Research paper

Allometric relationships from coppice structure of seven North American willow (*Salix*) species

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ABSTRACT

Biomass yield and component coppice growth traits were assessed in up to 20 clones from seven native North American willow species, *Salix amygdaloides* (SAM), *Salix bebbiana* (BEB), *Salix discolor* (DIS), *S eriocephala* (ERI), *Salix humilis* (HUM), *Salix interior* (INT), and *Salix nigra* (NIG), established together in a clonally replicated common-garden field test. Aboveground mass, coppice stem number, stem length, and stem basal diameter measurements on up to 20 of the largest stems from 2-yr-old coppiced plants showed that ERI had the greatest aboveground mass, followed by INT, and then a close grouping of BEB, DIS, and HUM; the "tree" willows, AMY and NIG, had the lowest yields. The tree willows were not as prolific in coppice stem sprout production as were the shrub willows. The greatest number of stem sprouts was produced by ERI, with one coppice producing 67 2-yr-old stem sprouts, and ERI also showed an atypical, non-negative relationship between stem size and stem number; whereas the other six willows showed a varying but expected negative relationship between coppice stem size and stem number. Species differences in allometric relationships highlight the need to develop species-specific models for more accurate non-destructive biomass yield estimation.

1. Introduction

With more than 350 species worldwide, willows (*Salix* spp.) are widespread across the northern hemisphere, with 76 willow species native to Canada [1]. Yet despite this species richness and ecological importance, especially in early successional environments following site disturbances [2–4], native willows have received limited attention in North America as potential sources of woody biomass for industrial purposes [5–8]. More recently, native willows have been investigated for land reclamation purposes on highly disturbed sites following mining operations [4,9–11], where some willows grew surprising well on infertile coal mine overburden [12–16].

For short-rotation intensive culture (SRIC) biomass production based on coppice regrowth, it is important to understand variability in coppice growth form and allometric relationships in order to (1) assess biomass suitability and economic viability, (2) select superior clonal material for operational purposes [12,17], and (3) model

growth and predict yield [13,18–22]. There are few studies using clonally replicated common-garden studies of woody perennials, such as willows, to compare allometric growth and yield relationships in a number of closely related species within the same genus [13,18,23].

Salix amygdaloides (SAM), *Salix bebbiana* (BEB), *Salix discolor* (DIS), *S. eriocephala* (ERI), *Salix humilis* (HUM), *Salix interior* (INT), and *Salix nigra* (NIG) are native to much of eastern and central Canada, with several of these species extending as far west as the Rocky Mountains and beyond (e.g., AMY, BEB, DIS, and INT). These willows were selected as promising species for SRIC biomass production plantations [5,12–14,16]. Although these willows are all commonly associated with seasonally wet areas and riparian zones, they are also adapted to a wider range of ecological conditions on disturbed sites. For instance, BEB, DIS, and HUM can also be found colonizing well-drained, upland sites [12]; whereas ERI, INT, and NIG are most commonly associated with the fast-flowing water of riparian habitats, and AMY is most often found along the edges of hardwood swamplands (Table 1). This group of seven species consists of both tree-forming willows that can reach heights of up to 20 m across their geographic range (e.g., AMY and NIG) and shrub-forming species that normally attain heights of 2–8 m (e.g.,

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Table 1
Native North American willow (*Salix*) species field tested for biomass production and restoration of highly disturbed areas.

Salix species	Height and habit	Natural habitat
S. amygdaloides	8–15 m, tree	poorly drained, standing wetlands
S. bebbiana	4–6 m, shrub	seepage slopes, ditches, upland sites
S. discolor	4–10 m, shrub/small tree	seepage slopes, wetlands, and ditches
S. eriocephala	4–6 m, shrub	fast-flowing stream banks
S. interior	4–6 m, shrub	river banks, sandbars, floodplains
S. humilis	2–3 m, shrub	well-drained upland sites, forest openings
S. nigra	10–12 m, tree	river banks and floodplains

BEB, DIS, ERI, HUM, and INT).

Our objective was to use a common-garden and population genetics approach to assess seven willow species for variation in coppice structure and biomass yield for the purpose of identifying superior clonal material both for biomass production plantations and for land reclamation purposes. We wanted to quantify the important differences among species and clones in coppice structure and growth performance for the purposes of clonal selection for superior biomass production and to report important species-specific equations for various biomass growth relationships. The latter would be helpful for a simple nondestructive aboveground biomass yield estimation.

2. Material and methods

2.1. Common-garden experiments

During the winter of 2008, stem sections (cuttings) were collected from five clones from each of four natural populations located in southern and eastern Ontario and adjacent areas of the Ottawa River Valley in the province of Quebec, Canada (Fig. 1; Table 2) for each of seven native willow species. Natural populations of willows usually occur as small, isolated patches arising in response to localized disturbances. Therefore, we tended to collect whatever clones were available in a given patch, and no attempt was made to collect cutting material from plants with specific characteristics. Stem cuttings approximately 20 cm long were collected from vigorous 1- and 2-yr-old branches from plants located in natural populations and then stored in a freezer at −5 °C at the Atlantic Forestry Centre (AFC) in Fredericton, New Brunswick (NB), Canada. In preparation for field establishment, stem cuttings were removed from frozen storage to a refrigerator at 3 °C for several days of thawing, followed by 48 h of soaking in water immediately prior to establishment in a common-garden field test located at the AFC nursery in Fredericton, NB (Lat. 45°94′ N, Long. 66°62′ W). Fredericton has a climate with an average annual temperature of 5.6 °C and an annual precipitation of 1124 mm [24].

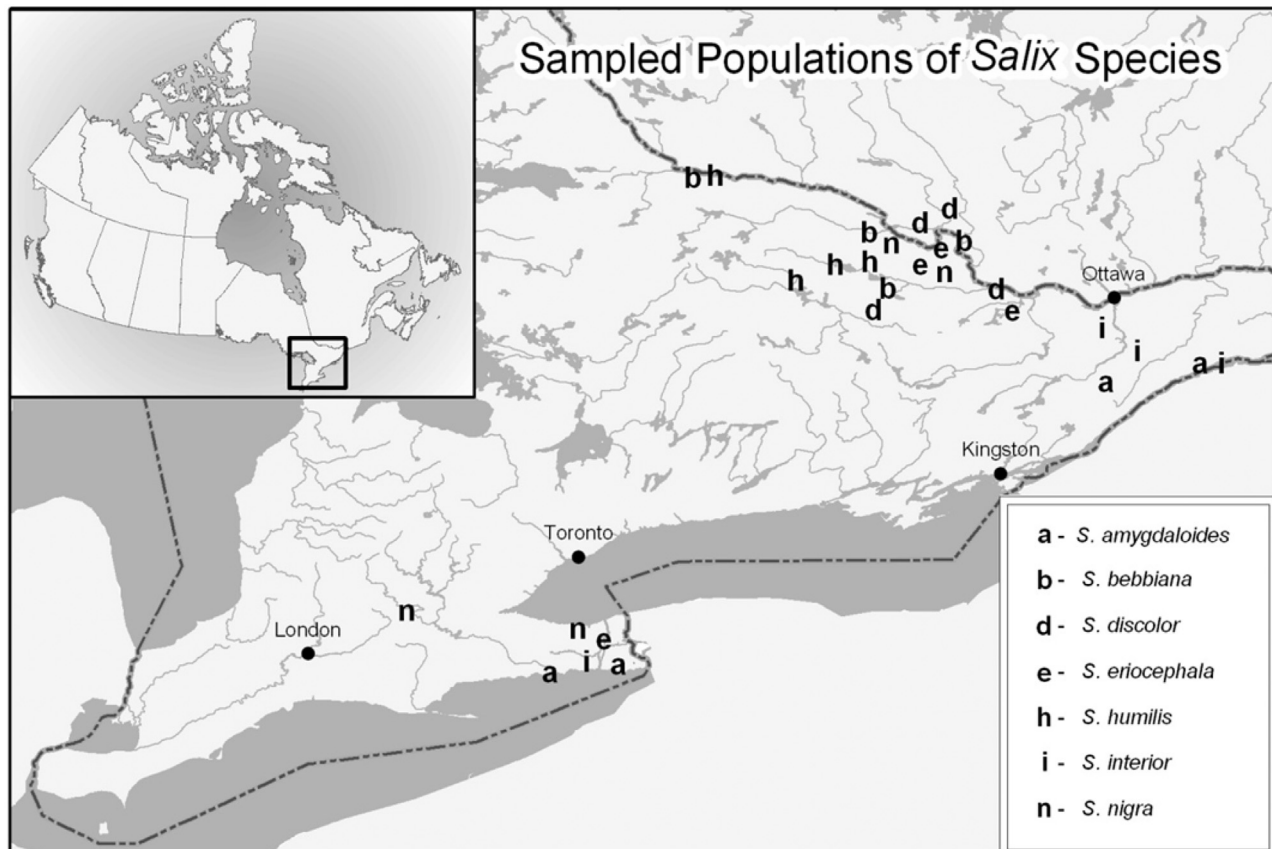The AFC nursery site consists of an artificially constructed soil of

Fig. 1. Map showing the locations of populations from which plant material was collected for clonal propagation and common-garden establishment.

Table 2
Soil properties for Atlantic Forestry Centre (AFC) common-garden field test.

Site	Organic matter (%)	Carbon (%)	Nitrogen (%)	Potassium (ppm)	Calcium (ppm)	Magnesium (ppm)	Phosphorus (ppm)
AFC	0.82 ± 0.40	0.48 ± 0.23	0.082 ± 0.017	55.5 ± 13.3	266 ± 262	60.8 ± 6.1	11.40 ± 2.02

Site	C:N ratio	Sulfur (%)	Sand (%)	Silt (%)	Clay (%)	pH
AFC	5.8 ± 0.6	0.002 ± 0.006	81.8 ± 2.2	15.3 ± 2.2	2.9 ± 1.5	6.4 ± 0.1

Table 3
Natural populations of seven willow species sampled for common-garden field test.

Species	Population	Latitude N	Longitude W	Elevation (m)
S. amygdaloides	Hanlon Marsh, ON	44° 52′	75° 45′	110
	Long Sault, ON	44° 60′	74° 58′	76
	Port Maitland, ON	42° 52′	79° 35′	179
	Wainfleet Bog, ON	42° 55′	79° 20′	182
S. bebbiana	Achray Road, ON	45° 49′	77° 23′	223
	Ft. Coulonge, QC	45° 59′	76° 46′	287
	Foymount, ON	45° 26′	77° 18′	525
	Klock Road, ON	46° 19′	78° 30′	197
S. discolor	Allumette Is., QC	45° 54′	77° 06′	114
	Ft. Coulonge, QC	45° 59′	76° 46′	287
	Foymount, ON	45° 26′	77° 18′	525
	Norway Bay ON	45° 32′	76° 25′	87
S. eriocephala	Allumette Is., QC	45° 54′	77° 06′	114
	Norway Bay, ON	45° 32′	76° 25′	87
	Wainfleet Bog, ON	42° 55′	79° 20′	182
	Westmeath ON	45° 49′	76° 54′	112
S. humilis	Achray Road, ON	45° 49′	77° 23′	223
	Aylen Lake, ON	45° 34′	77° 53′	298
	Bonnechere, ON	45° 40′	77° 37′	186
	Klock Road, ON	46° 17′	78° 30′	202
S. interior	Ottawa, ON	45° 04′	75° 32′	100
	Long Sault, ON	44° 60′	74° 58′	76
	Moodie Pond, ON	45° 14′	75° 47′	104
	Wainfleet Bog, ON	42° 55′	79° 20′	180
S. nigra	Nith River, ON	43° 17′	80° 34′	299
	Pembroke, ON	45° 50′	77° 07′	107
	Wainfleet Bog, ON	42° 55′	79° 20′	173
	Westmeath, ON	45° 49′	76° 54′	103

60 cm of fine- to medium-textured, washed sand, devoid of stones or rocks, contained within a polyethylene liner to permit experimental leachate collections. This site was covered in a sparse grass sod at the time of willow establishment. Six soil samples were taken in an equidistant grid across this flat, uniform site for a standard soil analysis that included percent sand, silt, clay, and organic matter; percent carbon (C), sulfur (S), and nitrogen (N); available potassium (K), calcium (Ca), and magnesium (K); phosphorus (P) concentration in ppm; pH and C:N ratio (Table 3).

The common-garden study was established in May 2008, using 20 cm long rootless stem cuttings collected from five clones from each of four natural populations from the seven species (140 clones in total) listed in Table 2. Clones (genotypes) were established at 1 m by 1 m spacing in a linear clonal plot of three ramets per plot,

with each clone replicated once within each of the three blocks (replicates). In 2011, the aboveground biomass was harvested, and in October 2013, the 2-yr-old coppice regrowth of the largest coppiced plant per clonal, three-ramet plot, was harvested, and the fresh weight of the aboveground biomass was measured in the field to the nearest 10 g using an electronic infant weigh scale (Electronic Infant Scale, model ACS-20A-YE). The number of coppice stems per plant was counted for each harvested plant, and the length of up to 20 of the largest stems per harvested plant was measured to the nearest 1 cm using a flexible aluminum meter ruler, and the basal diameter of each stem was measured to the nearest 0.1 mm using an electronic caliper on each of the 20 largest stems per plant. Three measures of coppice stem dimensions were used—(1) the average of the 20 largest stems, (2) the average of the three largest stems, and (3) the largest stem—to evaluate which was the best predictor of aboveground mass based on the coefficient of determination (R^2).

2.2. Statistical analysis

Coppice growth data, including total aboveground mass, average single stem mass, coppice stem number, stem length, and stem basal diameter, for the seven species were subjected to analyses of variance (ANOVA). Traits such as coppice stem numbers, stem length, and stem basal diameter were selected because they are easily measured in non-destructive sampling for biomass estimation. Species were considered as a fixed effect, whereas populations and clones were considered random effects. Populations were nested within species, and clones were nested within populations, which were nested within species. The ANOVA model used was as follows:

$$Y_{ijklm} = u + B_i + S_j + P_{k(j)} + C_{l(k(j))} + e_{ijklm}$$

where Y_{ijklm} is the dependent ramet trait of the ith replicate, of the jth species, of the kth population, of the lth clone, of the mth ramet, and u is the overall mean, B_i is the effect of the ith block (i = 1, 2, 3), S_j is the effect of the jth species (j = 1, 2, 3, 4, 5, 6, 7), $P_{k(j)}$ is the effect of the kth population (k = 1, 2, 3, 4) nested within the jth species, C_l is the effect of the lth clone (l = 1, 2, 3, 4, 5), nested within the kth population nested within the jth species, and e_{ijklm} is the random error component. The general linear model from Systat (Chicago, Illinois) was used for analysis. Tukey's *post hoc* mean separation test

Table 4
Mixed model ANOVA for willow productivity traits including source of variation, degrees of freedom (df), mean square values (MS), and *P* values. *P* values < 0.05 are in bold print.

| Source of Variation	df	Green mass (kg)		Number of stems		Average single stem mass (g)		Average basal diameter (mm)		Average stem length (m)	
		MS	*P* value	MS	*P* value	*MS*	*P* value	*MS*	*P* value	*MS*	*P* value
Block	2	0.658	0.012	20.55	0.365	2951.	0.219	5.96	0.305	0.111	0.185
Species	6	0.714	<0.001	132.88	<0.001	5453.	0.011	19.95	0.001	0.280	<0.001
Pop (species)	7	0.709	<0.001	43.60	0.038	4332.	0.031	18.92	0.001	0.199	0.004
Clone (pop(species))	7	0.867	<0.001	45.22	0.032	2914.	0.164	13.04	0.012	0.113	0.102
Error	346	0.145		20.31		1936.		5.00		0.066	
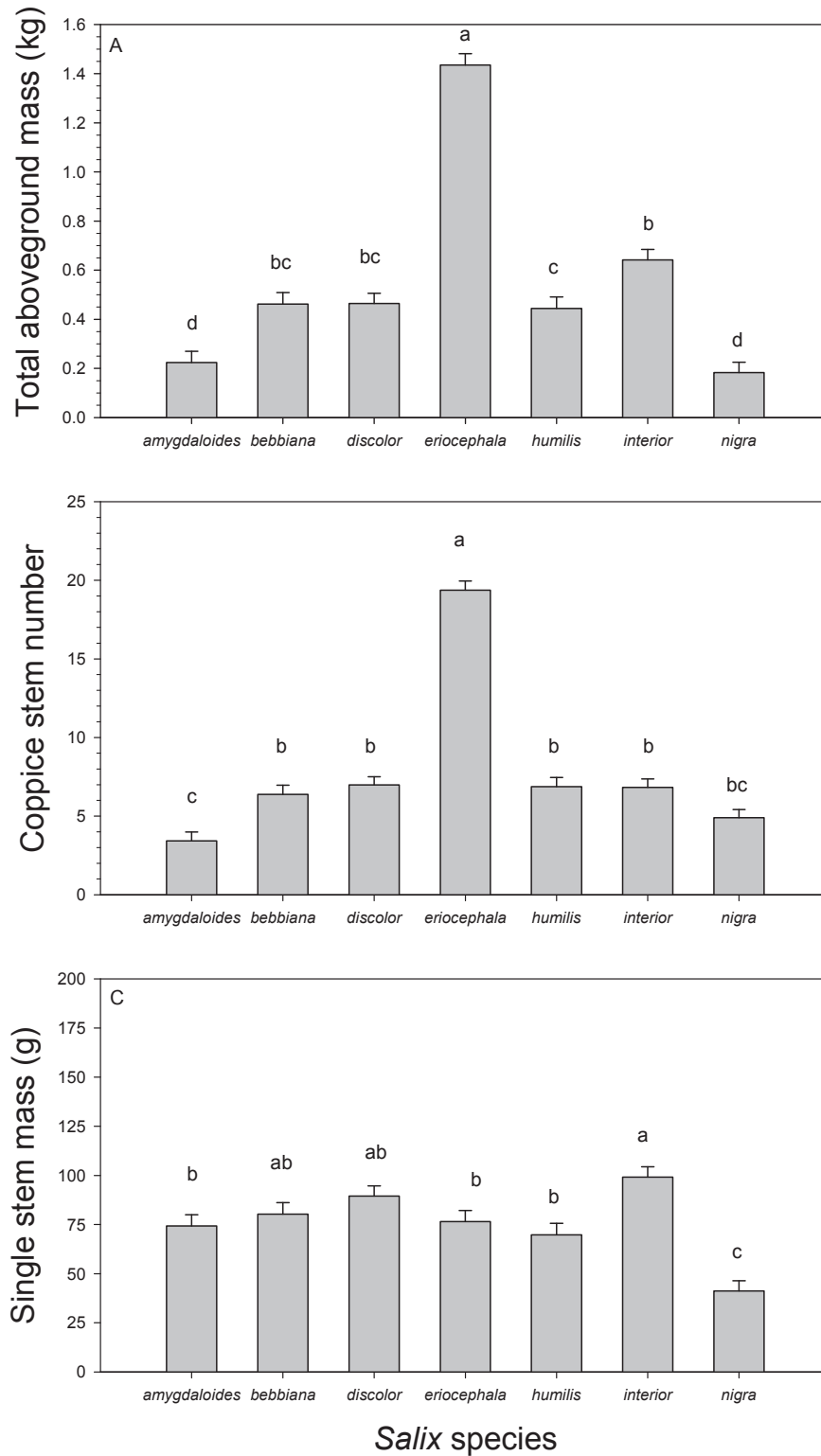
Fig. 2. Variation in total aboveground biomass (a), number of stems per coppice (b), and average single stem mass (c) for seven willow species.

was used to assess differences among species. All statistical tests were assessed at a significance level of α = 0.05, although individual *P* values are provided for all traits so that readers can make their own interpretations.

Allometric growth relationships were analyzed using analysis of covariance (ANCOVA) making multiple linear comparisons across species similar to that presented in Mosseler et al. [14]. In these analyses, three sources of variation were studied: (1) covariate (i.e., basal diameter), (2) independent effect (species), and (3) independent effect × covariate. The analyses were done based on the
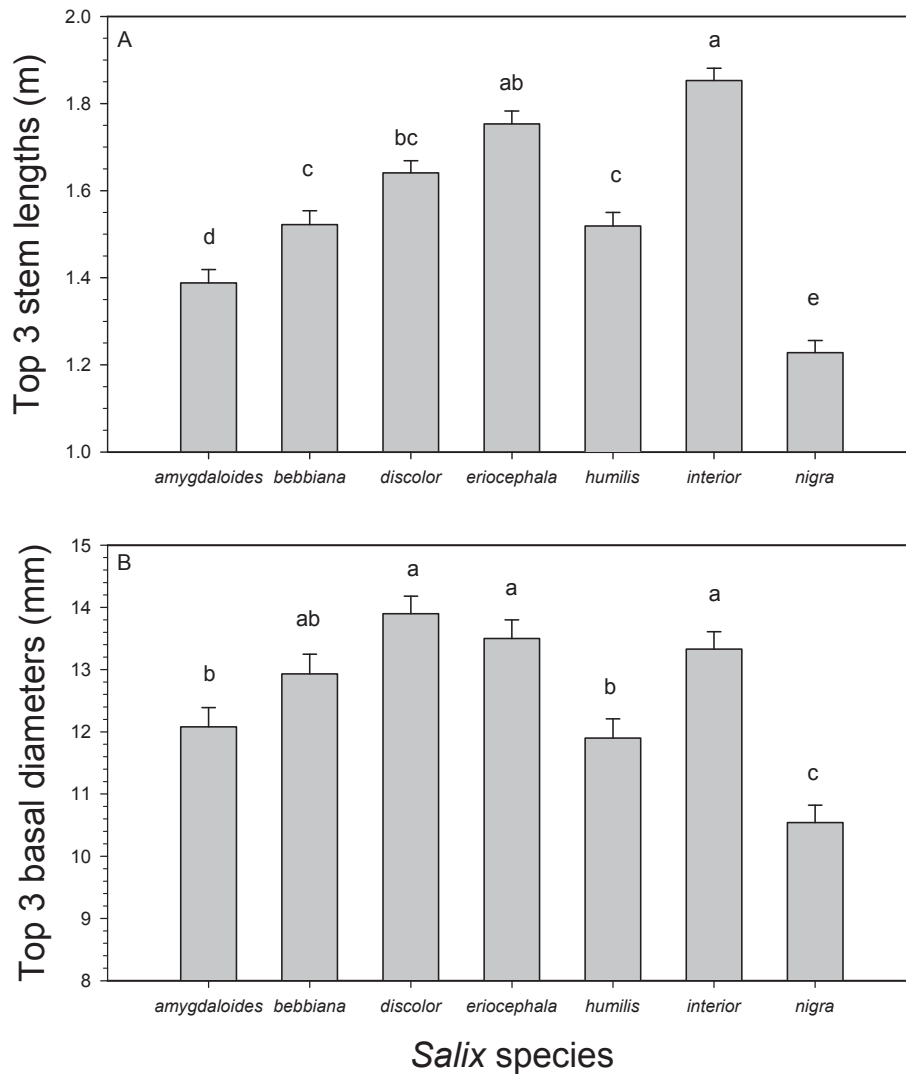
Fig. 3. Variation in stem length (a) and stem basal diameter (b) of the three largest stems per coppice plant for seven willow species.

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 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 $\alpha = 0.05$. The data had satisfied normality and equality of variance assumptions. The general linear model from Systat was used for analysis.

3. Results

Species and population (nested within species) were significantly different for all coppice traits examined (Table 4). However, at the level of genotype within population within species, differences among genotype were significant only for aboveground mass, number of stems per coppice, and average stem basal diameter, with ERI having by far the greatest aboveground mass and number of stems per coppice (Fig. 2a, b). The tree willows AMY and NIG produced the lowest aboveground mass and the fewest stems per

coppice. INT, DIS, and BEB had the greatest single stem mass, whereas NIG had the lowest (Fig. 2c). In analyzing the three largest stems per coppice, ERI, INT, and DIS produced the longest stems and those with the highest basal stem diameter (Fig. 3a, b). Once again, the tree willows AMY and NIG had among the smallest coppice stems in terms of length and basal stem diameter.

Five of the seven willows, showed significant negative relationships between average stem size (length and basal diameter) and coppice stem number (Fig. 4a, b). However, ERI showed an unusual and slightly positive relationship between stem number and stem length, with as many as 67 stems per coppice compared with a mean of 19.4 stems per coppice. The removal of this 67-stem outlier from the data set did not change the positive relationship both in nature and statistically. NIG showed a nearly horizontal regression of average stem length to coppice stem number, but had only a maximum of 10 stems (Table 5; Fig. 4a); however, this trend was not repeated for the relationship between average stem basal diameter and coppice stem number, which was strongly negative (Fig. 4b). For average stem length, the relationship to coppice stem number was similar among the remaining five species, approximately a loss of 25 cm per increase of 10 coppice stems (Fig. 4a). INT, followed by DIS, was able to maintain greater average stem length
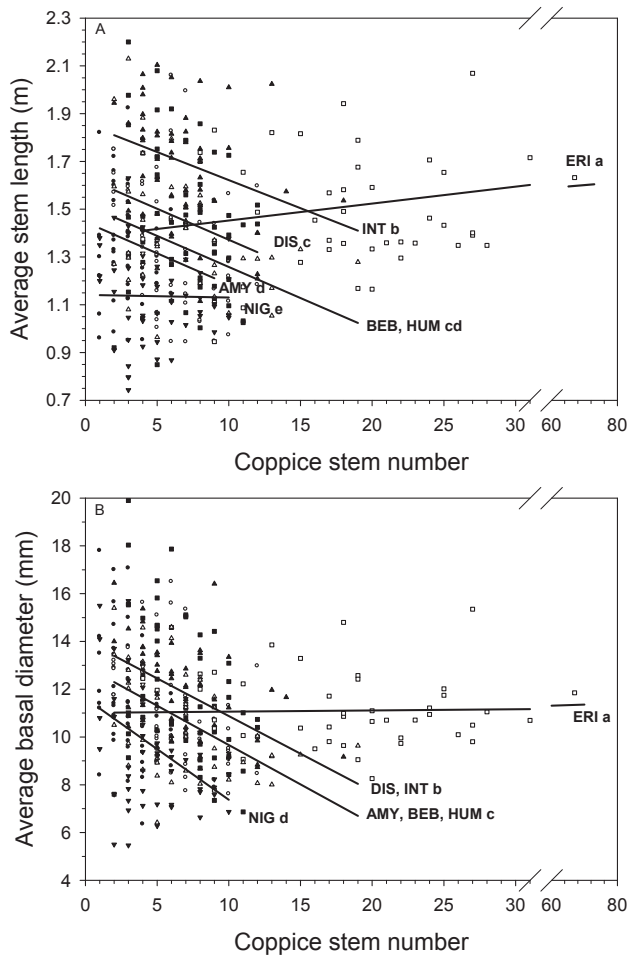
Fig. 4. Allometric relationships between coppice stem number and average stem length (a) and average stem basal diameter (b) for seven willow species. Species symbols are as follows: AMY ●, BEB o, DIS ■, ERI □, HUM, INT Δ, NIG.

at a given coppice stem number than BEB, HUM, and AMY. For all species except ERI, there was an average decrease of 33 mm in basal stem diameter for each increase of 10 stems per coppice (Fig. 4b). DIS and INT were able to maintain a greater basal diameter at a given stem number than AMY, BEB and HUM, with NIG showing the steepest drop in basal stem diameter as coppice stem numbers increased.

Each of the seven species showed strong positive relationships between aboveground mass and coppice stem number, with significant differences among species (Fig. 5). Among the seven species, ERI and INT showed the same and strongest positive relationship between aboveground mass and stem number, with an approximate 0.6 kg increase with every additional 10 stems per coppice (Table 5). BEB, DIS, and HUM were not statistically different but had a statistically lower rate of increase, with only a 0.35 kg gain for every addition of 10 coppice stems compared with INT and ERI. The tree willows AMY and NIG had the lowest rate of aboveground increase in mass with additional coppice stem numbers at a rate of 0.29 kg with each increase of 10 coppice stems (Table 5), and with NIG having a significantly lower Y-axis intercept of almost 0.1 kg. Thus, the relationship between aboveground mass and stem number divided these seven willows into four distinct species groups, with the tree willows (AMY and NIG) at the low extreme, ERI and INT at the high extreme, and a cluster of the other shrub willows forming an intermediate group (Fig. 5).

Three measures of coppice stem dimensions were used—(1) the average of the 20 largest stems, (2) the average of the three largest stems, and (3) the largest stem—to evaluate which was the best predictor of aboveground mass based on the coefficient of determination (R^2). For stem length, the average of the three longest, the maximum stem length, and the average of the 20 longest stems had an R^2 of 0.768, 0.750, and 0.724, respectively. For basal diameter, the average of the three largest diameters, the maximum, and average of the 20 largest stems had an R^2 of 0.772, 0.753 and 0.738, respectively. The average of the top three stem lengths in relation to aboveground mass showed three distinct statistical species groupings (Fig. 6a). ERI was in a class of its own, with approximately a 0.20 kg increase with each 0.1 m increase in the average length of the top three stems (Table 5); whereas BEB, DIS, HUM, and INT indicated only a 0.08 kg increase with each 0.1 m increase in the average length of the top three stems. The tree willows, AMY and NIG, showed the least amount of increase, with only a 0.04 kg increase with each 0.1 m increase in the average length of the top three stems. The relationship between the average basal diameter of the top three stems to aboveground mass indicated four statistically distinct species groupings (Fig. 6b). Again ERI was in a group of its own, with a 0.30 kg increase with each 1 mm increase in average basal diameter of the largest three stems (Table 5). INT was in a group of its own, with a 0.13 kg increase with a 1 mm increase in average basal diameter of the largest three stems, and the grouping of BEB, DIS, and HUM had a 0.08 kg increase. The two tree willows, AMY and NIG, had only a 0.03 kg increase with each 1 mm increase in average stem basal diameter of the largest three stems.

The relationship between average stem basal diameter and stem length for the three largest stems was strongly positive for all seven species and fell into four species groupings (Fig. 7). INT and ERI had the same rate of increase of 0.13 m with each 1 mm increase in the average basal diameter of the top three stems; however, INT had a 0.1 m greater stem length intercept for a given basal stem diameter (Fig. 7). BEB, DIS, and HUM formed their own species grouping, and the tree willows AMY and NIG formed a group, with both groups showing the same rate of 0.09 m stem length increase with each 1 mm increase in average basal diameter of the top three stems. However, BEB, DIS, and HUM had a 0.15 m greater stem length intercept.

4. Discussion

We found important differences among species and clones in coppice structure and growth performance and that coppice structure in willows can be a defining characteristic of the species. This was most evident in ERI, which produced a multi-stemmed coppice structure that averaged approximately 19 stems per coppice, and in one case, produced a coppiced plant with 67 stems. These ERI coppices produced by far the greatest biomass yields, but INT coppices also produced good biomass yields. Also, the root stem sprouting and colony-forming habit of INT can add substantially to overall biomass production on a per hectare basis [16]. There were also distinct species groupings in the numbers of stems produced, with the two tree willows, AMY and NIG, having the fewest stems per coppice, ERI the highest number of stems per coppice, and the other shrub willows, BEB, DIS, HUM, and INT falling into a third, intermediate species group in number of stems per coppice.

Most species produced coppices with upright stems, but the outermost stems of ERI coppices had a pronounced basal sweep. As a result, ERI coppices covered a much larger area of ground compared with the other six species. The expansive, recumbent coppice structure of ERI may explain the unusual absence of the expected negative relationship between stem number and stem size (both stem length and basal diameter; Fig. 4a, b) observed in

Table 5
Species-specific equations for various biomass growth relationships for 2-year-old coppiced plants found in the accompanying figures.

Average stem length in relation to stem number (Fig. 4a)			
Salix species	Equation	R^2	Species and stem number range
ERI,	y = 1.385 + 0.007x	0.183	ERI 4-67
INT	y = 1.865−0.024x	0.183	INT 2-18
DIS	Y = 1.633−0.026x	0.087	DIS 2-12
BEB, HUM	y = 1.518−0.026x	0.087	BEB 2-12, HUM 2-19
AMY	y = 1.445−0.026x	0.087	AMY 1-9
NIG	y = 1.151−0.002x	0.001	NIG 1-10
Average basal diameter in relation to stem number (Fig. 4b)			
Salix species	Equation	R^2	Species and stem number range
ERI	y = 11.018 + 0.005x	0.149	ERI 4-67
DIS, INT	y = 14.03−0.315x	0.208	DIS 2-12, INT 2-18
AMY, BEB, HUM,	y = 12.94−0.315x	0.208	AMY 1-9, BEB 2-12, HUM 2-19
NIG	y = 11.61−0.424x	0.272	NIG 1-10
Total aboveground green mass in relation to coppice stem number (Fig. 5)			
Salix species	Equation	R^2	Species and coppice stem number range
ERI, INT	y = 0.247 + 0.061x	0.781	ERI 4-67, INT 2-18
BEB, DIS, HUM	y = 0.256 + 0.035x	0.181	BEB 2-12, DIS 2-12, HUM 2-19
AMY	y = 0.125 = 0.029x	0.261	AMY 1-9
NIG	y = 0.035 = 0.029x	0.261	NIG 1-10

Total aboveground green mass in relation to top 3 stem lengths (Fig. 6a)			
Salix species	Equation	R^2	Species and coppice stem length range (m)
ERI	y = −2.012 + 1.965x	0.532	ERI 1.1−2.6
BEB, DIS, HUM, INT	y = −0.459 + 0.782x	0.522	BEB 0.9−2.2, DIS 1.1−2.4, HUM 1.1−2.3, INT 1.2−2.6
AMY, NIG	y = −0.318 + 0.394x	0.578	AMY 0.9−2.2, NIG 0.7−1.8
Total aboveground green mass in relation to top 3 basal stem diameters (Fig. 6b)			
Salix species	Equation	R^2	Species and coppice stem basal diameter range (mm)
ERI	y = −2.626 + 0.302x	0.619	ERI 9-19
INT	y = −1.063 + 0.128x	0.619	INT 9-18
BEB, DIS, HUM	y = −0.576 + 0.082x	0.598	BEB 9-19, DIS 8-21, HUM 7-17
AMY, NIG	y = 0.173 + 0.033x	0.261	AMY 7-22, NIG 5-16
Top 3 stem lengths mass in relation to top 3 basal stem diameters (Fig. 7)			
Salix species	Equation	R^2	Species and basal diameter range (mm)
INT	y = 0.166 + 0.127x	0.719	INT 9-18
ERI	y = 0.054 + 0.127x	0.719	ERI 8-19
BEB, DIS, HUM	y = 0.563 + 0.086x	0.741	BEB 9-19, DIS 8-21, HUM 7-17
AMY, NIG	y = 0.326 + 0.086x	0.741	AMY 7-22, NIG 5-16

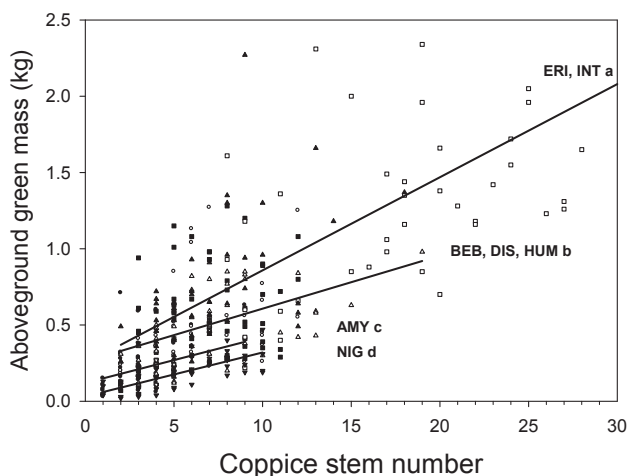most other willows because individual stems of ERI may experience

Fig. 5. Allometric relationship between coppice stem number and aboveground green mass for seven willow species.

less intra-coppice competition for light. However, this recumbent, spreading coppice structure with its sweeping stems may make it more difficult to fully harvest the biomass from ERI in SRIC biomass plantations using current harvesting technology, perhaps making this coppice structure less desirable for SRIC biomass production. Technological modification of harvesting equipment and/or selecting for clones that have demonstrated a more upright coppice structure may alleviate this issue with coppice structure. Also, a tighter spacing with ERI tends to force a more upright coppice stem structure in clones that demonstrate these spreading coppices. With possible modifications in harvesting technology, clonal selection, and adjustments in plant spacing, ERI remains one of the most promising species for biomass production given its very high biomass yields.

The negative relationship between stem number per coppice plant and stem diameter and the strong positive relationship between stem length and basal diameter have also been noted by Tharakan et al. [20]. 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 [25]. Our results with coppice growth in short-rotation willow biomass plantations suggest that stem diameter−length relationships and their relationship to biomass yield [14] might also
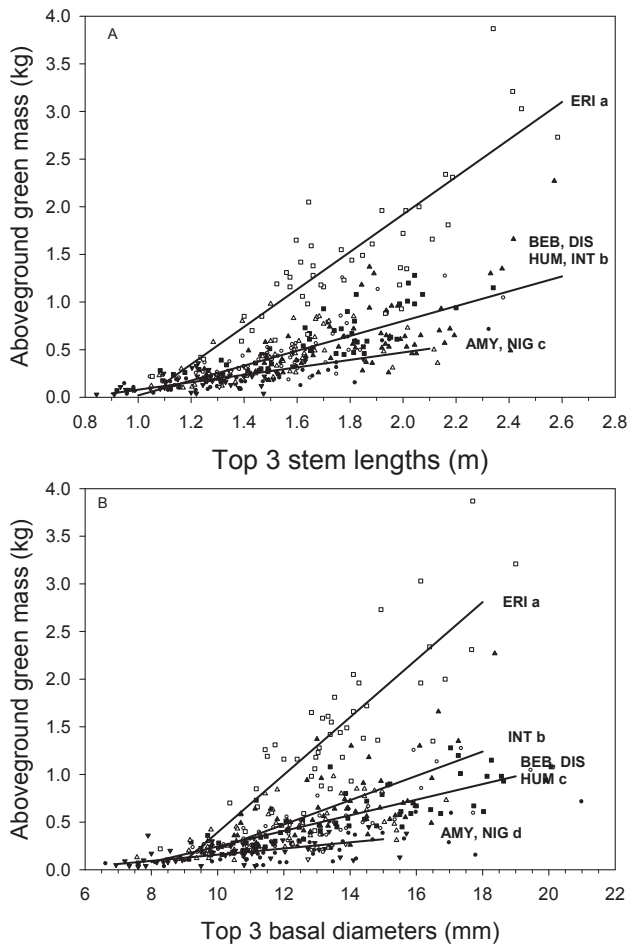
Fig. 6. Allometric relationships between aboveground green mass and the length of the three longest stems (a) and the three largest stems in basal diameter (b) for seven willow species.
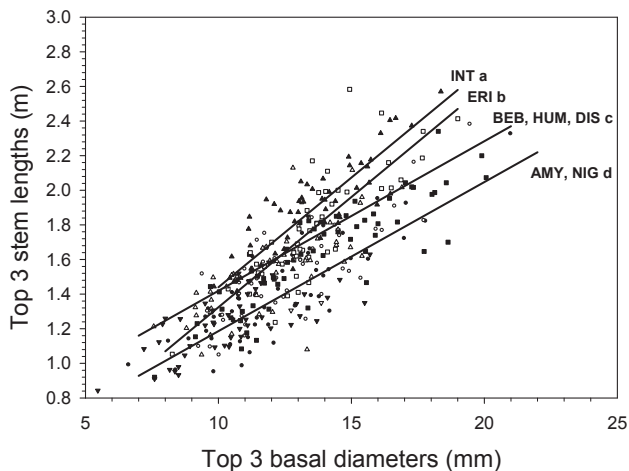
relationships between stem length, basal stem diameter, number of stems per coppice plant, and biomass yield similar to those shown among closely related *Eucalyptus* species in Australia [30].

Predicting biomass yields per hectare from non-destructive sampling measures may well be important for assessing economic feasibility of SRIC [32], thus a few simple measurements based on stem number, stem length or basal stem diameter could suffice for developing biomass yield estimates based on allometric relationships presented here by species groupings (Figs. 5 and 6; Table 5). For most willows, the relationship between stem length and stem diameter is strongly positive, but these relationships did fall into four distinct species groupings with significant differences among these groups: INT > ERI > BEB, DIS, and HUM > AMY and NIG.

The strength and consistency of the stem diameter–length relationship in coppice growth in these seven willow species indicate that growth models developed for assessing biomass volume based on simple, non-destructive measures such as stem number, stem length, and/or basal stem diameter may be useful in predicting biomass yields for economic viability modeling [19,21,33]. The effect of the number of stems per plant, especially in the case of INT and ERI, indicates that clonal selection for increased numbers of stems per plant should result in significant increases in biomass yield, others things being equal. Among the age-related [22,34], species-related [14,30,35,36], and site-related [14,27,37,38] factors that can affect allometric relationships to biomass yield, this investigation on allometric relationships has confirmed a strong species effect on yield even within a closely related group of species within the same genus (e.g., *Salix*). This indicates that major gains in biomass yield can be made through proper species, clone, and trait selection. Differences in the allometric relationships identified among these seven willows highlight the need to develop allometric models aimed at yield estimation based on species characteristics that define coppice structure and thus biomass yield.

Acknowledgments

be useful in site quality assessments similar to the way that these relationships have been used for site quality assessment in conventional single-stemmed trees [21,26–30], as well as for other shrubs [31]. These seven willow species showed allometric

Fig. 7. Allometric relationship between the three longest coppice stems and basal diameter for seven willow species.

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