe N supply rate data (Figure 5a; red circle). These data should not be included in the analysis, because they introduce unnecessary variability into the data set and are a negative bias, as evidenced by a much stronger relationship without these data (Figure 5b). However, the correlation analysis with and without the inclusion of the 2005 Arborfield data are reported and it is up to the reader to decide for themselves which is more appropriate. Notwithstanding this, it is important to keep in mind that with or with out the inclusion of the Arborfield data, the relationship with seedling growth is much stronger with the PRS™-probe data than similar correlations with conventional soil test data (Pritchett and Fisher, 1987).

Table 3. Mean (n>18) cumulative nutrient supply rates, measured using *in situ* burials of PRS™-probes, at two Meadow Lake hybrid poplar sites from early May to late August, 2005 in plots with and without fertilizer N and P applications.

Site	Treatment	NH_4^+	NO_3^-	Total N	P	K	S	Ca	Mg	Cu	Zn	Mn	Al	Fe	B	Pb
		μg/10cm^2/15 weeks														
Cubbon	Fertilizer-2[*]	34a[†]	1000b	1034b	33.3a	1215a	224a	3963b	341b	0.5a	4.4a	168.5a	101.4ab	77.9a	3.0ab	0.5a
	Fertilizer-4[**]	35a	1830a	1865a	30.5a	950a	182b	4689a	437a	0.6a	4.1ab	133.4ab	110.3a	84.6a	2.8b	0.6a
	No Fertilizer	32a	952b	983b	32.6a	1338a	221a	4177ab	402a	0.6a	3.8b	81.8b	96.3b	81.1a	3.3a	0.6a
Culbert	Fertilizer-2	17a	1035b	1052b	13.9a	1048a	186a	5215ab	764b	1.2a	4.9a	60.7a	67.7a	147.4a	3.4a	1.5a
	Fertilizer-4	16a	1978a	1993a	13.1a	611a	150b	5993a	935a	1.2a	4.2a	40.6ab	69.8a	96.9a	3.4a	1.3a
	No Fertilizer	16a	1166b	1183b	18.6a	1034a	200a	5195b	884ab	1.3a	4.8a	39.4b	65.8a	118.6a	3.6a	1.5a

[*] 100 kg N/ha of NH_4NO_3 fertilizer broadcast applied on June 4, 2003 during the second growing season.

[**] 100 kg N/ha of NH_4NO_3 and 25 kg P/ha of $(NH_4)H_2PO_4$ fertilizer broadcast applied on June 9, 2005 during the fourth growing season.

[†] For each site, means within a column followed by the same letter are not significantly different (P >0.05) using LSD.

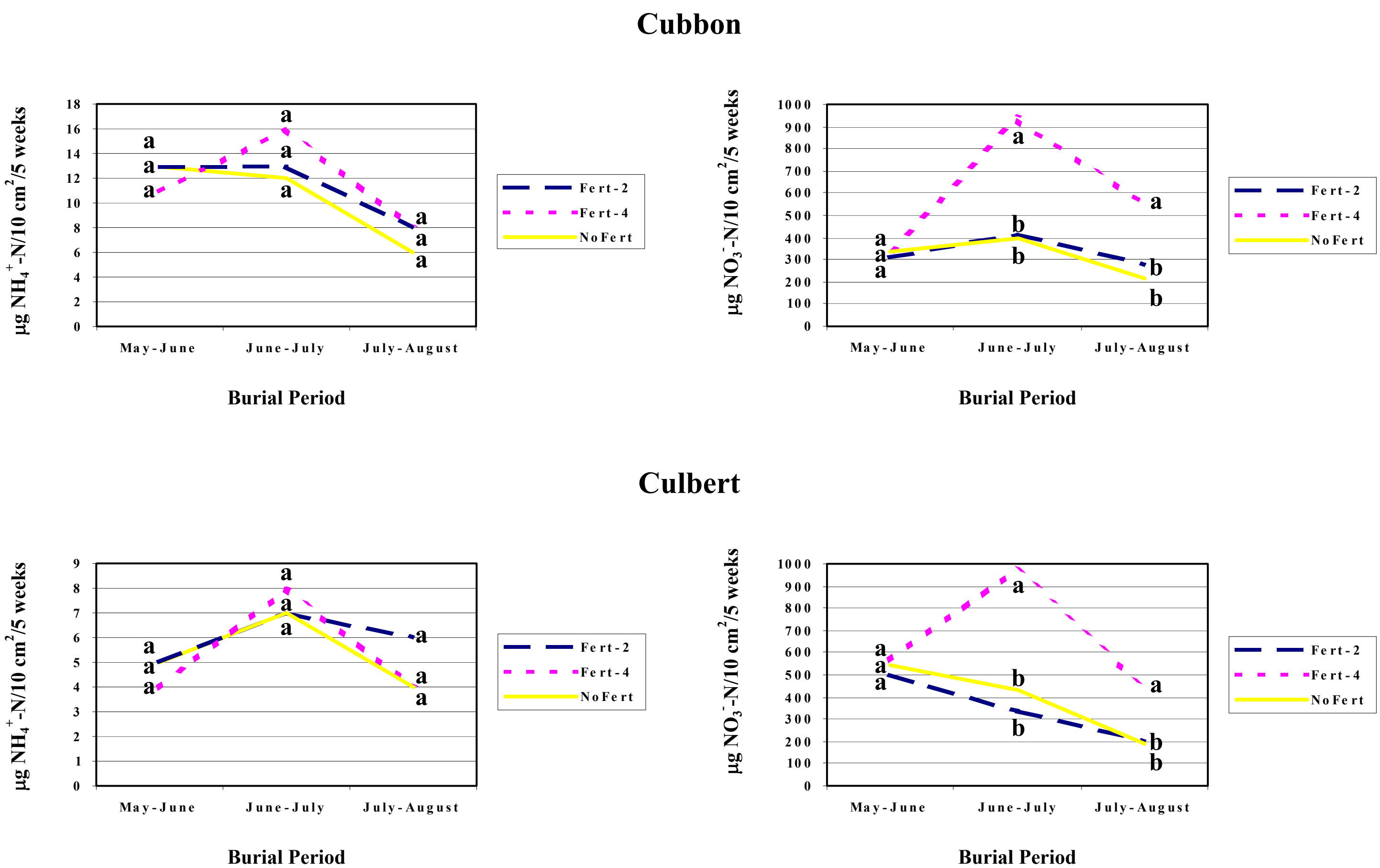

Figure 4. Mean (n>18) NH_4^+-N and NO_3^--N supply rates, measured using *in situ* burials of PRS™-probes, in 2005 at two Meadow Lake hybrid poplar sites in plots with (Fert-2 and Fert-4) and without (NoFert) broadcast applied fertilizer. Fertilized split-plots received either NH_4NO_3 (100 kg N/ha) on June 4, 2003 during the second growing season (Fert-2) or NH_4NO_3 (100 kg N/ha) and $(NH_4)H_2PO_4$ (25 kg P/ha) on June 9, 2005 during the fourth growing season (Fert-4). For each burial period, means having the same letter are not significantly different (P >0.05) using LSD.

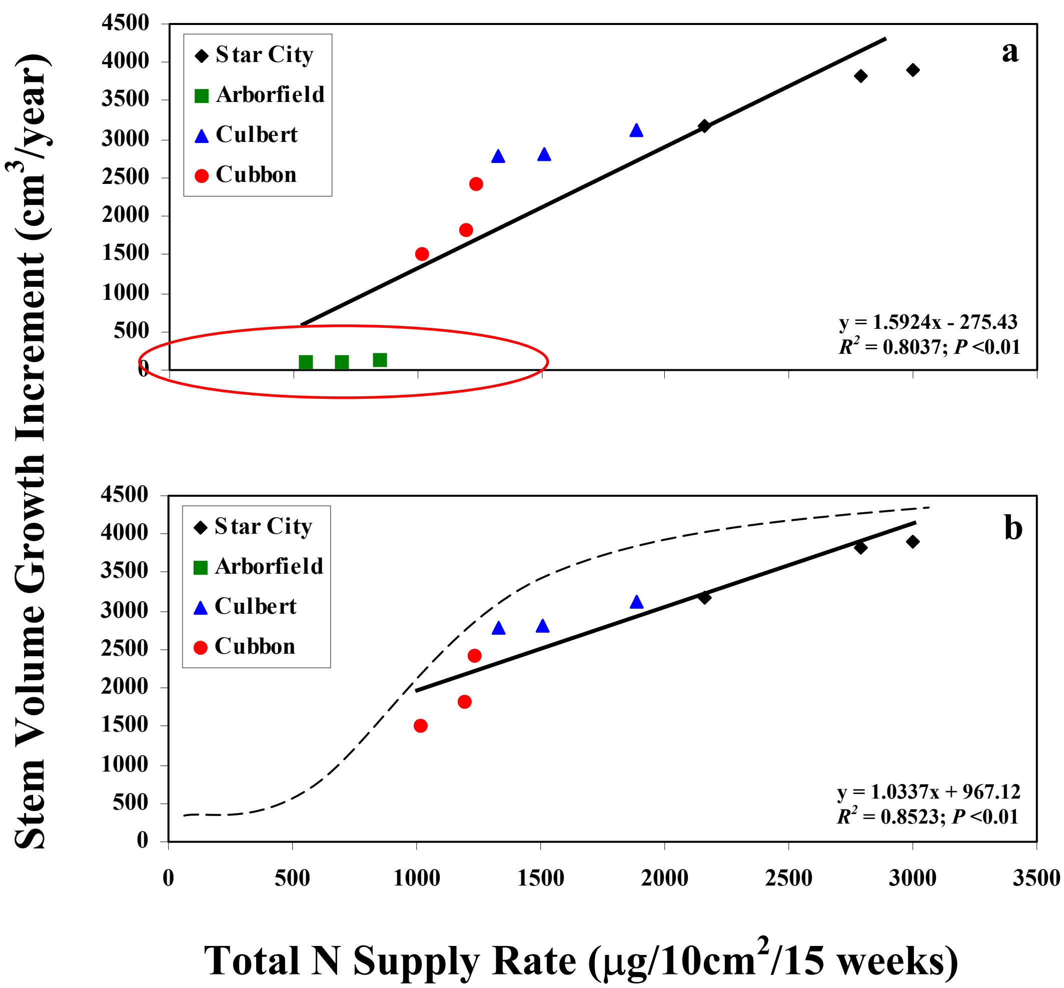

Figure 5. Relationship between total N supply rate, measured using *in situ* burials of PRS™-probes, and hybrid poplar (var. Walker) seedling stem volume growth increment in 2005. Each data point is a mean of either nine (Arborfield) or twenty-five (Star City, Cubbon, and Culbert) seedlings of the same clone planted as rooted cuttings with no fertilizer applied or pruning and ranging in age from 2-4 years depending on the site. Due to high seedling mortality at Arborfield in 2003, these seedlings (red circle) were replaced in 2004 and, therefore, had stem volume growth increments a magnitude smaller than the other sites. Results of the correlation analysis with (a) and without (b) these seedling growth data included are presented. The dashed curvilinear line is the growth response boundary limit.

Mechanistic models that predict the early growth of outplanted seedlings not only require accurate estimates of soil N supply throughout the growing season (Kelly and Mays, 1999), but more importantly, a biologically meaningful index of N availability that is correlated with outplanted seedling N uptake and growth. The development of a mechanistic model providing fertilizer recommendations for hybrid poplar plantations is beyond the scope of this study, however, the baseline soil nutrient supply rate data accrued over these three growing seasons, and its relationship with the early growth of hybrid poplar seedlings, is useful for providing an index of relative soil fertility for supporting effective pre- and post-planting nutrient management decisions. For example, when developing a constrained-resource model used to predict the early growth of hybrid poplar, it is advantageous to know the upper limit (i.e., dashed curvilinear line in Figure 5b) of growth response expected under a variety of site types and growing season conditions, in order to provide a reasonable estimate of growth.

Conclusion

The three-year results of this study continue to support the assertion that *in situ* burials of ion-exchange membrane provide biologically meaningful data and, therefore, are a very useful tool for measuring nutrient availability in hybrid poplar plantations during the early establishment phase. Specifically, the PRS™-probes were sensitive enough to measure differences in soil nutrient supply rates among sites differing in past management practices, soil types, and climatic conditions. In addition, they were capable of quantifying differences in nutrient availability between fertilizer N treatments and their data were strongly correlated with seedling growth. During each year of this study, there has been adequate variability in growing season conditions among the sites and also from year to year, which supports the widest possible inference space for applying this baseline soil fertility data for diversifying farmers growing hybrid poplar.

Indeed, there are many biotic and abiotic factors that can have a deleterious impact on plantation productivity including: drought, winter kill, animal (i.e., moose, deer, rabbit, and wild boar) and insect damage, disease, and competition from non-crop vegetation (Figure 6). Given that there are so many factors that can potentially affect plantation productivity, it is prudent to effectively manage something that can be controlled, such as preventing possible nutrient deficiencies, in order to better manage the risk by producing high quality vigorous seedlings that are more resistant to these attacks.

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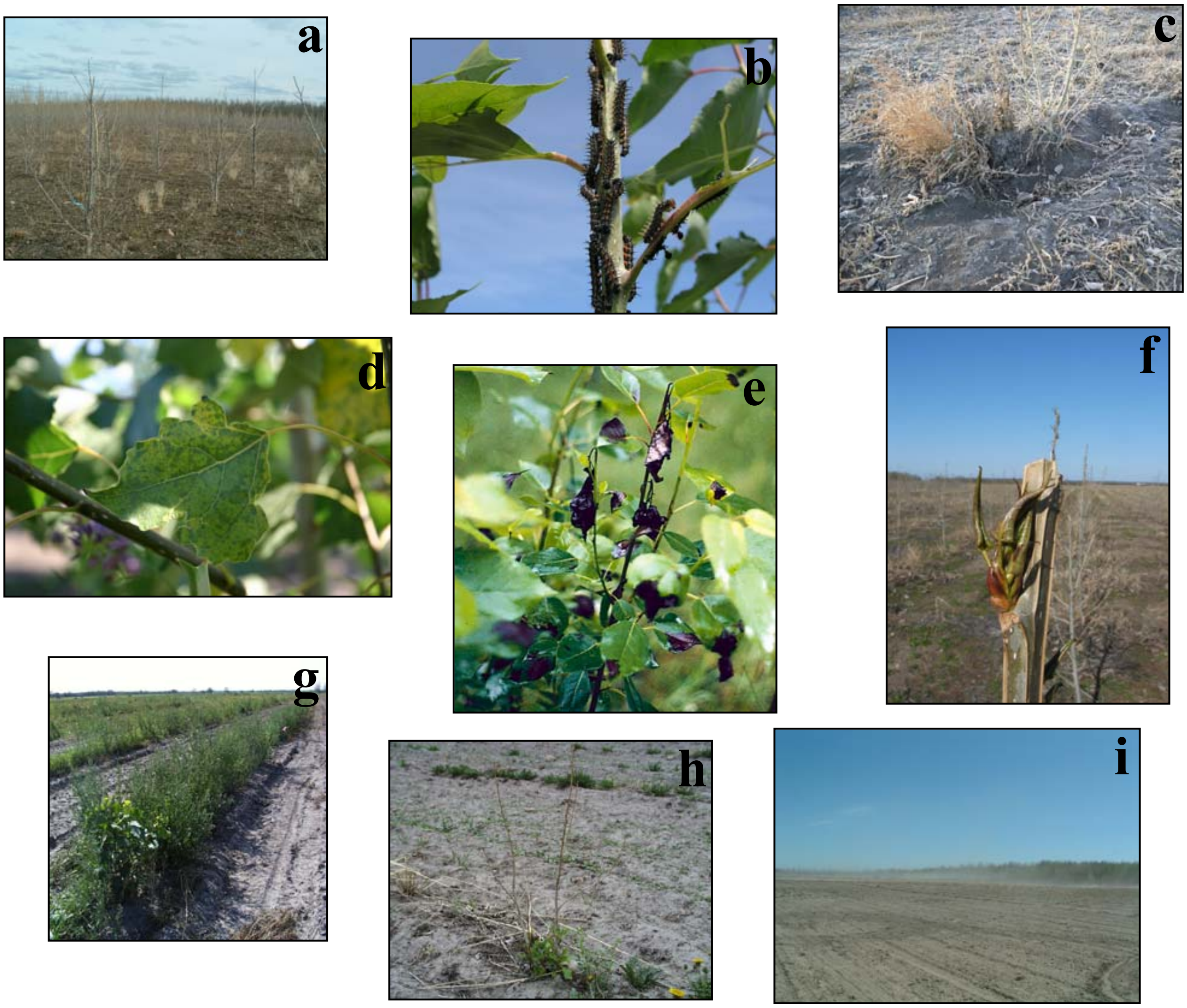

Figure 6. Biotic and abiotic factors that can influence hybrid poplar plantation productivity, including: moose (a), insects (b), wild boar (c), nutrient deficiencies (d), disease (e) deer (f), non-crop vegetation (g), winter kill (h), and drought (i). (Photos courtesy of Rick Block, Garth Inouye, and Dr. Ken Van Rees).

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