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Early growth and nutrition of hybrid poplars fertilized at planting in the boreal forest of western Quebec

Toma Guillemette, Annie DesRochers *

Université du Québec en Abitibi-Témiscamingue, Chaire Industrielle CRSNG-UQAT-UQAM en Aménagement Forestier Durable, 341 Principale Nord, Amos, Qc J9T 2L8, Canada

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Abstract

In order to maximize growth and diagnose nutritional requirements of hybrid poplars (*Populus* spp.) grown in the boreal forest of western Quebec, the Diagnosis and Recommendation Integrated System (DRIS) was evaluated in conjunction with N:P ratios of trees fertilized at planting. Three hybrid poplar clones (747210; *P. balsamifera* × *trichocarpa*, 915005; *P. balsamifera* × *maximowiczii,* and 915319; *P. maximowiczii* × *balsamifera*) were fertilized with 18 combinations of nitrogen (N), phosphorus (P) and potassium (K). Fertilizers used were granules of ammonium nitrate (34.5-0-0) at 3 levels (0, 20 and 40 g tree^{-1} of N), triple-superphosphate (0-45-0) at 3 levels (0, 25 and 50 g tree^{-1} of P), and potassium sulfate (0-0-50) at 2 levels (0, 20 g tree^{-1} of K). After two growing seasons, P fertilization was the most effective in promoting growth and 25 g tree^{-1} increased mean stem volume by 41% compared to unfertilized trees. The predictive accuracy of the N:P and DRIS diagnosis methods was generally reliable, however they failed to predict some co-limitations of N and P.

Keywords: Hybrid poplar; Fertilization; N:P ratio; DRIS

1. Introduction

Hybrid poplar (*Populus* spp.) plantations are economically attractive to the forest industry, even in the boreal forest, because of their fast growth rates and high yield potential. The decrease of wood supplies in native forests due, in part, to competing land uses and to more sustainable management practices, will accentuate the need to manage more intensively some portions of the available land. However, many operationally established hybrid poplar plantations do not meet expected volume productivity, often because of a lack of maintenance during the establishment phase (Welham et al., 2007). Growing poplars in plantations is challenging, and good establishment the first year is critical to long-term success (Stanturf et al., 2001).

One option to improve plantation establishment and early growth across a wide range of site conditions is fertilization at planting. Hybrid poplars have high nutrient requirements and have generally been found to respond well to fertilization at planting (van den Driessche, 1999; Brown and van den Driessche, 2002), except for plantations established on soils of high pH fertilized with ammonium nitrate (van den Driessche et al., 2005; Choi et al., 2005; DesRochers et al., 2006). Fertilizers are often added as broadcast applications just before canopy closure of plantations, corresponding to the peak nutrient demand of the trees (Hansen, 1994). Placed fertilization at planting, however, requires lesser amounts of fertilizer per hectare since the contact area between the fertilizer and the soil particles is reduced, limiting adsorption processes and increasing fertilization efficiency (Baldock and Burgess, 1995). Moreover, placed fertilization limits nutrient uptake by weeds compared to broadcast applications, which is particularly important since weeds are known to reduce hybrid poplar growth (Thomas et al., 2001), even in rich soils (Welham et al., 2007).

The boreal region has a long daily photoperiod during summer but a short growing season. Intensive short-rotation forestry in boreal regions thus commonly relies on the use of fertilizers to achieve high productivity (Weih, 2004), but also to correct possible soil nutrient deficiencies. No previous study has dealt with fertilizer requirements of hybrid poplars planted in the boreal regions of eastern Canada, while field fertilization trials gave mitigated results in western Canada (van den Driessche

* Corresponding author. Tel.: +1 819 732 8809; fax: +1 819 732 8805.
E-mail address: annie.desrochers@uqat.ca (A. DesRochers).

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et al., 2005; DesRochers et al., 2006). Nitrogen (N) is generally considered the most limiting nutrient in poplar plantations (Ménétrier and Vallée, 1980; van den Driessche, 1999). Phosphorus (P) fertilization, however, is reputed to promote growth when it is applied at planting (Chapin et al., 1983; Liang and Chang, 2004; Brown and van den Driessche, 2005). Potassium (K) applied with P and N may also reduce mortality rate by increasing resistance to diseases (Leroy, 1969).

It is crucial to seek optimal nutritional balance and avoid fertilizing in excess of one nutrient for maximum productivity (Ingestad, 1974; Ingestad and Lund, 1986). Ratios of nutrient concentrations are thus often better indicators of nutrient deficiencies than are single nutrient concentrations (‘critical concentrations’; Jones and Bowen, 1981; Walworth and Sumner, 1987; Coleman et al., 2006). Two diagnosis methods using foliar nutrient concentration ratios have been developed to detect nutrient imbalances and predict fertilizer requirements: (1) N:P ratios (Koerselman and Meuleman, 1996) and (2) the Diagnosis and Recommendation Integrated System (DRIS) (Beaufils, 1973). The first method focuses on N and P, with the rationale that these two elements govern a large part of the growth and that plant species have critical N:P ratios indicating whether the plant is N or P limited (Koerselman and Meuleman, 1996). The second method goes further in the analysis and takes into account all pairs of nutrients susceptible to affect plant growth. The DRIS method can thus be viewed as a modified regression technique that uses boundary line conditions of an incomplete set of independent variables to describe the dependant variable, yield (Walworth and Sumner, 1987). The average ratio of foliar nutrient concentrations of a random selection of faster growing trees becomes the norm or the ‘field standards’, by which growth performance of the slower growing trees is judged (Leech and Kim, 1981).

The first objective of this study was to assess the potential of placed fertilization at planting to increase early growth of hybrid poplars in the boreal region of eastern Canada. Secondly, we wanted to determine if it was possible to match tree responses to fertilizers with the two diagnosis methods, N:P ratios and the Diagnosis and Recommendation Integrated System (DRIS). Preliminary field standards are proposed for three hybrid poplar clones and their use is evaluated on unfertilized trees of two plantations.

2. Methods

2.1. Study sites

Two hybrid poplar plantations were established in spring 2003 in the region of Abitibi-Témiscamingue, Québec, Canada. The first plantation (agricultural site) was established on an abandoned farmland site near the locality of Amos (48°35′N, 78°05′W), which is part of the western balsam fir-paper birch (*Abies balsamea – Betula papyrifera*) bioclimatic domain (Grondin, 1996). This site is part of the clay belt of Quebec and Ontario resulting from deposits left by the proglacial Lakes Barlow and Ojibway (Vincent and Hardy, 1977). The soil texture was a heavy clay Grey Luvisol (Canada Soil Survey Committee, 1987). The average number of degree-days above 5 °C for the region range from 1215 to 1450 and has had a yearly rainfall between 610 and 680 mm for the last three decades (Environment Canada, 2004). No agricultural activity had taken place on this site for the last 25 years. The site was dominated by grasses and a few patches of alder (*Alnus incana* ssp. *rugosa*), willow (*Salix* spp.) and trembling aspen (*Populus tremuloides* Michx.). The second plantation (forest site) was established on a previously forested site located near Roullier (47°92′N, 79°18′W) and is part of the western balsam fir – yellow birch (*Betula alleghaniensis*) bioclimatic domain (Grondin, 1996). This site was previously dominated by a trembling aspen forest which was commercially harvested in 2000. Its soil type is classified as a Humo-Ferric Podzol with a sandy-loam soil texture (Canada Soil Survey Committee, 1987). The site was dominated by scattered trembling aspen, white birch (*Betula papyrifera* Marsh.) and wild red cherry (*Prunus pensylvanica* L.f).

Stumps at the forest site were removed with a bulldozer and chains, followed by ploughing with a specially designed forestry cultivator made of two rows of independent hydraulic discs pulled by a skidder. At the agricultural site, the smaller shrub and aspen stumps were pulled by a farm tractor and the site was cultivated with a conventional agricultural plough. The planting sites were ploughed to approximately 30 cm in depth in the fall of 2002, followed by disking in the spring of 2003 to level the soil and incorporate organic matter into the mineral soil as well as to remove the remaining debris and logs. The hybrid poplars were planted in the first week of June at the farmland site and in the first week of July at the forest site, due to delays in the field preparation at this site. The trees were kept dormant in a refrigerator at 2–3 °C until planting. The trees were planted at a 3 m × 3 m spacing and consisted of bare-root hybrid poplar stock of approximately 1.5 m in height (Table 1). Three locally produced clones from the Quebec Ministry of Natural Resources were chosen based on their availability at a local tree nursery and on their differing parentage: 747210 (*P. balsamifera* × *trichocarpa*), 915005 (*P. balsamifera* × *maximowiczii*) and 915319 (*P. maximowiczii* × *balsamifera*). The experiment was laid out as a split-plot design where 3N × 3P × 2K fertilizers were fully crossed factors within each of the three hybrid poplar clones. The clones were randomized and replicated into 3 blocks. The treatment unit was two trees of one clone ($n = 324$ per site). Fertilizers used were granules of ammonium nitrate (34.5-0-0) at 3 levels (0, 20 and 40 g tree^{-1}; equivalent to 0, 22, and 44 kg ha^{-1}), triple-superphosphate (0-45-0) at 3 levels (0, 25 and 50 g tree^{-1}; equivalent to 0, 28 and 56 kg ha^{-1}), and potassium sulfate (0-0-50) at 2 levels (0, 20 g tree^{-1}; equivalent to 0 and 22 kg ha^{-1}). The fertilizers were applied at planting by inserting the granules into a spade slit made at 15 cm from the trees to a depth of about 15 cm. Vegetation control was done twice a year (June and August) by cross-cultivating the plantations using a farm tractor.

Soils were sampled at 0–20 and 20–40 cm depth in each site before planting. Samples were air-dried, sieved with a 2-mm screen, and analyzed for particle size distribution using a pipette. The pH of each sample was determined from a 1:40

Table 1
Mean basal diameter, stem height and stem dieback of each clone at planting and after each growing season

Clone	Farmland site			Forest site		
	747210	915005	915319	747210	915005	915319
At planting						
Basal diameter (mm)	9.59b	11.43a	9.62b	9.10b	11.44a	9.65ab
Height (cm)	133.54c	170.85a	152.48b	128.49b	168.43a	152.29ab
Stem dieback (cm)	9.51c	20.45b	85.26a	11.72a	12.13a	38.43a
After the first growing season						
Basal diameter (mm)	16.58a	16.81a	12.71b	14.25a	15.64a	13.17a
Height (cm)	143.83b	163.85a	92.16c	127.48a	163.98a	125.94a
After the second growing season						
Basal diameter (mm)	26.81a	27.91a	20.67b	25.08a	26.14a	22.63a
Height (cm)	175.13a	196.88a	141.44b	164.20a	190.34a	173.45a

Note: values with the same letter within a line and site are not significantly different.

dilution after 1 h agitation (Conseil des Productions Végétales du Québec, 1988). Available phosphorus (P) was determined using the Mehlich-III methods (Mehlich, 1985). Exchangeable potassium, calcium and magnesium (K, Ca and Mg) were extracted with $BaCl_2$–NH_4Cl (Amacher et al., 1990) and their contents were determined by inductively coupled plasma (ICP; Perkin Elmer plasma model 40). Soil analyses from both sites are presented in Table 2. Basal diameter and height of trees were measured right after planting and at the end of the first and second growing seasons. Stem volumes (*V*) were estimated as:

$$V = \text{ba} * \frac{h}{3} \quad (1)$$

where ba = basal area and h = height (as used by Brown and van den Driessche, 2005). Bud formation was examined at the end of the first growing season, while observations on bud burst were done at the beginning of the second growing season and characterized according to the Quebec Ministry of Natural Resource method (Gagnon et al., 1991).

2.2. Foliar analysis

Foliar samples were collected in mid-august of each growing season. Fifteen fully expanded leaves were collected from the upper tree crowns from each of the two trees in an experimental unit. The samples were then pooled into two replicates by combining leaves from two of the three replicates. Leaves were oven-dried to constant weight at 70 °C, ground and digested in a solution of sulphuric acid (H_2SO_4), peroxide (H_2O_2) and selenium catalyser (Se) (Parkinson and Allen, 1975). N was calibrated by flow injection analysis (FIA), while P, K, Ca and Mg were also digested in a solution of H_2SO_4, H_2O_2 and Se and then determined by inductively coupled plasma (ICP) (Perkin Elmer plasma model 40). N and P foliar concentrations were used to calculate N:P ratios for the 18 possible fertilizer combinations.

The field standards for N, P, K, Ca and Mg presented in this study consist of foliar nutrient concentrations and ratios of the best growing trees (high-yielding group) of each clone. The cut-off limit between the fast and the slow growing groups was 75% of maximal yield (Needham et al., 1990). The high-yielding groups were equally composed of trees located at both sites, in order to alleviate bias due to specific site conditions and to encompass a greater range of foliar nutrient data. One DRIS formula per clone (Table 3) was elaborated to give accurate diagnostics because clones often show different responses to

Table 2
Mean soil characteristics for each site

Variable	Site			
	Farmland		Forest	
Depth (cm)	0–20	20–40	0–20	20–40
Texture	Heavy clay		Sandy loam	
pH ($CaCl_2$)	4.36	4.82	4.25	4.60
N (%)	0.14	0.02	0.12	0.03
C.O. (%)	2.38	0.53	2.45	0.75
S.B. (%)	83.97	96.57	39.58	47.50
CEC (cmol (+) kg^{-1})	6.69	9.79	2.60	0.74
K (ppm)	133.64	114.66	70.82	24.04
Na (ppm)	19.72	31.33	5.28	3.41
Ca (ppm)	559.57	939.21	105.63	37.63
Mg (ppm)	226.11	492.37	19.89	8.90
P (ppm)	8.87	12.87	21.98	13.74
Al (ppm)	1225.35	970.16	1955.02	1913.41

Table 3
DRIS formulas used for each hybrid poplar clone

Clone	DRIS formulas
747210	N index = [+*f* (N/P) − *f* (K/N) − *f* (Ca/N) + *f* (N/Mg)]/4
	P index = [−*f* (N/P) + *f* (P/K) + *f* (P/Ca) − *f* (Mg/P)]/4
	K index = [+*f* (K/N) − *f* (P/K) − *f* (Ca/K) + *f* (K/Mg)]/4
	Ca index = [+*f* (Ca/N) − *f* (P/Ca) + *f* (Ca/K) − *f* (Mg/Ca)]/4
	Mg index = [−*f* (N/Mg) + *f* (Mg/P) − *f* (K/Mg) + *f* (Mg/Ca)]/4
915005	N index = [−*f* (P/N) − *f* (K/N) − *f* (Ca/N) − *f* (Mg/N)]/4
	P index = [+*f* (P/N) − *f* (K/P) + *f* (P/Ca) − *f* (Mg/P)]/4
	K index = [−*f* (K/N) + *f* (K/P) − *f* (Ca/K) + *f* (Mg/K)]/4
	Ca index = [+*f* (Ca/N) − *f* (P/Ca) + *f* (Ca/K) + *f* (Ca/Mg)]/4
	Mg index = [+*f* (Mg/N) + *f* (Mg/P) − *f* (K/Mg) − *f* (Ca/Mg)]/4
915319	N index = [−*f* (P/N) + *f* (N/K) − *f* (Ca/N) + *f* (N/Mg)]/4
	P index = [+*f* (P/N) + *f* (P/K) + *f* (P/Ca) + *f* (P/Mg)]/4
	K index = [−*f* (N/K) − *f* (P/K) − *f* (Ca/K) − *f* (Mg/K)]/4
	Ca index = [+*f* (Ca/N) − *f* (P/Ca) + *f* (Ca/K) + *f* (Ca/Mg)]/4
	Mg index = [−*f* (N/Mg) − *f* (P/Mg) + *f* (Mg/K) − *f* (Ca/Mg)]/4

Table 4
DRIS norms and coefficients of variation (CV) for each clone

Clone 747210			Clone 915005			Clone 915319		
	Mean	CV (%)		Mean	CV (%)		Mean	CV (%)
N (%)	2.03	10.24	N (%)	1.77	11.52	N (%)	2.07	6.71
P (%)	0.13	11.24	P (%)	0.11	12.08	P (%)	0.14	13.15
K (%)	1.32	11.16	K (%)	1.36	18.16	K (%)	1.65	20.39
Ca (%)	0.39	18.41	Ca (%)	0.46	13.92	Ca (%)	0.56	27.72
Mg (%)	0.19	32.79	Mg (%)	0.17	38.30	Mg (%)	0.22	35.30
N/P	15.60	15.24	P/N	0.06	17.33	P/N	0.06	8.29
K/N	0.66	20.08	K/N	0.78	29.27	N/K	1.31	25.18
P/K	0.10	14.27	K/P	12.63	25.40	P/K	0.09	31.66
Ca/N	0.19	15.09	Ca/N	0.26	10.46	Ca/N	0.27	23.38
P/Ca	0.35	17.40	P/Ca	0.24	15.17	P/Ca	0.25	17.19
Ca/K	0.30	28.10	Ca/K	0.35	32.48	Ca/K	0.37	45.99
N/Mg	11.69	25.92	Mg/N	0.09	31.80	N/Mg	10.41	30.23
Mg/P	1.43	33.85	Mg/P	1.52	31.03	P/Mg	0.67	24.17
K/Mg	8.08	43.32	K/Mg	9.43	52.16	Mg/K	0.14	52.75
Mg/Ca	0.48	18.28	Ca/Mg	2.94	29.46	Ca/Mg	2.67	10.39

The means represent average nutrient ratios of first-year high-yielding trees located at both sites.

fertilizers. Hence, three DRIS norms (Table 4) are presented to evaluate their efficiency in detecting nutrient imbalances of first-year unfertilized trees. Of the three possible nutrients ratios (e.g. N/P, P/N or N*P) used to express growth performance, the one with the highest variance between the fast and the slow growing groups of trees was chosen because it also maximizes the chances to detect a nutritional imbalance. In our case, no product (multiplication) ratio resulted in the highest variance between the two groups.

Data was analyzed by an analysis of variance (ANOVA) using the general linear model and mixed procedures of SAS (SAS 8.3, SAS Institute, Cary, NC). Volume data were log transformed to homogenize the variance, and were analyzed separately for each growing season. Since there were significant stem volume and stem dieback differences at planting, they were included as covariates in the analysis. Sites were analyzed separately as they introduced too many meaningless interactions. Least squares means were compared using Fisher's Protected LSD. A significance level of $p \leq 0.05$ was chosen.

3. Results

3.1. Clones

At planting, rooted stock from clone 915005 had the greatest height and basal diameter (Table 1). Trees from all three clones showed some stem dieback shortly after planting, particularly those of clone 915319 which lost more than half their length at the farmland site and a quarter of their length at the forest site (Table 1). Over all fertilizer treatments and across sites, trees from clone 915005 were the tallest after the first growing season even though they had the least height growth during that season (Table 1). Over the 2-year period, trees from clone 747210 had the greatest basal diameter growth while those from clone 915319 had the greatest height growth (Table 1). None of the fertilizer treatments delayed fall bud formation on any of the three studied clones. Bud burst happened within 1 week for all

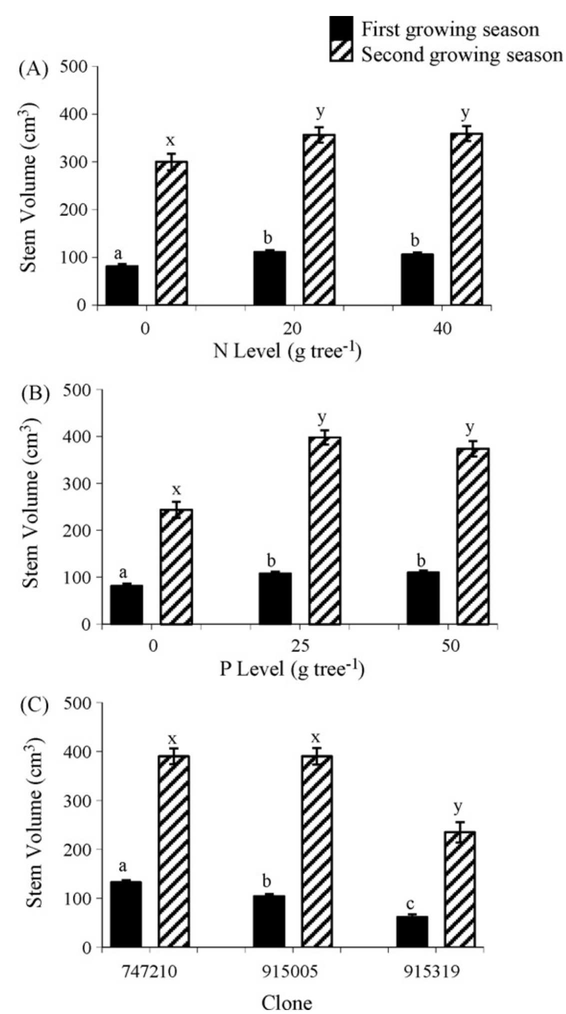

Fig. 1. Mean stem volume for trees grown at the farmland site for each: (A) N fertilization level; (B) P fertilization level; and (C) clone. Error bars are S.Es. Bars labelled with the same letter within a graph and growing season are not significantly different at $p < 0.05$.

Table 5
Analysis of variance showing sources of variation, degrees of freedom (d.f.), and F values for volume (cm^3) after each growing season and on each site

		Farmland site				Forest site			
		Volume after year 1		Volume after year 2		Volume after year 1		Volume after year 2	
	d.f.								
Block	2	4.29	(0.10)	0.33	(0.74)	2.56	(0.19)	3.22	(0.15)
Clone	2	67.61	(<0.001)	8.1	(0.04)	2.72	(0.18)	0.16	(0.86)
Block*clone (error)	4	1.25	(<0.29)	3.67	(0.007)	5.75	(<0.001)	12.23	(<0.001)
N	2	16.29	(<0.001)	5.09	(0.007)	12.47	(<0.001)	8.59	(<0.001)
P	2	14.83	(<0.001)	26.8	(<0.001)	14.7	(<0.001)	12.41	(<0.001)
K	1	1.03	(0.31)	0.05	(0.82)	0.05	(0.83)	0.05	(0.82)
N*P	4	1.22	(0.30)	1.24	(0.29)	2.01	(0.09)	1.07	(0.37)
N*K	2	1.15	(0.32)	2.17	(0.12)	0.94	(0.39)	0.75	(0.48)
P*K	2	0.78	(0.46)	0.78	(0.46)	0.07	(0.93)	0.28	(0.76)
N*P*K	4	0.24	(0.92)	0.39	(0.81)	1.48	(0.21)	1.5	(0.20)
Clone*N	4	0.44	(0.78)	0.75	(0.56)	3.14	(0.02)	2.71	(0.03)
Clone*P	4	0.25	(0.91)	0.21	(0.93)	0.87	(0.49)	0.47	(0.76)
Clone*K	2	0.2	(0.82)	0.23	(0.79)	1.19	(0.30)	0.83	(0.44)
clone*n*p	8	0.2	(0.99)	0.94	(0.48)	1.08	(0.38)	1.07	(0.38)
Clone*N*K	4	0.33	(0.86)	0.89	(0.47)	1.78	(0.13)	2.89	(0.02)
Clone*P*K	4	0.53	(0.71)	2.09	(0.08)	1.31	(0.27)	0.84	(0.50)
Clone*N*P*K	8	0.94	(0.49)	0.62	(0.76)	0.32	(0.96)	0.71	(0.69)
Dieback covariate	1	8.44	(0.004)	1.83	(0.18)	162.29	(<0.001)	35.48	(<0.001)
Volume covariate	1	197.63	(<0.001)	36.91	(<0.001)	752.99	(<0.001)	58.08	(<0.001)
Error	222								

P-values are given in parentheses.

clones and did not vary among the fertilizer treatments (data not shown). Mean survival of clones 747210 and 915005 after 2 years was 98% at both sites. Mean survival was 84% for clone 915319, mostly due to poor stock quality.

3.2. Growth response to fertilizers

At the farmland site, stem volume was increased by 26% and 24% in the N20 and P25 treatments, respectively, after the first growing season (Fig. 1A and B). The effect of N and P fertilization on stem volume was still significant after the second growing season (Table 5), and trees grew, respectively 1.2 and 1.7 more stem volume in the N20 and P25 treatments (Fig. 1A and B). The different clones did not interact with the fertilizer treatments at this site (Table 5), however there were differences in stem volume between clones: Clone 915319 had 40% less volume than the other two clones after 2 years (Fig. 1C).

First-year stem volume also increased with N and P fertilization at the forest site, however the increase appeared smaller than at the farmland site (Fig. 2). An interaction with N (Table 5) showed slight differences between clones, with 12–17% volume increases in the N20 treatment after one growing season (Fig. 2A). Trees at the forest site also responded to P fertilization, with 14% and 21% volume increases after one and two growing seasons, respectively (Fig. 2B). At both sites, the addition of more P (P50 treatment) or more N (N40 treatment) did not produce further increases in stem volume (Fig. 3). However, clones interacted with N and K fertilization at the forest site during the second growing season to produce a 40% stem volume increase in clone 915005 when K was added to the high dose of N (Fig. 3).

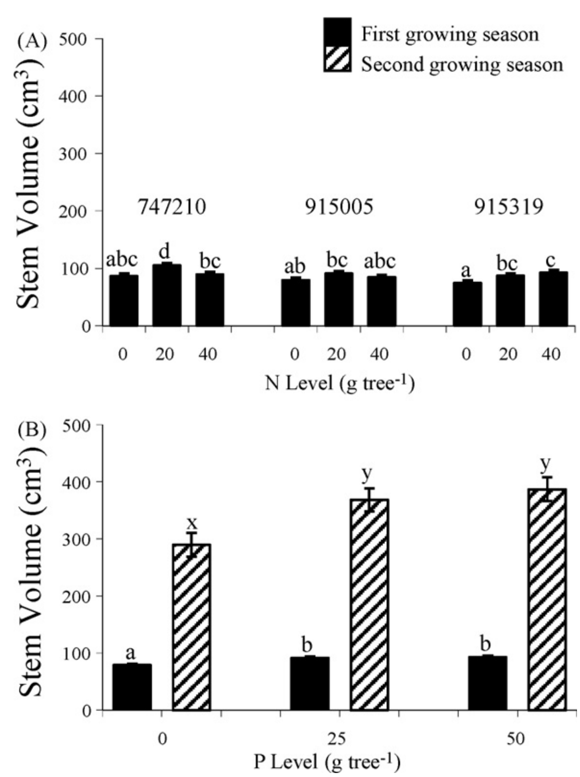

Fig. 2. Mean stem volume for trees grown at the forest site for each: (A) N and clone combination after the first growing season; and (B) P fertilization level for each growing season. Error bars are S.Es. Bars labelled with the same letter within a graph and growing season are not significantly different at $p < 0.05$.

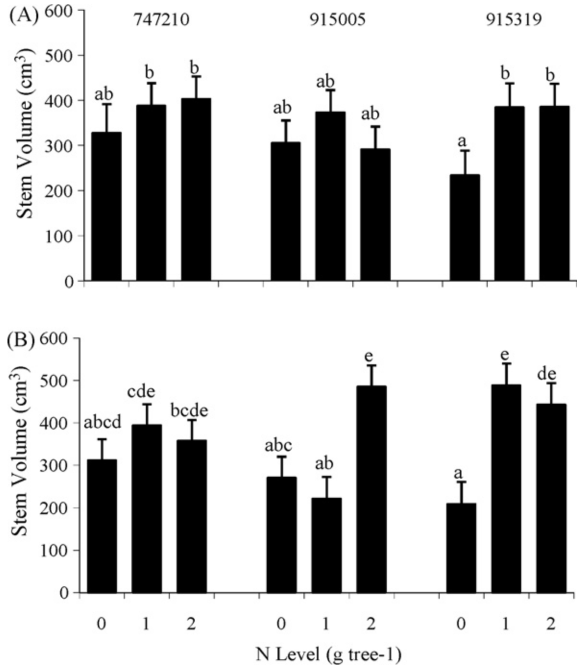

Fig. 3. Mean stem volume of trees grown at the forest site after two growing seasons for each N and clone combination: (A) without; or (B) with the addition of 20 g tree^{-1} of K. Error bars are S.Es. Bars labelled with the same letter within a graph are not significantly different at $p < 0.05$.

3.3. N:P ratios

Mean first-year foliar N:P ratios of unfertilized trees planted at the farmland site were 17, 21 and 15 for clones 747210, 915005 and 915319, respectively (Fig. 4A–C). At the forest site, unfertilized trees from clone 747210 had a mean foliar N:P ratio of 12 during the first year (Fig. 4D), while clones 915005 and 915319 had N:P ratios of 15 and 16, respectively (Fig. 4E and F). As expected, addition of N at planting resulted in increased N:P ratios, while P fertilization resulted in decreased ratios (Fig. 4).

The optimal ranges of N:P ratios, i.e. the N:P ratios at which the trees had the greatest volume growth over the study period, averaged 15 for clones 747210 and 915319, and 17 for clone 915005 at the farmland site after 2 growing seasons (Fig. 4A–C). At the forest site, average N:P ratios at which volume growth was best were 14, 16, and 10 for clones 747210, 915005 and 915319, respectively (Fig. 4D–F). Ranges of optimal N:P ratios were greater for clones 747210 and 915005 at the forest site compared to the farmland site (Fig. 4).

3.4. DRIS indices

DRIS indices obtained for trees planted at the farmland site showed that N was the most limiting nutrient for growth of clones 915005 and 915319, while P was most limiting for clone 747210 (Table 6). At this site, Ca was the nutrient with the highest positive imbalance for clones 747210 and 915005, while it was P for clone 915319 (Table 6). K and Mg were generally slightly in excess (Table 6). At the forest site, the DRIS indices showed a deficiency in N for all clones (Table 6). P was also deficient for clones 747210 and 915005, while K was deficient only for clone 915005. Ca and Mg were usually in supra-optimal conditions, except for clone 915319 which showed a slight deficiency in Mg at the forest site (Table 6).

4. Discussion

Placed fertilization at planting successfully increased early growth of all hybrid poplar clones used in this study. The greatest stem volume growth responses were obtained with the lower doses of N or P fertilization (20 and 25 g of N and P per tree, respectively), at both sites (Figs. 1–3). These doses correspond to approximately 22 kg and 28 kg of P ha^{-1}, which is relatively small compared to rates that are usually applied in poplar plantations: Czapowsky and Safford (1993) used 448 kg N and 112 kg P ha^{-1} while Ferm and Hytonen (1989) used 100–300 kg N ha^{-1}, both applied the year of planting. Heilman and Xie (1993) used 500 kg N ha^{-1} over 3 years (applied during the 2nd, 3rd, and 4th growing season), while Heilman (1992) recommended 50–70 kg N ha^{-1}, 12–16 kg P ha^{-1} applied at 3-year intervals for short-rotation forest crops in general. Fertilizers are usually added as broadcast applications, however this promotes competing vegetation until the weeds are shaded out by the canopy. A more efficient use of fertilizer with the least stimulation of competing vegetation can be achieved by placing the fertilizer into the ground beside the seedling or cutting (van den Driessche, 1999). Limiting growth of weeds is important for poplar growers in Quebec, since the use of herbicides is prohibited in plantations and mechanical removal of weeds is expensive.

Reported adequate levels of macronutrients for *P. trichocarpa*, *P. deltoides* and some of their hybrids range 2.8–4% N, 0.25–0.5% P, 1.5–2.2% K, 0.8–1.5% Ca and 0.23–0.4% Mg (White and Carter, 1970; Leech and Kim, 1981; Heilman, 1985; Heilman and Xie, 1993; Hansen, 1994; McLennan, 1996; van den Driessche, 1998). Compared to these values, nutrient concentrations of our best growing trees were generally lower for macronutrients (Table 4). Volume responses to P fertilization were important (Figs. 1B and 2B), and since the sites were relatively acidic (Table 2) they may have had benefited from liming. Reliance on 'critical levels' of nutrients, however, has to be considered carefully, because they may not portray temporal changes of nutrient requirements and poplar growers may miss opportunities to increase production through fertilization when levels are adequate (Coleman et al., 2006).

Work by Koerselman and Meuleman (1996) showed that for a wide variety of plants from European freshwater wetlands, N:P ratios > 16 corresponded to a P limitation, N:P ratios < 14 corresponded to a N limitation, while N:P ratios = 16 corresponded to a N and P co-limitation. In our study, N:P of unfertilized trees at the farmland site were 16–17 for clones 747210 and 915005, respectively (Fig. 4), and trees correspondingly showed greater volume increases with P fertilization (Fig. 1A and B). However, DRIS indices for clone 915005 showed a greater limitation for N while they failed to predict a P limitation for clone 915319 (Table 6); Unfertilized trees from

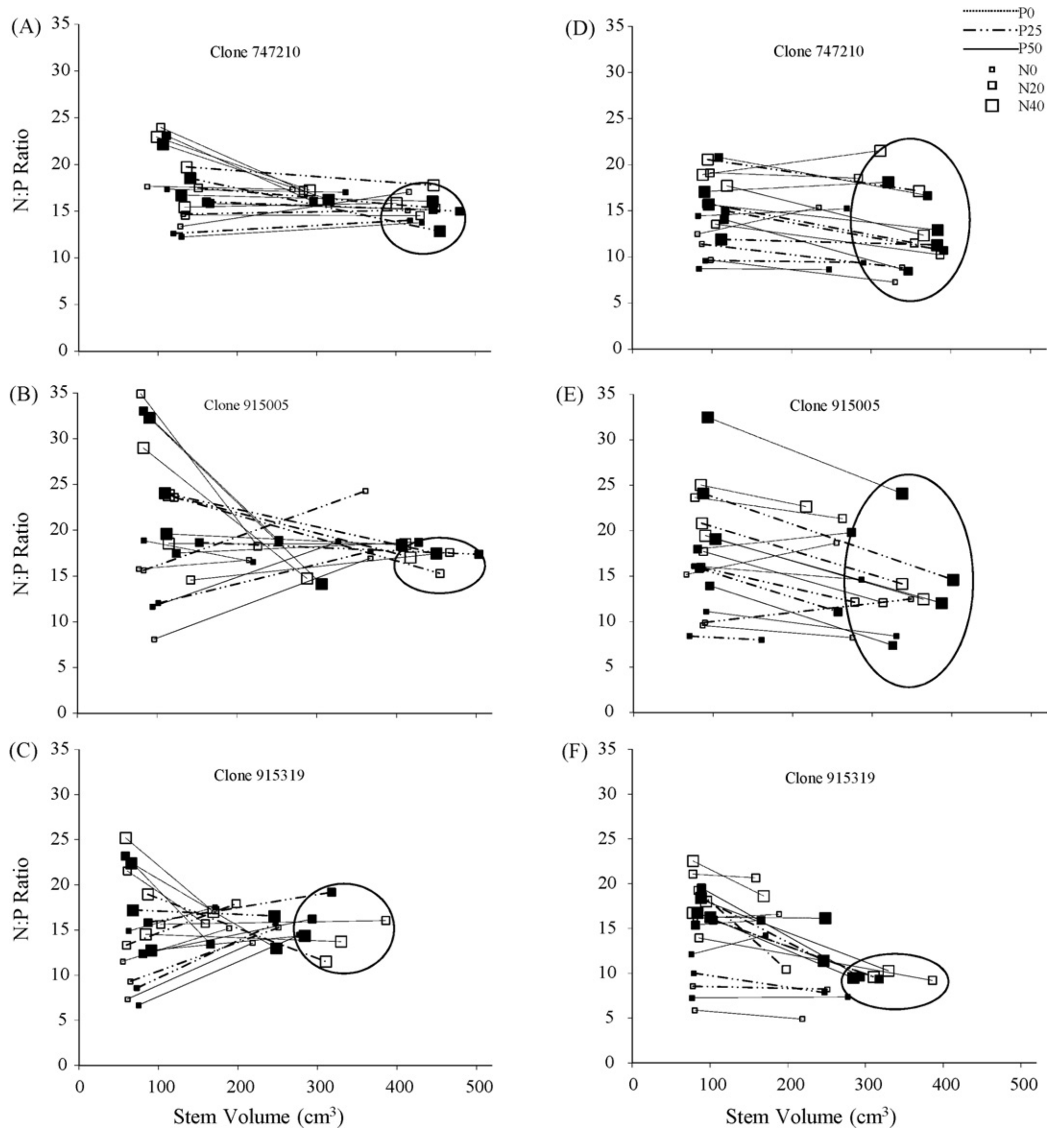

Fig. 4. Relationship between foliar N:P ratios and first and second year stem volume for each fertilization combination, for each clone at the farmland site (A, B, and C) and at the forest site (D, E, and F). Circles around symbols indicate fertilization treatments for which stem volumes are not significantly different from the fastest growing trees after the second growing season. Closed and open symbols represent treatments with or without the addition of K, respectively.

the latter clone had a mean N:P ratio of 12, suggesting a greater limitation for N than for P, however trees did not benefit from N fertilization unless P was also added (Fig. 4C).

At the forest site, ranges of optimal N:P ratios were so wide for clones 747210 and 915005 (Fig. 4D and E), that the N:P ratios were not useful to give an accurate diagnosis of N or P limitations. These greater ranges suggest that other elements other than N or P were limiting growth. Unimodal graphical displays of N:P foliar ratios, such as those obtained at the farmland site (Fig. 4), indicate that maximal biomass production was obtained at critical or optimal N:P ratios (Güsewell, 2004). DRIS indices indicated N and P limitation for clones 747210 and 915005, which was reflected in their growth response (Figs. 2 and 3). Volume growth of clone 915005, however, did not respond to N fertilization unless K was added (Fig. 3), which was effectively showed by a small K

Table 6
DRIS indices of first-year unfertilized hybrid poplar clones calculated from field standards

Clone	Farmland site					Forest site				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
747210	−5.6	−8.7	−0.7	12.0	7.0	−15.5	−4.8	8.5	17.3	1.4
915005	−21.3	−12.2	7.5	18.1	8.0	−4.8	−6.8	−3.9	10.5	19.9
915319	−22.2	9.6	5.5	−1.2	8.3	−7.4	−0.4	3.5	7.2	−2.9

limitation in the DRIS indices (Table 6). For clone 915319, N:P ratios of unfertilized trees decreased from 16 to a mean of 10 for the fastest growing trees (Fig. 4F); DRIS indices for this clone were showing a N limitation (Table 6), and trees indeed benefited from the addition of N (Fig. 3). The N fertilization may have in turn stimulated the mobilisation of P (Treseder and Vitousek, 2001), reducing N:P ratios during the second growing season (Fig. 4F).

Overall, our optimal N:P ratios were higher than reported ratios for other poplar varieties: 9 for *P. nigra* × *P. maximowiczii* (Kelly and Ericsson, 2003), 8 for *P. simonii* Carr. (Jia and Ingestad, 1984), and 7–8 for *P. trichocarpa* × *deltoides* clones (Zabek and Prescott, 2007). Our higher N:P ratios are probably related to the low levels of available P at both sites (Table 2), in comparison with suggested minimum concentrations of 37 mg kg^{-1} for optimal hybrid poplar growth (van den Driessche, 2000).

Most of the interactions between clones and fertilizers were not significant (Table 5), however DRIS indices suggest different requirements for the clones (Table 6). Clone 915319 differed from the others in that it showed sufficient or supra-optimal levels of P. This may have been related to the higher stem dieback and subsequent higher stem height growth of this clone (Table 1), creating a stronger sink for N compared to the other clones. Stem dieback of newly planted trees is a recurring problem in this region, most likely related to cultural and storage practices in the nursery; it is apparent in the days after the trees are planted and it is rarely observed in the following years after planting (*personal observations*). Similar stem dieback has also been observed in willow (*Salix* spp.) plantations in Europe, and would be caused by bacterial infections, facilitated by frost injuries aggravated by excess N fertilization and mild storage temperatures (Nejad et al., 2004; Cambours et al., 2006). Under the rigorous winter conditions prevalent in the boreal forest, none of the fertilizer combinations applied in our study caused further stem dieback.

The reliability of N:P ratios or DRIS indices to predict nutrient deficiencies or growth limitations remains unclear. These methods may be more useful when trees are subject to large nutrient deficiencies. According to a literature review by Güsewell (2004), biomass production is most likely to be enhanced by N fertilization in vegetation with N:P ratios below 10 and by P fertilization in N:P ratios higher than 20 whereas within this range, the effects of fertilization are not unequivocally related to N:P ratios. N:P ratios of unfertilized trees in our study were well within this range (Fig. 4). We could see, however, that unbalanced fertilization (with large doses of N or P only) often resulted in N:P ratios above 20 or below 10 during the first growing season, and that these trees rarely reached the group of fastest growing trees after two growing seasons (Fig. 4).

5. Conclusion

Placed fertilization at planting was an effective management tool to improve early growth of hybrid poplar plantations established on heavy clay and sandy loam textured soils typical of the region. A moderate application of 25 g $tree^{-1}$ of P increased stem volume by a mean of 41%, while 20 g $tree^{-1}$ of N increased stem volume to a mean of 16%, over the 2-year period. The predictive accuracy of the N:P and DRIS diagnosis methods was generally reliable, however they failed to predict some co-limitations of N and P. Perhaps the use of a larger spectrum of high-yielding trees of each hybrid poplar clone growing in different sites across the region would refine the DRIS field standards and result in better nutrition diagnoses and fertilization recommendations.

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