Forest Ecology and Management 320 (2014) 190–196

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

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

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ARTICLE INFO

Article history:
Received 12 December 2013
Received in revised form 14 February 2014
Accepted 19 February 2014

Keywords:
Allometric relationships
Biomass yield
North American *Salix* species
Site quality effects
Willow coppice structure

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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http://dx.doi.org/10.1016/j.foreco.2014.02.027
0378-1127/

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′