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Allometric relationships in coppice biomass production for two North American willows (*Salix* spp.) across three different sites

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ABSTRACT

Biomass yield and component coppice growth traits were assessed for two native North American willow species, *Salix discolor* (DIS) and *Salix eriocephala* (ERI), established together in clonally replicated common garden field tests on three sites of differing quality but similar climates. These willows are widely distributed across eastern and central Canada and were selected for use in biomass production plantations. There was no species effect on the average stem length–diameter relationship, but there was a strong site effect. Increased number of stems within a plant decreases average stem diameter but not average stem length. Yield is positively related to site quality and number of stems per plant but also to the interaction between species and number of stems per plant. Allometric relationships between stem basal diameter, stem length, number of stems per plant, and biomass yield (t ha^{-1}) clearly reflected site quality differences and could be used in the same way that stem height at a specific age has been used for single stemmed trees to define site quality (site index) in forest timber production. Plant stem length and basal stem diameter measurements on up to 20 stems per plant indicated that measurements based on the average of the three longest stems per plant had the strongest relationship to biomass yield (R^2 = 0.813) and that the average stem diameter of the three largest stems had the strongest relationship to biomass yield (R^2 = 0.781).

1. Introduction

Over the past 40 years, interest in the use of willows (*Salix* spp.) as a source of biomass for energy has increased concomitantly with the search for alternative energy sources (Zsuffa, 1990; Labrecque et al., 1993; Labrecque and Teodorescu, 2005; Volk et al., 2006) and with growing concerns over the impact of carbon emissions on climate warming (Goodale et al., 2002; Houghton, 2005; Harper et al., 2007; Intergovernmental Panel on Climate Change (IPCC), 2007). With more than 350 species worldwide, willows are widespread across the northern hemisphere. Canada alone has some 76 native willows, which are distributed across every region of Canada and are adapted to a large range of site conditions (Argus, 2010). Yet, despite abundant species richness and ecological importance, native North American willows have received limited attention as a potential biomass resource and little is known about their growth potential (Mosseler et al., 1988; Kopp et al., 2001; Labrecque and Teodorescu, 2005; Tharakan et al., 2005).

It is important to understand variability in growth and allometric relationships across different site types in order to assess economic viability of biomass production; for selection of clonal material for operational purposes (Sixto et al., 2011; Mosseler et al., 2014); and for growth modeling and yield predictions (Ceulemans et al., 1996). With increasing concerns about the impacts of climate change, interest in the role of trees and forests as potential carbon sinks for removing and storing atmospheric carbon has been growing (Jarvis, 1989; Goodale et al., 2002; Houghton, 2005; Lambert et al., 2005; Peichl and Arain, 2007; Canadell and Raupach, 2008; Keith et al., 2009). Within forest management, there has also been increasing interest in financial markets aimed at trading in emissions reduction and carbon credits and the potential of carbon markets to fund improved forest management (Harper et al., 2007; van Breugel et al., 2011). Afforestation and plantation forests have received special attention under the Kyoto Protocol for carbon accounting and emissions reduction purposes because the rapid growth of younger trees may provide a higher carbon sink capacity than older, natural forests (Jarvis, 1989).

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Currently, native willows are being investigated in Canada both for bioenergy purposes and for afforestation and restoration of highly disturbed sites such as urban brownfields or those affected by mining and fossil fuel extraction (Pitre et al., 2010; Mosseler et al., 2014). There are very few studies that have used clonally replicated woody perennials such as willows to assess allometric relationships and components of growth in common garden studies where the same clones have been established on a number of different sites (Ronnberg-Wastljung and Thorsen, 1988; Telenius and Verwijst, 1995).

Salix discolor (DIS) and *Salix eriocephala* (ERI) are native to eastern and central Canada and appeared promising as fast-growing sources of woody biomass production (Mosseler et al., 1988). Although both DIS and ERI are commonly found in wet areas on a wide variety of disturbed sites, DIS is also commonly found colonizing drier, upland sites and is common in the vicinity of the highly disturbed coal mine spoils, which constituted one of the three test sites investigated here; whereas ERI is most commonly associated with disturbed stream banks adjacent to fast-flowing water. Our objective was to assess biomass production and the structure of coppice growth in a set of selected clones of DIS and ERI replicated across three sites of widely differing quality.

2. Material and methods

2.1. Common garden experiments

In 2005, a common garden experiment was established at the Montreal Botanical Gardens (MBG) in Montreal, Quebec, Canada (Lat. 45°56′ N, Long. 73°57′ W) that included six clones collected from each of 12 natural populations of DIS and ERI distributed across New Brunswick (NB), Quebec (QC), and Ontario (ON), for a total of 144 clones (72 clones per species) to assess population genetic variation in these two willows. In subsequent years, a selection of some of the better performing clones from this MBG common garden experiment were used to establish common garden experiments in several locations in eastern Canada: in NB, at the Atlantic Forestry Centre experimental tree nursery (AFC) in Fredericton (Lat. 45°94′ N, Long. 66°62′ W), and on the Salmon Harbour coal mine overburden (SH) near Minto (Lat. 46°07′ N, Long. 66°05′ W), a former coal mine operated by NB Coal Ltd., a subsidiary of the local electrical power utility, NB Power, and at the MBG site described above. These three common garden sites have an average annual temperature of 5.8 °C, 5.6 °C, and 5.7 °C, and an annual precipitation of 1046 mm, 1124 mm, and 987 mm for MBG, AFC, and SH, respectively (Environment Canada, 2013). Four better performing clones from each species of DIS and ERI (eight clones in total), were used at each of the three common garden field tests to assess biomass yield and structural traits of 2-year-old coppiced plants (Table 1).

The MBG common garden was established on a deep, fertile loam soil that had been prepared for horticultural demonstrations and was lying fallow and covered with sod at the time of site preparation for willow establishment. The AFC site has an artificially constructed soil consisting of a 60 cm depth of fine to medium textured sand contained within a polyethylene liner to permit experimental leachate collections. This site was covered in a thin grass sod at the time of willow establishment. The SH site consisted of crushed or broken shale coal mine overburden with very little organic matter or soil development because the site had recently been bulldozed into a gently sloped terrain to minimize surface runoff and erosion into an adjacent watercourse following cessation of surface strip mining for coal. A soil analysis based on six soil samples taken at each of these three sites indicated significant site differences in fertility and quality among sites, with the MBG site having the highest percent organic matter, carbon (C), and nitrogen (N), and the highest available potassium (K), calcium (Ca), and phosphorus (P) (Table 2). AFC had the greatest sand but lowest silt and clay content; whereas MBG had the lowest sand but greatest silt and clay content. Soil samples from SH contained an average of 56.5% stones that would not pass through a 2-mm sieve, whereas the AFC and MBG sites had few stones.

Both the AFC and SH common garden experiments were established in 2008, and the eight clones of DIS and ERI were replicated in three blocks (replicates) as three- or five-tree (ramet) linear plots in each common garden and were established with unrooted stem cuttings, approximately 20 cm in length, collected during the dormant season from vigorous 1- and/or 2-year-old stem sections (as per Densmore and Zazada, 1978). At SH, each genotype (clone) was represented by a single five-ramet linear row plot in each of three blocks (replicates), with plants spaced at 0.5 m within each row-plot, and with row-plots spaced 2 m apart, providing approximately 1 m^2 of growing space per plant. Plants at AFC and MBG were established as a single three-ramet row plot within each of three replicates per site, and plants were established at 1 m × 1 m spacing between plants. Each clonal row-plot was randomly assigned within each of the three blocks at each of the three sites.

In 2011, the aboveground biomass was harvested in each of the three common gardens (MBG, AFC, and SH) and in 2013, the 2-year-old coppice growth of one plant per plot was harvested, and the fresh weight was measured in the field to the nearest 10 g using an electronic weigh scale (Electronic Infant Scale, model ACS-20A-YE). Previous measurements of fresh and dry weights of stem samples harvested in late fall at the MBG common garden demonstrated that percent moisture was approximately 50 ± 2% regardless of species or clones (Mosseler, unpublished). The number of stems per plant was counted for each harvested plant. The length of up to 20 of the largest stems per harvested plant was measured to the nearest 1 cm using an aluminum meter ruler, and the basal diameter of each stem was measured to the nearest

Table 1
Origins of clones of *Salix discolor* and *S. eriocephala* used in coppice biomass measurements.

Species	Clone	Origin of clone	Latitude N	Longitude W
S. discolor	LEV-D3	Levis, QC	46°78′	71°18′
	MON-D1	Montmagny, QC	46°94′	70°60′
	MUD-D4	Mud Lake (Westmeath), ON	45°88′	76°78′
	RIC-D2	Richmond Fen, ON	45°13′	75°82′
S. eriocephala	BRI-E2	Bristol, NB	46°47′	67°58′
	FRE-E1	Fredericton, NB	45°94′	66°62′
	GRE-E1	Green River, NB	47°34′	68°19′
	SHE-E3	Shepody Creek, NB	45°71′	64°77′

Table 2
Soil properties for the three sites; Atlantic Forestry Centre (AFC), Montreal Botanical Gardens (MBG) and Salmon Harbour (SH) coal mine. Sites with different letters are significantly different using Tukey's mean separation test, $\alpha = 0.05$.

Site	Organic matter (%)	Carbon (%)	Nitrogen (%)	Potassium meq 100 g^{-1}	Calcium meq 100 g^{-1}	Magnesium meq 100 g^{-1}	Phosphorus (ppm)
AFC	0.82 ± 0.40 b	0.48 ± 0.23 b	0.082 ± 0.017 b	0.142 ± 0.034 b	1.33 ± 1.31 c	0.50 ± 0.05 a	11.40 ± 2.02 b
MBG	5.72 ± 0.40 a	3.32 ± 0.23 a	0.303 ± 0.017 a	0.393 ± 0.034 a	18.15 ± 1.31 a	0.62 ± 0.05 a	40.69 ± 2.02 a
SH	0.79 ± 0.40 b	0.46 ± 0.23 b	0.102 ± 0.017 b	0.233 ± 0.034 b	7.33 ± 1.31 b	0.66 ± 0.05 a	3.98 ± 2.02 c

Site	Sand (%)	Silt (%)	Clay (%)	pH	C:N ratio	Sulfur (%)
AFC	81.8 ± 2.2 a	15.3 ± 2.2 c	2.9 ± 1.5 b	6.4 ± 0.1 b	5.8 ± 0.6 b	0.002 ± 0.006 b
MBG	50.6 ± 2.2 c	34.9 ± 2.2 a	14.5 ± 1.5 a	7.3 ± 0.1 a	10.8 ± 0.6 a	0.019 ± 0.006 b
SH	67.2 ± 2.2 b	23.4 ± 2.2 b	9.4 ± 1.5a	6.8 ± 0.1 ab	4.6 ± 0.6 b	0.008 ± 0.006 a

0.1 mm using an electronic caliper on each of the 20 largest stems per harvested plant. Mean fresh yield in t ha^{-1} (t = tonne) was calculated by converting the harvested fresh weight per plant to biomass production per hectare by multiplying by 10 (e.g., multiplying by 10,000 plants per ha divided by 1000 kg per tonne) to facilitate yield comparison among species and clones on a land area basis.

2.2. Statistical analysis

Allometric growth relationships were analyzed using analysis of covariance (ANCOVA). In these analyses, three sources of variation were studied: (1) covariate (i.e., diameter), (2) independent effect (site or species), and (3) independent effect × covariate. The analyses were done based on the following model:

$$Y_{ij} = B_0 + B_{0i} + B_1 X_{ij} + B_{1i} X_{ij} + e_{ij}$$

where Y_{ij} is the dependent trait of the jth plant of the ith site or species, B_0 and B_1 are average regression coefficients, B_{0i} and B_{1i} are the site or species-specific coefficients, X_{ij} is the independent variable, and e_{ij} is the error term. Results were considered statistically significant at $\alpha = 0.05$, although individual P values are provided for all traits so that readers can make their own interpretations. The data had satisfied normality and equality of variance assumptions. The general linear model from Systat (Chicago, Illinois) was used for analysis.

3. Results

Covariate analysis of average stem length using average diameter as covariate and testing for species effect showed no significant species × diameter interactive effect ($P = 0.659$). Further analysis showed no species effect ($P = 0.850$) but a significant average diameter effect ($P < 0.001$, $R^2 = 0.794$). We show the actual species regression lines to illustrate the species average stem length to average diameter relationship was almost equal (Fig. 1A). The three sites could be clearly differentiated according to site quality as reflected by the stem diameter–length relationship. Allometric analysis of average stem length using average diameter as covariate and testing for site effect showed no significant site × diameter interactive effect ($P = 0.246$). Further analysis showed a site ($P < 0.001$) and diameter effect ($P < 0.001$, $R^2 = 0.953$) (Fig. 1B).

A significant inverse relationship was observed between the total number of stems per plant and average stem diameter (Fig. 2A), but no relationship with average stem length (Fig. 2B). Site quality was significant, with the best site at MBG showing the largest plant part dimensions, the poorest site at SH showing the smallest dimensions, and the intermediate site quality at AFC showing intermediate dimensions. Covariate analysis showed no significant site × number of stems interactive effect ($P = 0.218$). Further analysis showed a significant site ($P < 0.001$) and number of stems effect ($P = 0.013$, $R^2 = 0.660$) (Fig. 2A). Analysis of species effect on

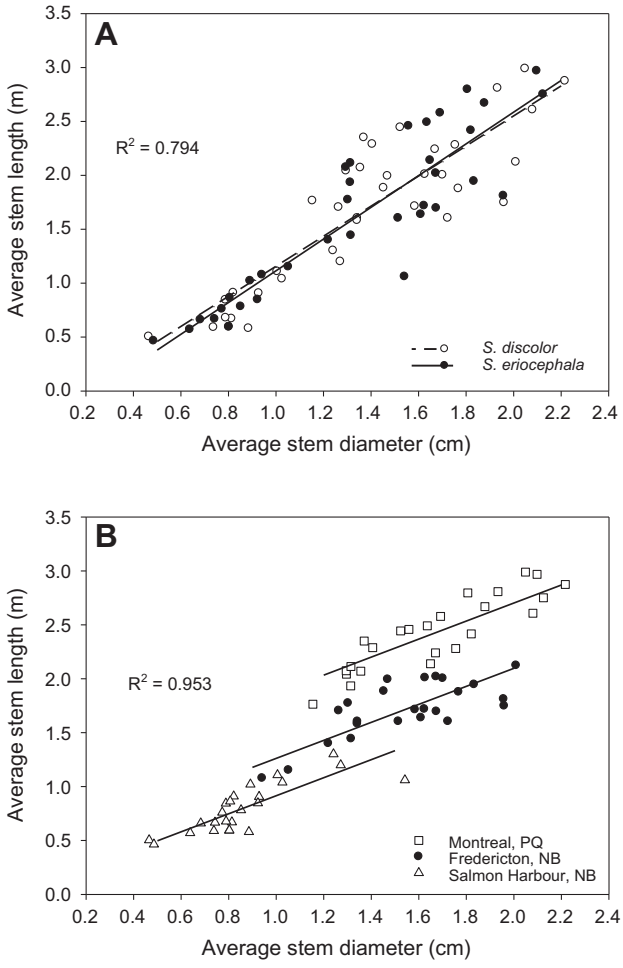

Fig. 1. Covariate analysis of (A) average stem length versus average stem diameter by species: although shown by species, together the relationship is $y = 0.304 + 1.437x$, and (B) average stem length versus average stem diameter by site; MBG = 1.030 + 0.836x; AFC = 0.426 + 0.836x; and SH = 0.080 + 0.836x.

average stem diameter showed a non-significant species × number of stems ($P = 0.943$) and species effects ($P = 0.149$) (not shown). Allometric analysis showed no significant site × number of stems interactive effect ($P = 0.330$). Further analysis showed a consistent site ($P < 0.001$) but non-significant number of stems effect ($P = 0.068$, $R^2 = 0.777$) (Fig. 2B). Analysis of species effect on average stem length showed a non-significant species × number of stems effect ($P = 0.610$) but a significant species effect ($P = 0.008$), which resulted in a greater average stem height for DIS compared with ERI of 0.5 m per unit number of stems (not shown).

The relationship between mean biomass yield (t ha^{-1}) and number of stems per plant was positive across all sites (Fig. 3A) showing yield increasing with increases in number of stems, and

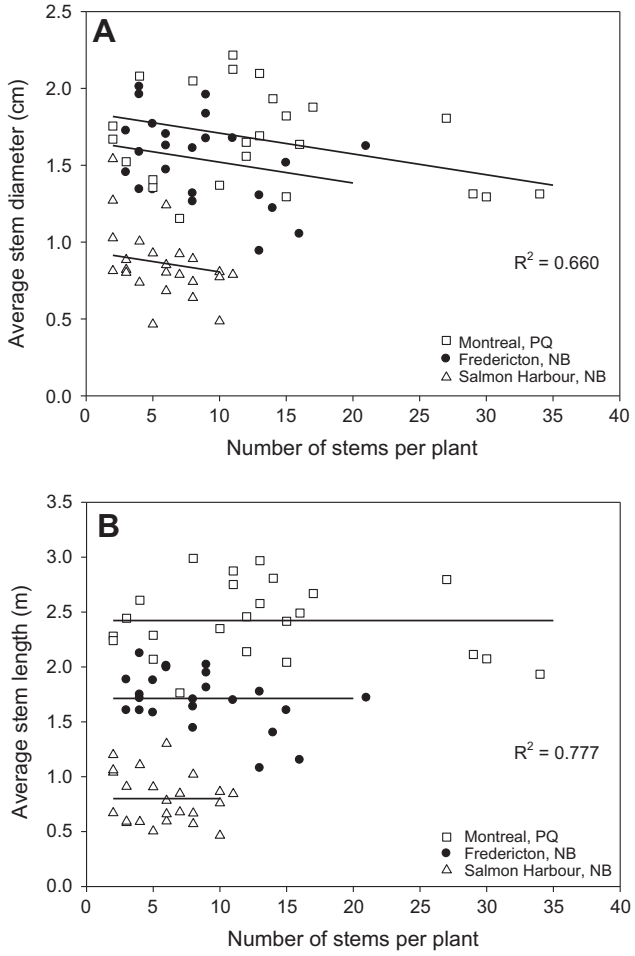

Fig. 2. Covariate analysis of (A) average stem diameter versus number of stems by site: MBG = 1.844 − 0.013*x*; AFC = 1.655 − 0.013*x*; SH = 0.941 − 0.013*x*, and (B) average stem height versus number of stems by site: MBG = 2.423; AFC = 1.713; and SH = 0.801.

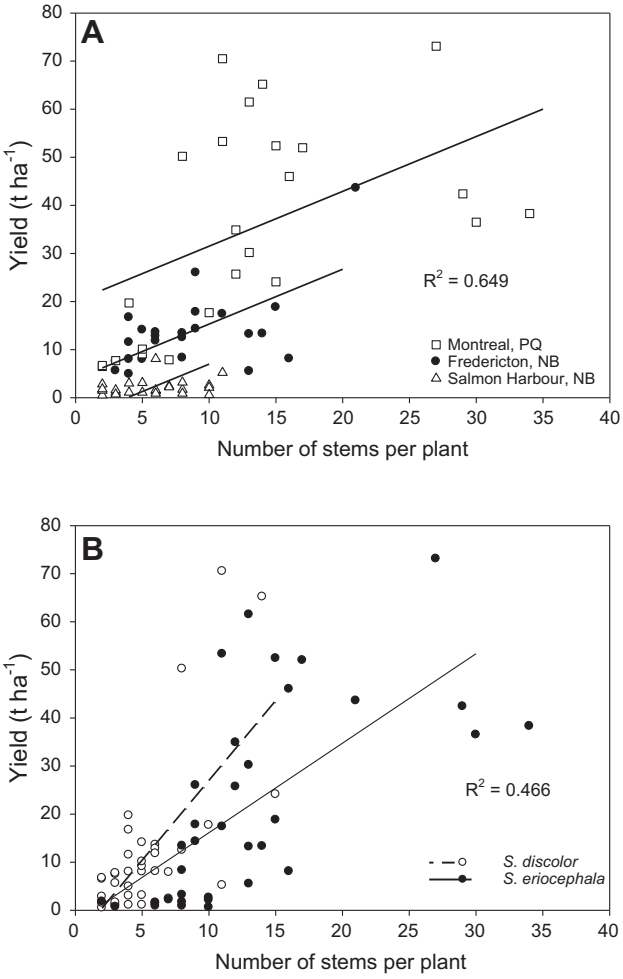

Fig. 3. Covariate analysis of yield versus number of stems (A) by site: yield: MBG = 20.095 + 1.141*x*; AFC = 3.914 + 1.141*x*; SH = −4.427 + 1.141*x*, and (B) by species: yield: DIS = −6.208 + 3.322*x*; ERI = −2.461 + 1.861*x*.

the effect on yield increased as site quality increased. Covariate analysis of yield using number of stems as covariate and testing for site effect showed no significant site × diameter interactive effect ($P = 0.419$). Further analysis showed a consistent site ($P < 0.001$) and number of stems effect ($P < 0.001$, $R^2 = 0.649$) (Fig. 3A). Allometric analysis of yield using total number of stems as covariate and testing for species effect showed a species × number of stems interactive effect ($P = 0.075$, $R^2 = 0.466$). Although the interactive term was not significant at $\alpha = 0.05$, we graphed the species interactive effect, as the number of stems contribution to yield was very different for each species despite the species variation (Fig. 3B).

The relationship between yield and stem diameter was always positive, but the strength of this relationship varied with site quality, with MBG showing the strongest response, SH the weakest, and AFC being intermediate (Fig. 4). Covariate analysis showed a significant site × average stem diameter interactive effect ($P = 0.004$, $R^2 = 0.681$) (Fig. 4A). Covariate analysis showed a significant interaction between site × average diameter of the largest three stems ($P < 0.001$, $R^2 = 0.781$) (Fig. 4B) and a significant site × maximum stem diameter interactive effect ($P < 0.001$, $R^2 = 0.754$) (Fig. 4C). The best predictor of yield was the use of the largest three stem diameters ($R^2 = 0.781$), followed by using the maximum stem diameter ($R^2 = 0.754$), and then by average stem diameter ($R^2 = 0.681$).

The relationship between yield and stem length was also always positive, and once again, the strength of this relationship varied with site quality, with MBG showing the strongest response, SH the weakest, and AFC being intermediate (Fig. 5). Covariate analysis showed a significant site × average stem height interactive effect ($P = 0.001$, $R^2 = 0.708$) (Fig. 5A). Covariate analysis showed a significant interaction between site × the average length of the three longest stems ($P < 0.001$, $R^2 = 0.813$) (Fig. 5B) and a significant site × maximum stem length interactive effect ($P < 0.001$, $R^2 = 0.756$) (Fig. 5C). The best predictor of yield was the use of the average of the three longest stems ($R^2 = 0.813$), followed by using the maximum stem length ($R^2 = 0.756$), and then by average stem length ($R^2 = 0.708$).

A significant species effect was observed for biomass yield in relation to both basal stem diameter (Fig. 6A) and stem length (Fig. 6B). Covariate analysis of yield using only the largest three stem diameters as covariate and testing for species effect showed no significant species × diameter interactive effect ($P = 0.212$) but a significant species ($P = 0.006$) and average diameter for the three largest stems ($P < 0.001$, $R^2 = 0.712$) effect (Fig. 6A). The result was curvilinear, we tested a quadratic (square) and cubic non-linear response curve. The quadratic response curve showed significant species ($P = 0.011$), average diameter of the three largest stems ($P = 0.029$), and diameter^2 for the three largest stems ($P < 0.001$) effects. The cubic test did not increase fit significantly. Using the

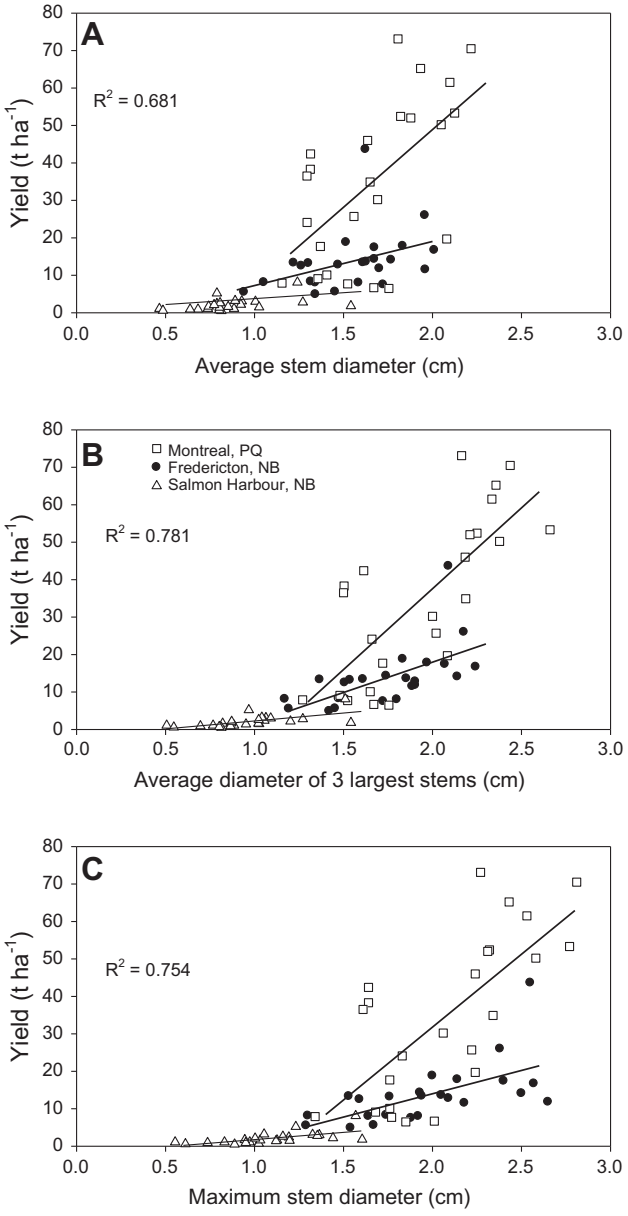

Fig. 4. Covariate analysis of yield versus (A) average stem diameter by site: yield: MBG = −34.046 + 41.478*x*; AFC = −4.531 + 11.779*x*; SH = 0.600 + 3.168*x*, (B) average diameter of the three largest stems by site: yield: MBG = −48.745 + 43.162*x*; AFC = −14.499 + 16.227*x*; SH = −1.939 + 4.211*x*, and (C) maximum stem diameter by site: yield: MBG = −45.983 + 38.898*x*; AFC = −10.890 + 12.448*x*; and SH = −2.090 + 3.855*x*.

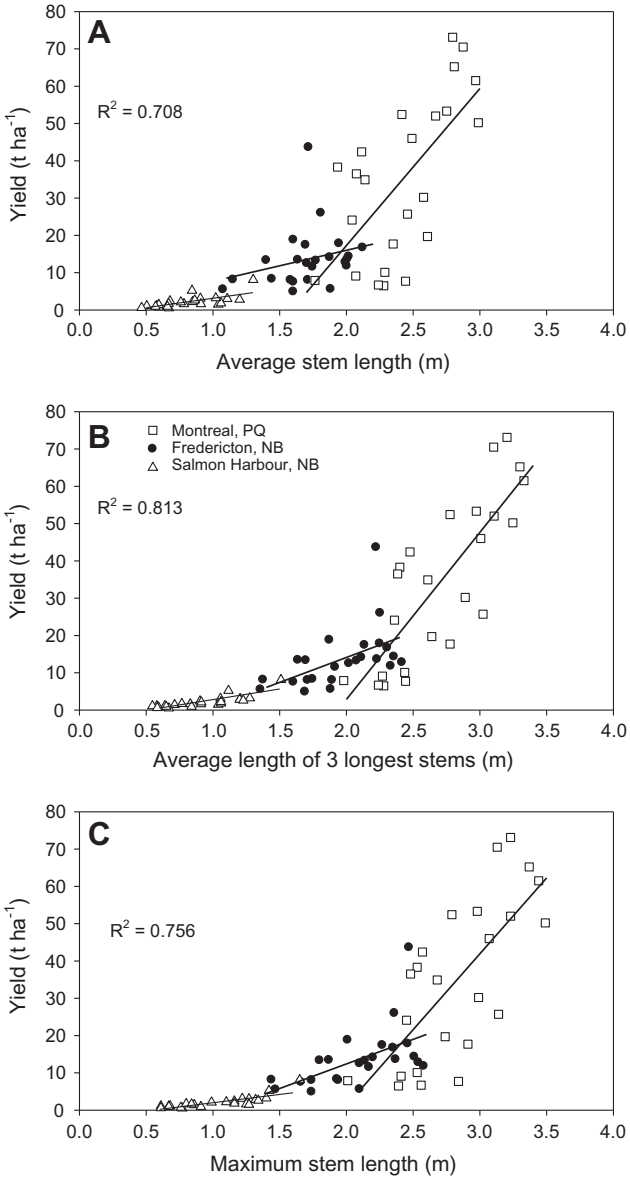

Fig. 5. Covariate analysis of yield versus (A) average stem length by site: yield: MBG = −66.866 + 42.078*x*; AFC = −0.626 + 8.312*x*; SH = −1.927 + 5.071*x*, (B) average of the three longest stems by site: yield: MBG = −86.687 + 44.780*x*; AFC = −12.636 + 13.375*x*; SH = −2.528 + 5.111*x*, and (C) maximum stem length by site: yield: MBG = −80.071 + 40.662; AFC = −13.988 + 13.190*x*; and SH = −2.422 + 4.421*x*.

same quadratic model for yield in relation to the average stem length of the three largest stems produced significant effects for species ($P = 0.002$), average for the three longest stems ($P = 0.001$), and length^2 for the three longest stems ($P < 0.001$, $R^2 = 0.828$) (Fig. 6B).

4. Discussion

The climate is similar for the three common garden sites. Thus, differences in growth responses in both DIS and ERI for a number of biomass traits (current study and Mosseler et al., 2014) are most probably driven by significant differences in site quality among the three common gardens (Table 2), with MBG producing the greatest biomass yields, SH the lowest, and AFC intermediate biomass yields. Growth trends and relationships for these DIS and ERI clones partitioned well, were generally consistent across the three sites, and indicated a clear ranking by site quality differences. This ranking of site quality was well demonstrated by the basal stem diameter and stem length relationships to biomass yield. The negative relationship between stem number per plant and stem diameter and the strong positive relationship between stem length and stem diameter were also observed by Tharakan et al. (2005). Relationships between stem height (length) at a certain age have long been used in forest management to characterize site quality according to a site index that reflects site productivity (Avery and Burkhart, 1994). Our results with coppice growth in short-rotation willow biomass plantations show that stem diameter–length relationships and their relationship to biomass yield can be used in site quality assessments similar to the way that these relationships have been used for site quality assessment in single-stemmed trees (Crow and Laidly, 1980; Koerper and

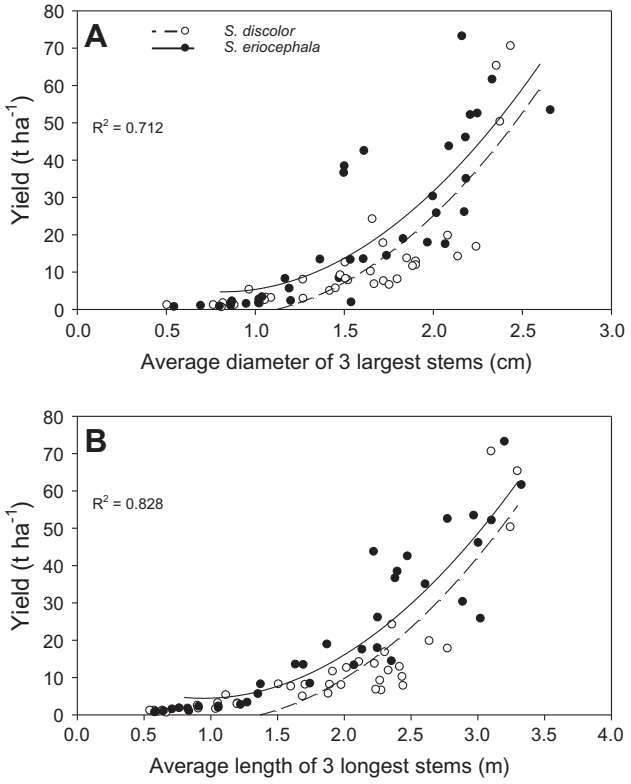

Fig. 6. Covariate analysis of yield versus (A) the average diameter of the three largest stems by species: yield: DIS = 10.862 − 31.144x + 19.141x^2; ERI = 17.364 − 31.144x + 19.141x^2, and (B) average length of the three longest stems by species: yield: DIS = 7.449 − 19 .771x + 10.463x^2; ERI = 13.776 − 19.771 x + 10.463x^2.

Richardson, 1980; Alemdag and Horton, 1981; Dillen et al., 2007; Paul et al., 2013a,b), as well as shrubs (Brown, 1976).

These two willow species showed allometric relationships between stem length, basal stem diameter, number of stems per plant, and biomass yield similar to those among closely related *Eucalyptus* species in Australia (Paul et al., 2013b). Differences in these allometric relationships also related strongly to site quality differences, indicating that site-specific equations will need to be developed for reasonably precise predictions of biomass yield and that yield estimates are likely to be highly site specific (Koerper and Richardson, 1980; Gargaglione et al., 2010; Telenius and Verwijst, 1995; Paul et al., 2013a). This highlights the practical limitations of generalized biomass equations based on a single independent variable, either diameter or height, that may be used either in forest management practice or to obtain estimates for carbon accounting purposes (Alban and Laidly, 1982; Ter-Mikaelian and Korzukhin, 1997; Jenkins et al., 2003; Lambert et al., 2005; Fatemi et al., 2011) across sites of variable quality; a problem discussed by Jenkins et al. (2003). One of the advantages of short-rotation coppice stems for studying such allometric relationships is the ability to accurately measure stem length, which is usually not the case with larger, single-stemmed trees (Jenkins et al., 2003; Peichl and Arain, 2007; van Breugel et al., 2011; Butt et al., 2013). Furthermore, this study demonstrates the statistical and experimental power of using clonally replicated woody plants to study allometric relationships and their interaction with site quality differences.

The strength and consistency of the stem diameter–length relationship in coppice growth in these two willow species indicate that growth models developed for assessing biomass volume based on simple, non-destructive measures of stem length and/or diameter may be useful in predicting biomass yields for economic viability modeling (Ceulemans et al., 1996; Rae et al., 2004; Dillen et al., 2007). One could measure every coppice stem for length and diameter to obtain basal area or volume, and this would provide a very good relationship to yield. However, some willows can produce 40 + stems per coppice on productive sites. In this study, we were interested in examining a simple set of limited measurements to test relationships to yield. Interestingly, our results showed that measurements of stem diameter and length based on the three largest stems had a stronger relationship to biomass yield than measurements based on up to 20 of the largest stems per plant, resulting in a 7.2% and 7.1% improvement in yield estimation for stem diameter and stem length, respectively. Given the range of sizes in these 2-year-old coppiced plants, it appears likely that allometric relationships in coppiced willows in the currently envisioned operational ranges of 2- to 4-year-old plants for biomass harvesting should be similar to those described here.

Although, the strength of these allometric relationships varied strongly with site quality, they did not vary much by species. Nevertheless, there were some species effects on yield (Fig. 6) and these effects appeared to be related to the number of stems per plant (Fig. 3B). Species comparisons between DIS and ERI showed that ERI plants have a significantly greater number of stems per plant (Mosseler et al., 2014). This indicates that, despite a negative relationship between stem diameter and the number of stems per plant (Fig. 2), the number of stems has a strong positive influence on biomass yield. Therefore, other things being equal, selection and breeding of species and/or clones producing more stems per plant should increase biomass yield.

Among the age-related (Peichl and Arain, 2007; Fatemi et al., 2011), species-related (Ter-Mikaelian and Korzukhin, 1997; van Breugel et al., 2011; Paul et al., 2013b), and site-related (Koerper and Richardson, 1980; Gargaglione et al., 2010; Garcia Morote et al., 2012) factors that can affect allometric relationships, our results indicate that the main factor affecting such relationships in willow coppice growth is site quality. Nevertheless, in a subsequent study, we intend to conduct a multispecies investigation of potential species effects on allometric relationships based on seven different willow species native to eastern and central North America that have been assembled together in common garden field tests.

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