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DRIS-based fertilization efficiency of young hybrid poplar plantations in the boreal region of Canada

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Abstract In order to maximize early growth and establishment of planted hybrid poplars in the boreal region of Eastern Canada, growth response of four clones to fertilization was tested in two plantations. The first two fertilization treatments were based on Diagnosis and Recommendation Integrated System (DRIS), a method based on nutrient ratios: DRIS I was based on previously established norms from a study that had been conducted in the same area, and DRIS II was based on DRIS norms developed from hybrid poplars in northern Ontario, Canada. Nutrient status and growth of trees under these 2 treatments were compared to unfertilized trees and to trees under standard (STD) fertilization treatment (40 N–20P–20 K). Leaf nutrient concentrations and DRIS indices showed that fertilization treatments, and especially DRIS I corrected N deficiencies but failed to correct P deficiencies. Fertilization increased volume relative growth rate by 7.51, 4.76 and 13.25 % on average at the agricultural site for DRIS I, DRIS II and STD treatments respectively, compared to no fertilizer application. At the forest site, fertilization treatments based on DRIS indices (DRIS I and DRIS II) increased growth rates (6.67 %) slightly more than the standard treatment (5.80 %). Overall, although DRIS-based fertilization treatments generally increased growth rates, they were often equal to or less efficient than the STD treatment, and may not be as practical as using a standard fertilization recipe.

Keywords Forest plantations · Fertilization · DRIS · *Populus* spp · Growth · Nutrient balance index

Introduction

Nutritional deficiencies in plantations of fast-growing species have often been reported in boreal regions both on farmland and on forest sites (e.g., after a clearcut) (Tullus et al. 2007; Guillemette and DesRochers 2008). In boreal forest environments, soils are

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generally poor in many available nutrients because of slow decomposition of organic matter and low mineralization rate due to low temperatures and leaching (Piirainen et al. 2007; Allison et al. 2008, 2009). In conventional farming systems, the use of intensively-managed monocultures is common and may be a source of nutrient deficiencies (Varallyay 2007; Duggan et al. 2008; Toth et al. 2009). Nitrogen and phosphorus deficiencies can drastically affect yields of fast-growing plantations when they are established on farmland (Heilman and Xie 1993; Coleman et al. 2006). In addition to site history, tree growth in plantations may also be affected by inherent soil characteristics such as texture, depth, and pH which should be optimal to maximize growth of hybrid poplars (Stanturf et al. 2001). In an experiment conducted in Europe (Marron et al. 2010), tree growth of the same hybrid poplar clones (*P. deltoides* × *P. trichocarpa* and *P. alba* × *P. alba*.) varied significantly among three sites.

Understanding nutritional requirements of tree species used in plantations is important to maximize yields (Gregoire and Fisher 2004; Oskarsson and Brynleyfsdottir 2009). On one hand, nutritional deficiencies can lead to high mortality, slow early growth rates and low economic profitability (Pitre et al. 2007; Block et al. 2009; Pinno and Belanger 2009; Rivest et al. 2009). On the other hand, excess fertilization can lead to tree nutrient imbalances and consequently to lower yields (Fageria 2001). It may also negatively affect environment quality (Adler et al. 2007; Van Miegroet and Jandl 2007; Flint et al. 2008) through contamination of groundwater and surface waters by nutrient leaching or runoff (Lofgren et al. 2009). Nitrates and phosphates are the main constituents of the chemical pollution generated by fertilizer loss and wastage (Nikitishen and Lichko 2008). Therefore, accurate determination of the nutritional requirements of fast-growing trees should ensure high yields while mitigating effects on environmental quality and avoiding higher production costs (Jacobs and Timmer 2005).

Diagnosis methods that are based on foliar analysis have been developed to determine plant nutrient status because they are more reliable than those based on soil nutrient analyses (Beaufils 1973; Binkley 1986). Nutrient concentrations vary among the leaves of the same tree depending on their age and position (order and height) (Walworth and Sumner 1987) but these factors have much less impact on nutrient ratios than on their absolute concentrations (Beaufils 1973; Fageria 2001). Diagnosis and Recommendation Integrated System (DRIS) is based on the use of nutrient ratios that are standardized as DRIS formulas and then transformed into DRIS indices (Walworth and Sumner 1987). A nutrient index is a mean of the deviations of the nutrient ratios from their respective optimum or norm values (Sumner 1979). DRIS norms are obtained from highly-productive individuals of a population grown under field conditions, and assuming that their nutrient ratios are closest to tree optimal nutritional requirements, allows one to make fertilization recommendations.

DRIS has been successfully used as a fertilizer management tool for a number of agricultural crops (e.g., Walworth and Sumner 1987; Ruiz-Bello and Cajuste 2002; Reis and Monnerat 2003; Hartz et al. 2007; Hundal et al. 2007), but this approach is less common for forest plantations and its effectiveness is still being debated (Drechsel and Zech 1994; Ouimet and Camiré 1994; Campion and Scholes 2007; Lteif et al. 2008). The aim of the current study was to evaluate the efficiency of the DRIS method to correct nutritional imbalances and increase productivity in hybrid poplar plantations that have been established under boreal conditions. We hypothesized that (i) DRIS would accurately diagnose nutrient status of trees and be a good predictor of tree growth and (ii) DRIS-based fertilization would be more efficient to increase growth rates and correct nutrient deficiencies rather than using a standard fertilization formulae.

Materials and methods

Study sites and plant material

Four hybrid poplar clones were selected for planting on two sites in the Abitibi-Témiscamingue region of western Quebec (Canada). The first site was an abandoned farmland in the municipality of Duhamel (47°19′N, 79°25′W, Alt. 209 m). The site, which was located in the sugar maple-yellow birch western bioclimatic sub-domain (Grondin 1996), had been cultivated for hay in previous years (a perennial mixture of lucerne and timothy grass). Its soil type was a clayey (45 % clay) luvisol and mean annual precipitations was 820 mm. Annual mean temperature was 2.8 °C.

The second site was near the municipality of Duparquet, which was in the balsam fir-paper birch bioclimatic western sub-domain (Grondin 1996; 48°29′N, 79°26′W, Alt. 295 m), and had been previously forested until harvested in 2004. Mean annual precipitations and temperature were 918 mm and 0.7 °C respectively, and the soil of this site was classified as a heavy clay brunisol (70 % clay; Ministère de l'Agriculture du Canada and Ministère de l'Agriculture du Québec 1977).

Extensive site preparation and maintenance was performed both prior to planting and following the installation of the four clones. The agricultural site was ploughed using an agricultural cultivator in autumn 2004. Prior to plantation establishment at the forest site, stumps and remaining logs were removed with a bulldozer. The site was then ploughed to a depth of 30 cm in autumn of 2004 with a forestry plough pulled by a skidder and disked in spring 2005 to level the soil before planting. Trees were planted at both sites as bare-root stock in June 2005 at 4 × 1 m spacing. Following planting, weeds were mechanically removed twice a year by cultivating between rows with a farm tractor and by tilling between trees with a Weed Badger (4020-SST, Marion, ND, USA).

The clones that were used in this study had been recommended for the region by the Québec Ministry of Natural Resources and Fauna (MRNF). They were as follows: 747215, *Populus trichocarpa* Torrey & A.Gray × *P. balsamifera* L.; 915004 and 915005, *P. balsamifera* × *P. maximowiczii* Henry; and 915319 *P. maximowiczii* × *P. balsamifera*. At planting, the average height of the trees was 85.9 cm (714215), 89.4 cm (915004), 93.5 cm (915005), and 115 cm (915319), respectively. Stock type was 1-year old, dormant bareroot stock, grown in Trecesson provincial nursery (Ministry of Natural Resources and Fauna, Québec). Trees were lifted in the fall and stored over the winter in a refrigerator at 2 °C prior to planting. The experimental design was a split-plot where four fertilization treatments (sub-plot effect) were crossed within each of the four clones (main plot effect). Each fertilization treatment was applied to 15 trees (pseudo-replicates, three rows of five trees), and each clone-treatment combination was replicated in three blocks at each of the two sites (N = 1,440).

Height and basal diameter were measured at planting and at the end of 2005, 2006 and 2007 growing seasons. Stem volume was estimated with the formula:

$$V = A_b.H/3 \quad (1)$$

where V: stem volume (cm^3), A_b: basal area (cm) and H: height (cm) (Brown and van den Driessche 2002).

Relative growth rate (RGR, $cm^3\ cm^{-3}\ year^{-1}$) was used to take into account differences in tree volume among clones at planting ($p < 0.01$):

$$RGR = [\ln(V_{n+1}) - \ln(V_n)]/T_{n+1} - T_n \quad (2)$$

where V_{n+1} and V_n are the tree volume in years (T_n and T^{n+1}) respectively and ln is the natural logarithm.

Leaf sampling and fertilizer application

About 2 months after trees were planted (end of July 2005), two leaves from each of the five trees that formed the middle row of each fertilization × clone treatment combination were collected in each block and pooled together to determine the nutrient status of trees prior to fertilization and thereafter quantities of fertilizers to apply for treatments "DRIS I" and "DRIS II". Leaves were oven-dried (72 h at 70 °C) and ground through a 60 μm sieve of a Wiley mill (Thomas Scientific, Swedesboro, NJ, USA). Nitrogen concentrations were obtained by dry combustion method with a LECO N-analyzer (Leco Corp., MI, USA) (Leco Corp. 1986). P, K, Ca and Mg concentrations were determined using inductively-coupled plasma spectrophotometry (ICP) following a nitrichydrochloric acid digestion (Masson and Esvan 1995).

The first fertilization treatment (DRIS I) was based on DRIS functions taken from Guillemette and DesRochers (2008) but using foliar nutrient concentrations that were obtained from our trees. These functions had been determined from a study by using 18 combinations of N–P–K fertilizers on three hybrid poplar clones grown in the same region (747210: *P. balsamifera* × *P. trichocarpa*, 915005: *P. balsamifera* × *P. maximowiczii* and 915319: *P. maximowiczii* × *P. balsamifera*). The DRIS I treatment was thus composed of 10 g $tree^{-1}$ of ammonium nitrate (NH_4NO_3), 70 g $tree^{-1}$ of potassium sulphate (K_2SO_4) and 40 g $tree^{-1}$ of dolomite ($CaMg(CO_3)_2$). The DRIS II treatment was based on Leech and Kim's (1981) DRIS functions. The latter were obtained from an experiment in which growth response of hybrid poplars to various fertilization treatments was evaluated in northeastern Ontario. DRIS II consisted of 60 g $tree^{-1}$ of NH_4NO_3, 20 g $tree^{-1}$ of triple superphosphate ($Ca(H_2PO_4)_2)_3$), 30 g $tree^{-1}$ of K_2SO_4, and 30 g $tree^{-1}$ of calcium carbonate ($CaCO_3$). The third treatment (standard treatment, STD) had a 1:2:1 NPK ratio that is often used in agriculture (Wang et al., 2008) and which consisted of 40 g $tree^{-1}$ of NH_4NO_3, 20 g $tree^{-1}$ of $Ca(H_2PO_4)_2)_3$ and 30 g $tree^{-1}$ of K_2SO_4. A control treatment with no added fertilizer was also tested. In May 2006, fertilizers were placed in a 15 cm-deep hole 20 cm away from the base of each tree (Guillemette and DesRochers 2008). To avoid contamination between fertilization treatments, a buffer row of trees without fertilizers was retained between each treatment.

Leaves were sampled at the end of July 2006 (as described above in 2005) for nutrient analyses and to calculate DRIS indices.

Soil analyses

Five soil samples were collected in May 2007 at the farmland site and ten at the forest site (more heterogeneous) for chemical and physical characterization (Table 1). Soil samples were collected diagonally along plots. For each sample, two sub-samples from the 0–20 and 20–40 cm horizons were collected separately. Soil samples were subsequently dried in an oven at 50 °C, ground and sieved through a 60 μm mesh. The sub-samples at each level were then pooled for analysis. Soil pH was obtained after water-extraction of a saturated paste. Total carbon concentration in the soil was determined by high temperature combustion with a LECO N-analyzer (Leco Corp., MI, USA) and soil available cations concentrations and the cation exchange capacity (CEC, $cmol_c/kg$) were obtained by ICP after an ammonium acetate extraction at the Forest Resources and Soil Testing Laboratory, Lakehead University (Thunder Bay, Ontario).

Table 1 Soil physico-chemical characteristics of the two study sites

Soil sample depth	Site			
	Forest		Farmland	
	0–20 (cm)	20–40 (cm)	0–20 (cm)	20–40 (cm)
pH	4.92	5.81	5.61	5.48
Available cations (mg/kg)				
Ca	4,392	4,968	1,853	2,212
K	266	265	116	130
Mg	668	797	372	482
Na	43	51	16	27
CEC ($cmol_c$/kg)	28.3	32.3	12.7	15.5
MC (%)	0.0352	0.0348	0.0158	0.0207
C (%)	0.798	0.717	1.56	1.064
N (%)	0.082	0.062	0.132	0.087
Ca (%)	0.705	0.923	0.618	0.648
K (%)	0.750	0.730	0.291	0.38
Mg (%)	1.759	1.759	1.041	1.226
P (%)	0.037	0.055	0.054	0.046

CEC cation exchange capacity, *MC* moisture content

DRIS norms and indices

The DRIS approach allows the determination of a nutrient index, which is the degree of deviation of that nutrient from its optimum value or norm. The nutrient norms are obtained from a high-yielding population (Partelli et al. 2007), and a nutrient is considered balanced when its index is around zero. The more positive an index, the greater the degree to which the nutrient is in excess; conversely, the more negative an index, the greater the degree to which the nutrient is limiting (Walworth and Sumner 1987).

At the end of June (2005), leaf samples were collected to calculate DRIS field norms and indices. The field norms were established as the nutrient ratios for the best growing trees of each clone at each site (Table 2). Trees selected as field standards had a volume yield $\geq$80 % of the maximum yield (yield cutoff = 0.8). A DRIS function was developed for each clone at each site (Table 3) to take into account responses to fertilization due to genotype (clones) and environment (sites). For each pair of nutrients X and Y, there are three possible forms of nutrient expressions: X/Y, Y/X or X*Y. The selected expression was the one with the highest coefficient of variation (CV) between high-yielding and low-yielding groups. CV of X*Y were always the smallest in our experiment. The aim of this approach is to increase the diagnostic sensitivity and accuracy of nutrient imbalances (Walworth and Sumner, 1987).

$$f(\mathrm{X/Y}) = [(\mathrm{X/Y})/(\mathrm{x/y}) - 1] * 1{,}000/\mathrm{CV}, \quad \text{when } \mathrm{x/y} \leq \mathrm{X/Y} \tag{3}$$

or

$$f(\mathrm{X/Y}) = [1 - (\mathrm{x/y})/(\mathrm{X/Y}) - 1] * 1{,}000/\mathrm{CV}, \quad \text{when } \mathrm{X/Y} < \mathrm{x/y} \tag{4}$$

where X/Y is the ratio of the two nutrients in the leaves diagnosed (after fertilization) and x/y is the optimum value (norm) of that ratio. CV is the coefficient of variation of the norm ratio (x/y).

Table 2 Calculated DRIS norms of nutrient ratios and their coefficients of variation (CV, %) for each of the four clones tested at (a) farmland and (b) forest site

Clone											
747215			915004			915005			915319		
	Mean	CV(%)		Mean	CV(%)		Mean	CV(%)		Mean	CV(%)
(a)											
N/Ca	5.880	10.901	N/Ca	5.199	7.971	Ca/N	0.161	7.224	Ca/N	0.228	9.066
N/K	2.771	0.508	N/K	2.197	6.045	Ca/K	0.354	8.028	K/N	0.400	15.819
N/Mg	10.881	8.462	N/Mg	11.144	6.898	K/N	0.460	12.928	K/Ca	1.772	18.548
N/P	9.985	4.813	N/P	9.083	5.648	Mg/N	0.078	7.372	K/Mg	3.833	7.645
K/Ca	2.122	10.882	Ca/K	0.424	3.928	Mg/Ca	0.481	0.534	K/P	3.915	15.259
K/Mg	3.928	8.620	Ca/Mg	2.147	3.264	Mg/K	0.170	8.376	Mg/N	0.104	11.438
K/P	3.603	4.333	K/Mg	5.069	1.026	Mg/P	0.775	9.793	Mg/Ca	0.458	11.548
Mg/Ca	0.539	3.728	P/Ca	0.572	10.745	P/N	0.101	14.186	Mg/P	1.015	8.726
P/Ca	0.589	10.745	P/K	0.242	4.356	P/Ca	0.626	9.081	P/N	0.102	5.736
P/Mg	1.093	10.151	P/Mg	1.228	10.151	P/K	0.220	1.421	P/Ca	0.450	4.335
(b)											
Ca/N	0.182	4.814	N/K	1.254	4.994	N/K	1.432	9.813	Ca/N	0.181	32.233
Ca/Mg	2.128	2.446	N/P	7.942	3.261	N/P	7.597	2.610	Ca/K	0.290	29.275
Ca/P	1.730	4.605	Ca/N	0.221	7.672	Ca/N	0.149	9.752	Ca/Mg	1.846	12.332
K/N	0.504	7.482	Ca/K	0.278	12.078	Ca/K	0.211	5.333	Ca/P	1.516	26.516
K/Ca	2.770	2.731	Ca/P	1.760	9.778	Ca/Mg	1.773	7.228	K/N	0.617	7.889
K/Mg	5.897	5.101	Mg/N	0.096	6.644	Ca/P	1.129	10.513	K/P	5.295	6.878
K/P	4.799	7.387	Mg/Ca	0.435	2.103	K/P	5.354	9.739	Mg/N	0.095	22.668
Mg/N	0.085	3.477	Mg/K	0.121	10.469	Mg/N	0.084	5.852	Mg/K	0.154	20.486
Mg/P	0.813	2.387	Mg/P	0.764	8.089	Mg/K	0.119	4.714	Mg/P	0.806	16.136
P/N	0.105	2.177	P/K	0.158	2.541	Mg/P	0.636	4.839	P/N	0.117	7.684

Nutrient balance index (NBI) and correction index (CI)

The sum of the absolute values of the indices of different elements was divided by 5 (the number of nutrients considered) to obtain NBI (Nutrient Balance Index), where:

$$\mathrm{NBI} = \Sigma|\ \mathrm{X_{ind}}|/5 \tag{5}$$

This index gives quantitative information about the overall nutritional status before and after the application of fertilizers. To quantify the efficiency of each treatment in terms of correcting nutrient imbalances (deficiency or excess), a correction index (CI) was established. The CI is calculated for each nutrient and gives a value to the gap between the DRIS index of the nutrient and its optimum range. The closer to 0 the CI is, the more efficient is the fertilization treatment.

If DRIS index values of a nutrient X (e.g., N) are between -10 and 10 ($-10 \leq N_{ind} \leq 10$), the nutrient concentration is optimal and the correction index (CI) value is 0 (Mourão-Filho 2005):

$$\mathrm{If} -10 \leq \mathrm{X_{ind}} \leq 10 = > \mathrm{CI} = 0 \tag{6}$$

when nutrient index (X_{ind}) is out of [−10, 10] optimal interval

Table 3 DRIS formulas used for nutrient indices for each of the four clones in the farmland and the forest sites

	DRIS Formulae	
Clone	Farmland site	Forest site
747215	$N_{ind} = [+f(N/Ca) + f(N/K) + f(N/Mg) + f(N/P)]/4$ $P_{ind} = [+f(P/Ca) - f(K/P) + f(P/Mg) - f(N/P)]/4$ $K_{ind} = [-f(N/K) + f(K/Ca) + f(K/Mg) + f(K/P)]/4$ $Ca_{ind} = [-f(N/Ca) - f(Mg/Ca) - f(P/Ca) - f(K/Ca)]/4$ $Mg_{ind} = [+f(Mg/Ca) - f(K/Mg) - f(N/Mg) - f(P/Mg)]/4$	$N_{ind} = [-f(Ca/N) - f(K/N) - f(Mg/N) - f(P/N)]/4$ $P_{ind} = [-f(Ca/P) - f(K/P) - f(Mg/P) + f(P/N)]/4$ $K_{ind} = [+f(K/N) + f(K/Ca) + f(K/Mg) + f(K/P)]/4$ $Ca_{ind} = [+f(Ca/N) + f(Ca/Mg) + f(Ca/P) - f(K/Ca)]/4$ $Mg_{ind} = [-f(Ca/Mg) - f(K/Mg) + f(Mg/N) + f(Mg/P)]/4$
915004	$N_{ind} = [+f(N/Ca) + f(N/K) + f(N/Mg) + f(N/P)]/4$ $P_{ind} = [+f(N/Ca) + f(N/K) + f(N/Mg) + f(N/P)]/4$ $K_{ind} = [-f(N/K) - f(Ca/K) + f(K/Mg) - f(P/K)]/4$ $Ca_{ind} = [f(N/Ca) + f(Ca/Mg) + f(P/Ca) + f(Ca/K)]/4$ $Mg_{ind} = [-f(Ca/Mg) - f(K/Mg) - f(N/Mg) - f(P/Mg)]/4$	$N_{ind} = [-f(Ca/N) + f(N/K) - f(Mg/N) + f(N/P)]/4$ $P_{ind} = [-f(Ca/P) + f(P/K) - f(Mg/P) - f(N/P)]/4$ $K_{ind} = [-f(N/K) - f(Ca/K) - f(Mg/K) - f(P/K)]/4$ $Ca_{ind} = [+f(Ca/N) - f(Mg/Ca) + f(Ca/P) + f(Ca/K)]/4$ $Mg_{ind} = [+f(Ca/N) - f(Mg/Ca) + f(Ca/P) + f(Ca/K)]/4$
915005	$N_{ind} = [-f(Ca/N) - f(K/N) - f(Mg/N) - f(P/N)]/4$ $P_{ind} = [+f(P/N) + f(P/Ca) + f(P/K) - f(Mg/P)]/4$ $K_{ind} = [+f(K/N) - f(Ca/K) - f(Mg/K) - f(P/K)]/4$ $Ca_{ind} = [+f(Ca/N) - f(Mg/Ca) - f(P/Ca) + f(Ca/K)]/4$ $Mg_{ind} = [+f(Mg/Ca) + f(Mg/K) + f(Mg/N) + f(Mg/P)]/4$	$N_{ind} = [-f(Ca/N) + f(N/K) - f(Mg/N) + f(N/P)]/4$ $P_{ind} = [-f(K/P) - f(Ca/P) - f(Mg/P) - f(N/P)]/4$ $K_{ind} = [-f(N/K) - f(Ca/K) - f(Mg/K) + f(K/P)]/4$ $Ca_{ind} = [+f(Ca/N) + f(Ca/Mg) + f(Ca/P) + f(Ca/K)]/4$ $Mg_{ind} = [-f(Ca/Mg) + f(Mg/K) + f(Mg/N) + f(Mg/P)]/4$
915319	$N_{ind} = [-f(Ca/N) - f(K/N) - f(Mg/N) - f(P/N)]/4$ $P_{ind} = [+f(P/Ca) - f(K/P) - f(Mg/P) + f(P/N)]/4$ $K_{ind} = [+f(K/N) + f(K/Ca) + f(K/Mg) + f(K/P)]/4$ $Ca_{ind} = [+f(Ca/N) - f(Mg/Ca) - f(P/Ca) - f(K/Ca)]/4$ $Mg_{ind} = [+f(Mg/Ca) - f(K/Mg) + f(Mg/N) + f(Mg/P)]/4$	$N_{ind} = [-f(Ca/N) - f(K/N) - f(Mg/N) - f(P/N)]/4$ $P_{ind} = [-f(Ca/P) - f(K/P) - f(Mg/P) + f(P/N)]/4$ $K_{ind} = [+f(K/N) - f(Ca/K) - f(Mg/K) + f(K/P)]/4$ $Ca_{ind} = [+f(Ca/N) + f(Ca/Mg) + f(Ca/P) + f(Ca/K)]/4$ $Mg_{ind} = [-f(Ca/Mg) + f(Mg/K) + f(Mg/N) + f(Mg/P)]/4$

$$\text{If } X_{ind} < -10 = > CI = (X_{ind}/10) + 1 \quad (7)$$

$$\text{If } X_{ind} > 10 = > CI = (X_{ind}/10) - 1. \quad (8)$$

To simultaneously evaluate the effects of the different fertilization treatments on the nutrient status and the growth of trees at the same time, a grade was given to each combination of treatment/nutrient index:

F/0: unbalanced index (F) and RGR of treatment equal to control (0); *S/0*: balanced index (S) and RGR of treatment equal to control (0); *F/1*: unbalanced index and RGR of treatment higher than control (1); *S/1*: balanced index (S) and RGR of treatment higher than control (0); *f+/0 and f−/0*: reduced imbalance (index >10 or <−10) and RGR of the treatment equal to control (0); *f+/1 and f−/1*: reduced imbalance (index >10 or <−10) and RGR of the treatment higher than control (1).

Statistical analyses

The data were subjected to split-plot ANOVA analysis with clone as the whole plot and fertilization treatment as the sub-plot. Blocks (replicates) were considered as random effects while fertilizers and clones were considered as fixed effects. Analysis of variance was used to test the effect of the different fertilization treatments on DRIS indices obtained after their application, and relative growth rates. Each site was analyzed separately and the significance level for all tests was set to $\alpha = 0.05$. Linear Mixed Models package of R software were used to perform statistical analyses (R. Foundation for Statistical Computing, Vienna, Austria) and least square means were compared using Tukey's honest significant differences (HSD) function.

Results

Fertilizer-growth

Average relative growth rate of the four clones was increased by fertilization at both sites but clones responded differently to fertilization treatments in 2006 (Table 4). At the forest site, trees fertilized with DRIS I, DRIS II and STD had greater growth rates (average of four clones) than unfertilized trees (3.75, 3.70, 3.70 and 3.49 $cm^3\ cm^{-3}\ year^{-1}$, respectively) (Fig. 1a). A significant Clone x Treatment interaction ($p = 0.02$) was noticed as the "Treatment" effect depended on clones. Fertilization increased growth rates by 5.04 to

Table 4 Analysis of variance showing the variables tested, degrees of freedom (d.f) and F value for volume relative growth rate (RGR) in 2006 and 2007 on the farmland and the forest sites

Years	d.f	2006				2007			
		Farmland site		Forest site		Farmland site		Forest site	
		F value	*p*	F value	*p*	F value	*p*	F value	*p*
Clone	3	8.18	(<0.01)	7.54	(<0.01)	2.64	0.06	2.85	0.05
Treatment	3	0.86	0.45	2.88	0.03	0.88	0.46	1.71	0.18
Clone * treatment	9	2.29	0.02	2.26	0.02	2.02	0.06	1.35	0.25

d.f degrees of freedom

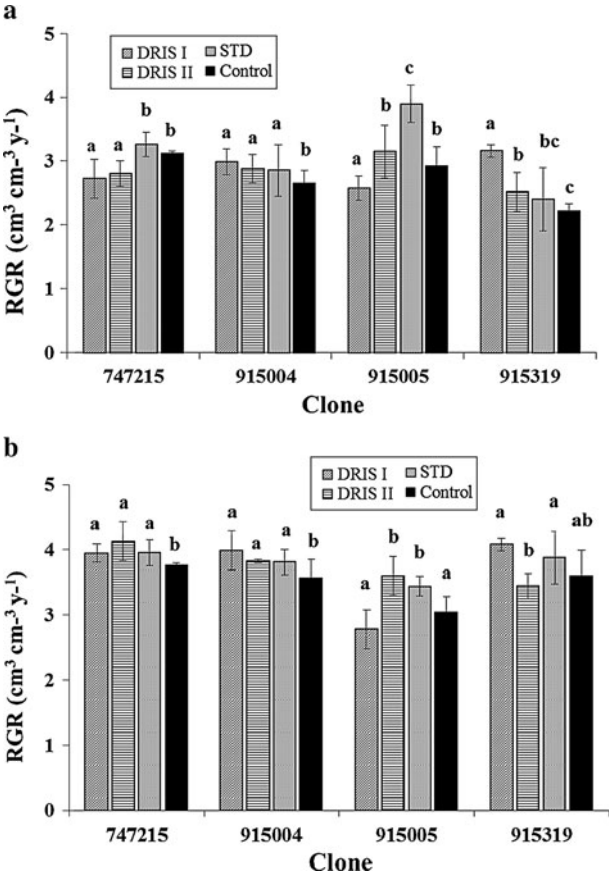

Fig. 1 Relative growth rate (RGR) of each clone according to the fertilization treatment in the year it was applied (2006, 2 year old trees) at the **a** farmland and **b** forest site. *Bars* labelled with the same letter within the same clone are not significantly different at $p < 0.05$

18.44 % depending on treatments and clones. DRIS I generated the greatest growth increases for clones 915319 and 915004 (13.55 and 11.90 %) and DRIS II for the other two clones (9.84 and 18.44 %) (Fig. 1a).

At the farmland site, relative growth rate was generally lower than at the forest site in 2006 and ranged between 2.73 cm^3 cm^{-3} $year^{-1}$ (unfertilized) and 3.10 cm^3 cm^{-3} $year^{-1}$ (STD), on average (Fig. 1b). DRIS I increased relative growth rate of clone 915319 by 42.08 %, but decreased it for two other clones by 11.95 and 12.82 %, compared to unfertilized trees. DRIS II had an overall better effect over the 4 clones and increased growth rate of three of the four clones by 7.4 to 13.44 %. However, STD treatment resulted in the greatest growth increases at the farmland site (13.25 % on average).

In 2007, variations in RGR were explained mainly by clones ($p = 0.05$) at the forest site (Table 4). Relative growth rate was increased by 6.94 to 20.47 % with DRIS I and by 5.41 to 17.18 % with DRIS II depending on clones. STD fertilizer treatment increased growth rate by 2.94 to 11.92 % on average compared to unfertilized trees (Fig. 2a).

A marginal but not significant clone x treatment interaction ($p = 0.06$) and clonal effect ($p = 0.06$) were detected in the agricultural site in 2007 (2 years following fertilizer

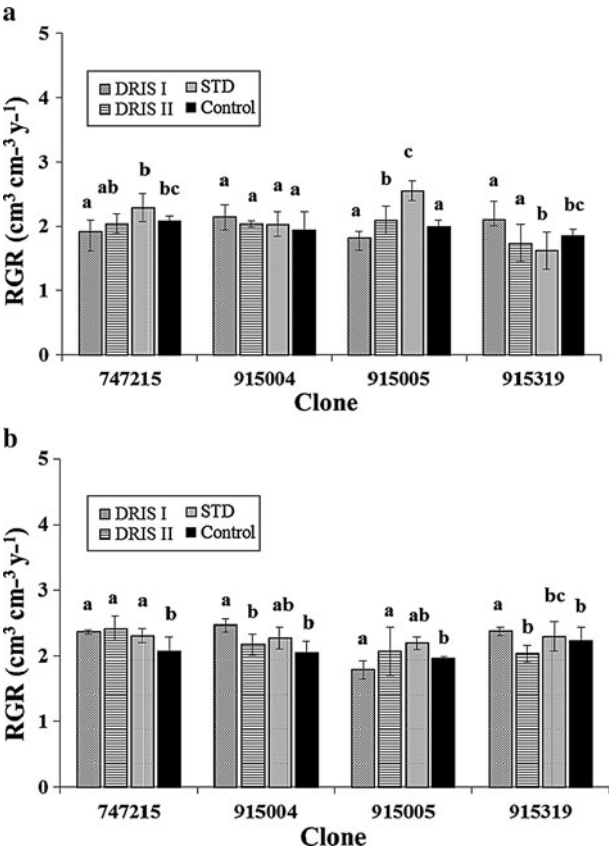

Fig. 2 Relative growth rate (RGR) of each clone according to the fertilization treatment, a year after it was applied (2007, 3 year old trees) at **a** farmland and **b** forest site. *Bars* labelled with the same letter within the same clone are not significantly different at $p < 0.05$

application) (Table 4). STD fertilizer generated the greatest relative growth rate (2.12 cm^3 cm^{-3} $year^{-1}$ on average) and increased it by 8.1 % compared to unfertilized trees. DRIS I and DRIS II increased growth for two clones but decreased it for the others so that the average effect was almost nil (Fig. 2b).

DRIS indices

At the agricultural site, the three fertilization treatments had no effect on N indices, which remained within optimum values in 2006 (between −10 and 10), except for clone 747215 (Table 5). Leaf N concentrations were higher or slightly lower in unfertilized trees, which implies that trees were not N-deficient (Table 6). Phosphorus (P) deficiency was apparent for non-fertilized trees, but fertilization failed to balance P DRIS indices, as their values ranged between −29 and −118 after fertilizer application (Table 5). Leaf P concentrations were consistent with DRIS indices, in that they did not increase with fertilization (Table 6). Significant potassium (K) deficiencies were noted for unfertilized trees of two clones (DRIS indices were −36.53 and −85.16 for clones 747215 and 915004, respectively); the

Table 5 DRIS indices of the four tested clones at the farmland and forest sites before fertilization (a, 2005) and after application of the four fertilization treatments (DRIS I, DRIS II, STD, and control; b)

Site	Farmland site					Forest site				
Clone	N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}	N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}
(a)										
747215	−9.82	2.25	3.31	−0.84	2.35	−15.15	3.26	−10.13	8.03	−6.16
915004	−12.30	−4.90	4.08	−6.32	−12.19	−25.30	3.21	−13.04	−1.26	0.55
915005	−20.84	−6.64	14.42	20.21	−3.15	−25.40	2.37	−12.73	−2.36	4.23
915319	2.15	3.51	4.54	−2.54	−2.83	−33.04	7.71	−1.78	−10.78	−6.92

Site	Trt	Farmland site					Forest site				
Clone		N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}	N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}
(B)											
747215	DRIS I	−40.73	−56.91	17.59	99.76	−19.70	1.82	−17.38	11.10	65.63	−61.17
	DRIS II	−28.82	−51.83	−20.53	102.60	−1.40	−41.03	−25.48	9.59	72.36	−15.43
	STD	−15.18	−63.23	−29.58	106.86	1.13	−7.61	−10.62	−6.67	61.18	−36.27
	Control	−14.68	−58.71	−36.53	101.70	8.22	−121.45	−5.32	24.16	94.04	8.57
915004	DRIS I	5.35	−92.32	−80.02	177.57	−10.58	49.92	−58.70	−29.17	105.34	−67.38
	DRIS II	−0.56	−62.74	−31.64	168.89	−73.94	44.34	−50.26	−41.53	100.54	−53.09
	STD	6.90	−87.05	−125.62	189.24	16.52	44.71	−31.15	−41.70	94.09	−65.94
	Control	−0.84	−76.17	−85.16	177.59	−15.41	−6.93	−17.95	−36.49	100.81	−39.43
915005	DRIS I	−10.16	−115.80	51.21	336.55	−26.18	62.85	−115.80	−5.15	66.06	−7.96
	DRIS II	−5.85	−101.07	37.30	315.24	−24.56	33.79	−83.90	−15.82	79.92	−13.99
	STD	−14.05	−118.28	55.88	331.74	−25.53	54.75	−103.37	−19.85	74.63	−6.16
	Control	−12.78	−115.32	56.48	286.46	−21.48	−33.21	−105.62	−25.41	128.93	35.31

Table 5 continued

Site	Trt	Farmland site					Forest site				
Clone		N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}	N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}
915319	DRIS I	−8.28	−44.32	0.86	63.66	−11.91	11.78	−30.17	−2.94	49.39	−28.06
	DRIS II	2.75	−42.32	4.74	42.22	−7.39	17.88	−13.67	−14.63	46.34	−35.92
	STD	−1.38	−29.38	2.80	54.73	−26.77	4.61	−18.15	−12.88	52.77	−26.34
	Control	−4.00	−13.56	3.74	37.83	−24.01	−39.59	−16.36	7.85	56.03	−7.92

Trt fertilization treatments

Table 6 Nutrient concentrations (%) for clones and treatments in 2006 at the farmland and the forest sites

Clones	Trt	Site									
		Farmland					Forest				
		Nutrients (%)									
		N	P	K	Ca	Mg	N	P	K	Ca	Mg
747215	DRIS I	2.443	0.212	0.936	0.778	0.270	2.573	0.259	1.402	0.554	0.194
	DRIS II	2.432	0.222	0.891	0.817	0.299	2.518	0.263	1.300	0.546	0.206
	STD	2.407	0.206	0.862	0.812	0.296	2.248	0.246	1.380	0.558	0.211
	Control	2.341	0.205	0.841	0.786	0.299	1.956	0.263	1.534	0.616	0.232
915004	DRIS I	2.285	0.169	0.930	0.767	0.210	2.335	0.209	1.379	0.638	0.179
	DRIS II	2.450	0.210	1.062	0.810	0.202	2.360	0.230	1.364	0.623	0.180
	STD	2.293	0.170	0.878	0.781	0.218	2.311	0.214	1.331	0.650	0.190
	Control	2.329	0.184	0.958	0.796	0.216	2.051	0.241	1.412	0.666	0.199
915005	DRIS I	2.589	0.187	1.183	0.639	0.194	2.591	0.224	1.657	0.492	0.185
	DRIS II	2.648	0.190	1.145	0.627	0.194	2.565	0.221	1.561	0.503	0.187
	STD	2.534	0.188	1.203	0.640	0.196	2.493	0.238	1.651	0.532	0.188
	Control	2.498	0.186	1.185	0.612	0.197	1.923	0.214	1.669	0.634	0.221
915319	DRIS I	2.962	0.271	1.158	0.934	0.274	2.754	0.243	1.516	0.832	0.205
	DRIS II	3.131	0.274	1.235	0.891	0.296	2.678	0.264	1.432	0.883	0.214
	STD	3.193	0.300	1.247	0.982	0.274	3.164	0.296	1.539	0.854	0.202
	Control	3.228	0.325	1.307	0.937	0.289	1.876	0.266	1.594	0.960	0.268

Trt fertilization treatments

deficiency was partially alleviated by DRIS I treatment but only for one clone (747215, Table 5). Unfertilized and fertilized trees had excess calcium (Ca), as reflected in the range of DRIS indices, i.e., from 37.8 to 286.5 (Table 5). With few exceptions, fertilization had no effect on leaf Ca concentration and the respective DRIS indices (Table 5 and 6). Control trees of two clones (915004 and 915319) had magnesium (Mg) deficiencies, which were corrected with DRIS I and DRIS II treatments but only for clone 915319 (Table 5).

At the forest site, all unfertilized trees showed nitrogen deficiencies, with DRIS values ranging between −121.5 and −6.9 (Table 5), and leaf N concentrations were low compared to the farmland site (Table 6). Trees N status was greatly improved by fertilization, particularly with the DRIS I treatment. Not all fertilization treatments improved K status. Except for one clone (915004), DRIS I was the most effective treatment for correcting K imbalances (Table 5). As for the agricultural site, P deficiencies were detected but were not corrected by fertilization; DRIS indices of fertilized trees ranged between −115.8 and −10.6 (Table 5). Similarly, fertilization did not increase leaf P concentration (Table 6). DRIS indices of fertilized and unfertilized trees also showed an excess of Ca for all clones at the forest site (56.03 to 128.9). The indices of fertilized trees were more balanced than unfertilized trees but still far from the optimum range (Table 5). Except for clone 915005, fertilization incurred magnesium deficiencies with DRIS indices ranging between −65.9 and −15.4 after fertilization (Table 5). Further, Mg leaf concentrations of clone 915319 were noticeably reduced by fertilization (Table 6).

Nutrient balance index (NBI) and correction indices (CI) showed that clones response to fertilization treatments was significantly different from one another (Table 7). Nevertheless,

Table 7 Correction index (CI) and nutrient balance index (NBI) for clones and treatments at the farmland and the forest sites

Site	Trt	Farmland						Forest					
Clone		Correction index					NBI = Σlindl/5	Correction index					NBI = Σlindl/5
		N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}		N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}	
747215	DRIS I	−3.07	−4.69	0.76	8.98	−0.97	46.94[a]	0	−0.74	0.11	5.56	−5.12	31.42[a]
	DRIS II	−1.88	−4.18	−1.05	9.26	0	41.05[b]	−3.10	−1.55	0	6.24	−0.54	32.78[a]
	STD	−0.52	−5.32	−1.96	9.69	0	43.20[b]	0	−0.06	0	5.12	−2.63	24.47[b]
	Control	–	–	–	–	–	43.97[b]	–	–	–	–	–	50.71[c]
915004	DRIS I	0	−8.23	−7.00	16.76	−0.06	67.56[a]	3.99	−4.87	−1.92	9.53	−5.74	62.11[a]
	DRIS II	0	−5.27	−2.16	15.89	−6.39	67.55[a]	3.43	−4.03	−3.15	9.05	−4.31	57.96[b]
	STD	0	−7.71	−11.56	17.92	2.65	85.07[b]	3.47	−2.12	−3.17	8.41	−5.59	55.52[b]
	Control	–	–	–	–	–	71.07[c]	–	–	–	–	–	40.33[c]
915005	DRIS I	−0.02	−10.58	4.12	32.66	−27.18	155.11[a]	5.29	−10.58	0	5.61	0	51.57[a]
	DRIS II	0	−9.11	2.73	30.52	−25.56	141.01[b]	2.38	−7.39	−0.58	6.99	−0.40	45.49[b]
	STD	−0.41	−10.83	4.59	32.17	−26.53	155.05[a]	4.48	−9.34	−0.99	6.46	0	51.76[a]
	Control	–	–	–	–	–	137.18[b]	–	–	–	–	–	65.70[c]
915319	DRIS I	0	−3.43	0	5.37	−0.19	25.80[a]	0.18	−2.02	0	3.94	−1.81	24.47[a]
	DRIS II	0	−3.23	0	3.22	0	19.88[b]	0.79	−0.37	−0.46	3.63	−2.59	25.69[a]
	STD	0	−1.94	0	4.47	−1.68	23.01[a]	0	−0.82	−0.29	4.28	−1.63	22.95[b]
	Control	–	–	–	–	–	16.63[c]	–	–	–	–	–	25.56[a]

Trt fertilization treatments

Values with the same letter within the same clone and site are not significantly different at $p < 0.05$

DRIS indices of fertilized trees were generally more balanced in forest than in the agricultural site. NBI values of DRIS I treatment, for example, were 46.94, 67.56, 155.11 and 25.8 at the farmland and 31.42, 62.11, 51.57 and 24.47 at the forest site for clones 747215, 915004, 915005 and 915319, respectively. Overall, the CI indicated that DRIS indices of clones 714215 and 915319 fertilized with DRIS I and DRIS II were closer to the optimum range (−10 and 10) than those of clones 915004 and 915005 at both sites (Table 7).

DRIS indices versus growth

Overall, when DRIS indices were balanced ($-10 < X_{ind} < 10$), RGR of fertilized trees were, often, greater than for unfertilized trees (Table 8). In 2006, when the DRIS index for N was corrected, growth of fertilized trees was usually better than that of the control ((F/0, S/1 and f/1; Table 8a). It was the same for K and Ca indices at the forest site and Mg indices at the farmland site. However, in some cases, growth did not increase even though the DRIS indices were corrected (Table 8a).

For the second growing season, DRIS indices were less accurate in predicting fertilizer effects on RGR, especially for N indices at the farmland site and for all nutrients at the forest site (Table 8b). At the farmland site, N DRIS indices of clones 915004, 915005 and 915319 were balanced for fertilized trees but without improving their relative growth rate (S/0). At the forest site, fertilization treatments were more efficient in enhancing growth rate for clones 747215 and 915004 than at the farmland site. However these growth increases did not correspond to predictions using DRIS indices which were rarely balanced. As for clones 915004 and 915005, relative growth rate of fertilized trees were not greater than those of unfertilized trees and DRIS indices were unbalanced in most cases (Table 8b).

Stem volume of all clones and treatments was negatively correlated with the Nutrient Balance Index (NBI) at the forest site. As NBI decreased, DRIS indices were more balanced (approached 0) and, consequently, stem volume of trees increased. When NBI values increased, DRIS indices deviated from 0 and stem volume decreased (Fig. 3). This relationship was evident for both growing seasons 2006 and 2007 with r^2 values of 0.59 ($p < 0.001$) and 0.42, respectively. ($p = 0.02$ respectively). No relationship between NBI and stem volume was found at the agricultural site (not shown).

Discussion

Hybrid poplar growth response to fertilization following DRIS norms have been shown to vary between sites and clones (Leech and Kim 1981; Guillemette and DesRochers 2008). In our study, effects of fertilization treatments on relative growth rates (RGR) also depended on the clone and site, which implies that quantities and types of fertilizers should be individually determined for each clone to optimize their respective growth rate. However, DRIS indices of the four clones were similar before fertilization (Table 5a) but application of the same fertilizer recipes resulted in different growth responses. Also, A significant Treatment*Clone interaction was obtained in both sites in 2006 which means that clones did not respond the same way to fertilization treatments. In fact, we noticed a more remarkable "Treatment" effect for clones 915005 and 915319. This might be explained by the genetic differences between clones in term of growth rate, biomass allocation and nutrient uptake and thus growth potential (Stanturf et al. 2001).

In the present study, nutritional imbalances were corrected more effectively at the forest site compared to the agricultural site. DRIS I was also the most effective fertilization

Table 8 DRIS indices and relative growth rates (RGR) for clones and fertilization treatments at the farmland and the forest sites after the first (a, 2006) and the second growing season (b, 2007)

Site	Trt	Farmland					Forest				
Clone		N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}	N_{ind}	P_{ind}	K_{ind}	Ca_{ind}	Mg_{ind}
(a)											
747215	DRIS I	F/0	f−/0	S/0	f+/0	F/0	S/1	F/1	S/1	f+/1	F/1
	DRIS II	F/0	f−/0	f−/0	f+/0	S/0	f−/1	F/1	S/1	f+/1	F/1
	STD	F/1	F/1	f−/1	f+/1	S/1	S/1	S/1	S/1	f+/1	F/1
915004	DRIS I	S/1	F/1	f−/1	F/1	S/1	f+/1	F/1	f−/1	F/1	F/1
	DRIS II	S/1	f−/1	f−/1	f+/1	f−/1	f+/0	F/0	F/0	F/0	F/0
	STD	S/1	F/1	F/1	f+/1	f+/1	f+/1	F/1	F/1	f+/1	F/1
915005	DRIS I	S/0	f−/0	f+/0	F/0	F/0	f+/1	F/1	S/1	f+/1	S/1
	DRIS II	S/0	f−/0	f+/0	F/0	F/0	f+/0	f−/0	f−/0	f+/0	f−/0
	STD	f−/1	F/1	f+/1	F/1	F/1	f+/1	f−/1	f−/1	f+/1	S/1
915319	DRIS I	S/1	F/1	S/1	F/1	S/1	S/1	F/1	S/1	f+/1	F/1
	DRIS II	S/1	F/1	S/1	F/1	S/1	F/0	f−/0	F/0	f+/0	F/0
	STD	S/0	F/0	S/0	F/0	F/0	S/0	F/0	F/0	f+/0	F/0
(b)											
747215	DRIS I	F/0	f−/0	S/0	f+/0	F/0	S/1	F/1	S/1	f+/1	F/1
	DRIS II	F/0	f−/0	f−/0	f+/0	S/0	f−/1	F/1	S/1	f+/1	F/1
	STD	F/0	F/0	f−/0	f+/0	S/0	S/1	S/1	S/1	f+/1	F/1
915004	DRIS I	S/0	F/0	f−/0	F/0	S/0	f+/1	F/1	f−/1	F/1	F/1
	DRIS II	S/0	f−/0	f−/0	f+/0	f−/0	f+/0	F/0	F/0	F/0	F/0
	STD	S/0	F/0	F/0	f+/0	f+/0	f+/1	F/1	F/1	f+/1	F/1
915005	DRIS I	S/0	f−/0	f+/0	F/0	F/0	f+/0	F/0	S/0	f+/0	S/0
	DRIS II	S/0	f−/0	f+/0	F/0	F/0	f+/1	f−/1	f−/1	f+/1	f−/1
	STD	f−/1	F/1	f+/1	F/1	F/1	f+/0	f−/0	f−/0	f+/0	S/0
915319	DRIS I	S/1	F/1	S/1	F/1	S/1	S/1	F/1	S/1	f+/1	F/1
	DRIS II	S/1	F/1	S/1	F/1	S/1	F/0	f−/0	F/0	f+/0	F/0
	STD	S/0	F/0	S/0	F/0	F/0	S/0	F/0	F/0	f+/0	F/0

F/0: unbalanced index (F) and RGR of treatment ≤ Control (0); *S/0*: balanced index (S) and RGR of treatment ≤ Control (0)

F/1: unbalanced index and RGR of treatment > Control (1); *S/1*: balanced index (S) and RGR of treatment > Control (0)

f+/0 and f−/0: reduced imbalance (index > 10 or <−10) and RGR of the treatment ≤ Control (0)

f +/1 and f−/1: reduced imbalance (index > 10 or < −10) and RGR of the treatment > Control (1)

treatment for correcting nutrient imbalances and increasing tree growth (Table 8). This was expected since DRIS I was based on DRIS formulae that had been developed in the same region with two of the four clones used in our study (Guillemette and DesRochers 2008). Although site conditions may not differ that greatly between northwestern Québec and Ontario, experience has shown that requirements can vary greatly between hybrids (Coleman et al. 2006, van den Driessche et al. 2008; Rivest et al. 2009), and interaction of clones with specific environmental conditions (Marron et al. 2010) can also result in different DRIS norms such as we found in our study between DRIS I (Québec) and DRIS II (Ontario). DRIS indices after fertilization were often—but not always—good predictors of

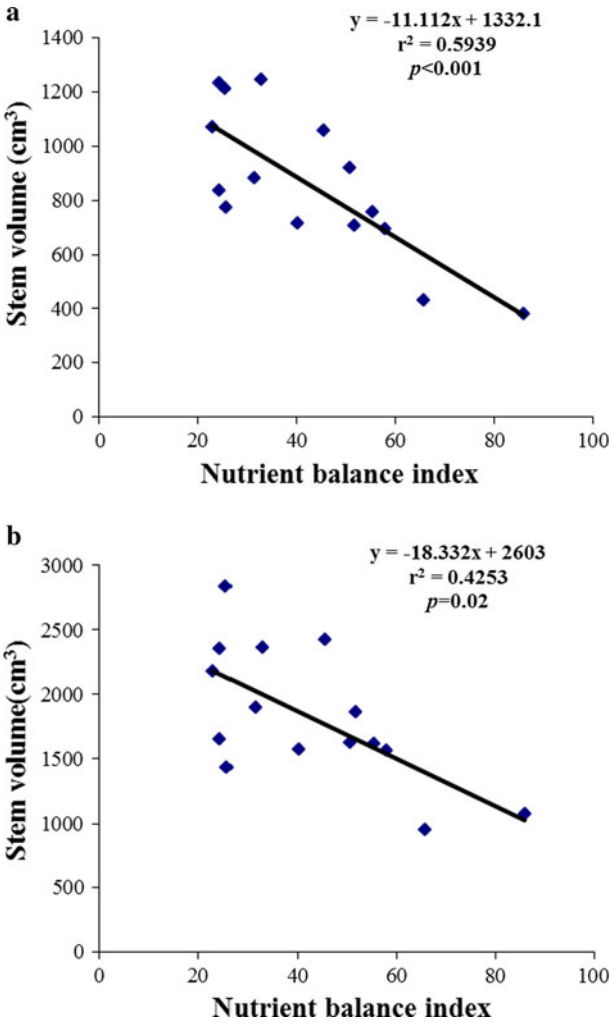

Fig. 3 Relationship between stem volume and nutrient balance index (NBI) at the forest site in 2006 (**a**, 2 year old trees) and 2007 (**b**, 3 year old trees). Each point is the mean of tree volume for the different treatments and clones

tree growth response to fertilization. Nutrient deficiencies are known to be a major factor limiting growth through the reduction of photosynthetic rate and biomass production. Also, nutrients in excess might be toxic or reduce the uptake of other nutrients (Hüner and Hopkins 2008). Indeed, the sum of DRIS indices (or NBI) was negatively correlated with tree volume at the end of the first (2006) and second (2007) growing seasons at the forest site (Fig. 3). This negative correlation shows that tree growth was inversely proportional to NBI which is an indicator of the deviation of DRIS indices from optimum values. Using NBI thus seems an easy way to predict fertilization treatment effects on growth, since it combines the overall imbalances into a single value (Nachtigall and Dechen 2007).

In the agricultural site, no significant relationship was detected between tree volume and NBI for the two growing seasons. Both foliar nutrient concentrations and DRIS indices of

unfertilized trees in the agricultural site indicated that trees were slightly nutrient deficient and that fertilization did not increase growth rates to the same degree as it did at the forest site (Tables 5 and 6). The trees may have benefitted from residual fertilizer in this previously agricultural site. Actually, soil N and P concentrations at the agricultural site (0.13 and 0.05 %, respectively) were higher than the forest site (0.08 and 0.03 %) (Table 1). N and P foliar concentrations of the four clones ranged between 23 and 32 mg N g^{-1} and from 2 to 3.2 mg P g^{-1}, respectively. On the other hand, the better growth rates that we found at the forest compared to the agricultural site might be explained by differences in the physical and chemical characteristics and history of each site (Hüttl and Schaaf 1995; Table 1). Guillemette and DesRochers (2008) reached the same conclusion in their study of hybrid poplars fertilization on two sites of the same region (farm vs. forest lands). Concentrations of exchangeable cations (particularly K^+ and Mg^{++}) at the farmland site were significantly lower than those at the forest site. Cation exchange capacity (CEC) was also 2 times greater at the forest compared to the farmland site (30.3 and 14.1 $cmol_c/g$, respectively; Table 1). Tillage with agricultural machinery frequently leads to soil compaction and structural deterioration, which can affect the soil chemical properties such as CEC (Domzl et al. 1993; Simansky et al. 2008).

Other experiments using hybrid poplars in similar environmental conditions (north-eastern Canada) have found lower N leaf concentrations ranging between 17 and 22 mg g^{-1} and P concentrations between 1.4 and 2 mg g^{-1} (Guillemette and Desrochers 2008; Rivest et al. 2009). In general, for North American poplars and their hybrids, optimal leaf N and P concentrations should be between 28 and 40 mg N g^{-1}, and 2.5 and 5 mg P g^{-1} respectively (Heilman and Xie 1993; van den Driessche et al. 2008), which are greater than those measured in our study.

In many cases, even when imbalances were completely or partially corrected, growth did not increase (e.g., N indices for 915004 at the forest site in 2006). This result may be explained by a tendency of hybrid poplars for luxury consumption, i.e., the assimilation of specific nutrients in excess of immediate growth requirements (Chapin 1980). After fertilization, luxury consumption can be a strategy for the plant to stock nutrients and use them later when they might become unavailable (especially for mobile nutrients such as NO_3^-) when soil freezes under boreal conditions. It may also be a strategy for overcoming competition effects even though it is linked to a greater investment in root system biomass at the expense of shoot growth (Van Wijk et al. 2003, de Mazancourt and Schwartz 2010). This phenomenon has been observed in other tree saplings and seedlings, i.e., increased N contents in plant tissues after fertilization without concurrent growth increases (Boivin et al. 2004; Salifu et al. 2009).

For all clones, N and P were often the most deficient nutrients, especially at the forest site (Table 5), and correspondingly soil N and P concentrations were low, which is a common problem in soils of boreal regions (Weih 2004; Cooke et al. 2005). Fertilization treatments often successfully corrected N deficiencies, but they failed to correct for P imbalances. DRIS I fertilization treatment did not contain any P because DRIS indices of 2005 did not show a deficiency for this nutrient at that time (Table 5a). However, DRIS indices of control trees showed a clear deficiency for P, especially at the agricultural site. It is possible, then, that P concentrations were balanced by pre-fertilization through residual P from the nursery, which became exhausted after a full growing season (Table 5b). For DRIS II and STD treatments, 50 kg ha^{-1} of P were applied, but DRIS indices still remained under the optimum range. This might be explained either by insufficient input of P or by insufficient uptake of available P because of negative interactions with other nutrients such as N or Ca, the high inputs of which may reduce P availability (Fageria

2001; DesRochers et al. 2007). Phosphorus uptake by roots might also be limited by N deficiency (Güsewell 2004). Calcium was always in excess in unfertilized trees at the two sites, and DRIS I and DRIS II introduced more calcium as calcium carbonate ($CaCO_3$) and as calcium-magnesium carbonate ($CaMg(CO_3)_2$), which may explain the high leaf concentrations of this nutrient after fertilization. However, the standard treatment (STD) did not contain calcium and its DRIS index remained in excess. This can be attributed either to a high concentration of this nutrient in the soil (Lteif et al. 2008) or to a low soil K^+ content which is known to significantly increase absorption of Ca^{++} and Mg^{++} (Fageria 2001; Garcia-Hernandez et al. 2006). Indeed, the clay soils in our study (luvisol and brunisol) are usually rich in calcium (McKeague and Stonehouse 2008). In the present study, soil Ca^{++} content was high as concentrations were 0.81 % and 0.63 % at the forest and farmland sites respectively (0.29 % or 14.5 $cmol_c$/kg is considered as high content; Tisdale et al. 1985).

Practical considerations

Overall, our study showed that even at an early age, fertilization increases hybrid poplar growth. At the farmland site, mean tree volumes of DRIS I, DRIS II and STD treatments exceeded those of unfertilized trees by 16.07, 10.51 and 62.61 %, respectively (Fig. 1), which represents volume gains of 0.17 $m^3ha^{-1}year^{-1}$, 0.11 $m^3ha^{-1}year^{-1}$ and 0.68 $m^3ha^{-11}year^{-1}$ (at 4 × 1 m spacing). At the forest site, mean tree volumes of the three fertilization treatments were respectively 33.63, 30.02 and 30.68 % greater than those of unfertilized trees, which corresponds to volume gains of 0.68 $m^3ha^{-11}year^{-1}$, 0.6 $m^3ha^{-11}year^{-1}$ and 0.62 $m^3ha^{-11}year^{-1}$ (Fig. 1). The positive effect of fertilization on tree growth was carried through the year following fertilizer application (2007), especially at the forest site where the volume gains associated with DRIS I, DRIS II and STD for the four clones were 1.09 $m^3ha^{-11}year^{-1}$, 0.47 $m^3ha^{-11}year^{-1}$ and 0.87 $m^3ha^{-11}year^{-1}$, respectively (Fig. 2). Productivity gains following fertilization were in the range of previous experiments on hybrid poplar plantations in North America i.e., between 15 and 80 % (Vance 2000; Brown and van den Driessche 2002; Coleman et al. 2006). The volume gains that were obtained in the first (2006) and the second growing season (2007) following fertilization are promising for successful plantation establishment in northwestern Québec. Fertilization also improves tree vigour and subsequent hybrid poplar resistance to pests (Weih 2004, Coleman et al. 2006), which may compensate for the costs of the fertilizer application.

However, although DRIS-based fertilization treatments (DRIS I and DRIS II) generally increased average growth, they were often equal or less efficient than the STD treatment in increasing volume growth rates. Moreover, they required expensive leaf analyses and diagnosis calculations. In our study, DRIS indices prior to fertilization revealed a similar nutrient status among the four clones and, thus, only one fertilization treatment was applied. Perhaps these early analyses reflected equivalent nursery conditions rather than clone and site particular requirements. Physiological processes that are related to nutrient metabolism such as luxury consumption, dilution or nutrient antagonisms may also distort growth prediction based on nutrient status. For instance, a fertilized plant may have a balanced nutrient status but the same growth rate as those that are unfertilized (Inno and Timmer 1997).

On the other hand, DRIS-based fertilization allows planting operations to save considerable quantities—and costs—of fertilizers by avoiding over-fertilization. Over time, DRIS recommendations of fertilizer mixture should be refined for plantations on different sites, thereby maximizing growth rates. In agriculture, over-fertilization may cost 20–50 %

more than what plants can actually use (Vance 2000; Jarecki and Lal 2003). For our study, the fertilizers costs of the three treatments were about \$95, \$106 and \$158 ha^{-1} for DRIS I, STD and DRIS II, respectively (prices were based on quotes provided in 2010). DRIS-based fertilization may also reduce nutrient losses through leaching and, thus, pollution of surface and groundwater (Stanturf et al. 2001). In our experiment, DRIS I reduced inputs of N by 75 % (compared to STD), which is a major pollutant of water by leaching and runoff (Gundersen et al. 2006). Thus, in sites with high risk of water contamination, diagnosis methods would be highly recommended, together with careful planning of the timing and frequency of fertilizer application, which takes into account site and soil characteristics such as slope, texture and precipitation (Heilman 1992; Smethurst et al. 2004).

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