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Controlling *Phalaris arundinacea* (reed canarygrass) with live willow stakes: A density-dependent response

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ABSTRACT

We tested the use of live willow stakes to manage reed canarygrass (*Phalaris arundinacea* L.) invasions on a wetland site. We planted willow at densities of 0.60 m (2 ft) centers, 0.91 m (3 ft) centers, 1.21 m (4 ft) centers, and control (no plantings) on a sloping wetland edge at Lake Washington, Seattle, U.S.A., where reed canarygrass dominated prior to the experiment. Soil moisture content was measured along the slope gradient, resulting in three soil moisture classes per replicate. Willow leaf area index and reed canarygrass aboveground biomass were measured after each of two consecutive growing seasons and analyzed using ANCOVA. Relative to the controls, the willows reduced total biomass of reed canarygrass by 44.9% with 0.60 m spacing in the first year and by 68.0% with 0.60 m spacing and 56.1% with 0.91 m spacing in the second year. Differences in soil moisture did not affect reed canarygrass aboveground biomass or effects of willow on reed canarygrass, but did affect willow growth, perhaps through reed canarygrass competition under lower soil moisture conditions. We recommend the 0.60 and 0.91 m spacings for wetland restoration projects attempting to manage reed canarygrass through live willow staking.

1. Introduction

Phalaris arundinacea (reed canarygrass) is a sod-forming, perennial grass species found in temperate regions worldwide. Reed canarygrass is native to Europe, Asia, and North America (Cronquist et al., 1977). It is reported as an invasive weed in Afghanistan, Hungary, Japan, Indonesia, Korea, Mauritius, New Zealand, Poland, Italy, Portugal, and U.S.A. (Holm et al., 1979). In Europe, dominance by reed canarygrass has reduced the conservation value of unmanaged wet grasslands (Joyce and Wade, 1998). Reed canarygrass has gradually come to dominate neglected floodplain grasslands in central Europe, is reported to expand rapidly into abandoned alluvial meadows in France, and has invaded river banks in England after disturbance such as berm excavation (Raven, 1986; Conchou and Patou, 1987; Prach, 1992; Straškrabová and Prach, 1998). In North America, reed canarygrass is invasive in the Pacific Northwest and the Midwest, where it infests many wetland restoration projects. Although reed canarygrass is native to North America, it is thought that introgression of germplasm from a Eurasian cultivar into native genotypes may account for the invasiveness of this species (Merigliano and Lesica, 1998). Reed canarygrass is found along streams, lake margins, springs, meadows, and even montane wetlands

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(Merigliano and Lesica, 1998). Furthermore, reed canarygrass grows densely in artificially modified wetlands (Fennessy et al., 1994). While its typical habitat is poorly drained and wet areas, it is as drought tolerant as many other cool-season grasses found in humid and sub-humid regions (Marten, 1985). Reed canarygrass has been introduced across the U.S.A. as a soil binder and as forage because of its rapid above- and belowground growth and tolerance of wet soils and has been planted for use in erosion and sedimentation management (Antieau, 2004). This strongly rhizomatous species suppresses other wetland plants, thereby diminishing biological diversity. For example, Lesica (1997) demonstrated that reed canarygrass displaced populations of the endangered aquatic plant *Howellia aquatilis*. Reed canarygrass has also been shown to reduce plant species richness in wetlands altered by beaver (Perkins and Wilson, 2005).

Management strategies for reed canarygrass infestations include mowing, herbicide application, grazing, cultivation, burning, shading, flooding, and mechanical barriers. Lindig-Cisneros and Zedler (2001) found that reed canarygrass did not germinate in the dark and observed that reed canarygrass easily established seedlings after canopy disturbance. Rapid development of a dense canopy in a managed wetland reduces the number of microsites available for reed canarygrass seed germination (Lindig-Cisneros and Zedler, 2002). Heavy shade decreases reed canarygrass aboveground biomass by up to 97% in greenhouse experiments (Maurer and Zedler, 2002; Perry and Galatowitsch, 2003), and barnyardgrass (*Echinochloa crus-galli*) reduced reed canarygrass biomass by 65% in an experimental wetland (Perry and Galatowitsch, 2003). Mature reed canarygrass is also reported to be intolerant of deep shade (Cooke, 1997), However, controlled experiments demonstrating responses to shade from trees are lacking.

Many chemical agents are available to land managers for invasive species control. However, biological agents are preferable due to minimal or acceptable side effects. In addition, ecological engineering principles (Bergen et al., 2001) suggest that an appropriate approach to the solution of problems caused by the invasion of reed canarygrass would include (1) design, (2) sustainable systems, and (3) would be consistent with ecological principles. Identifying effective biological means for managing reed canarygrass infestation is a top priority for restoration managers. We view willow staking as an appropriate technique. The design of the method can be tailored to the density of reed canarygrass and may be modified depending on site conditions (sun, water). The system is sustainable because of the hardy and vigorous nature of willows, yet in-planting may occur or areas of willow cleared after site conditions have been satisfactorily modified. The use of willows is consistent with ecological principles; competition from a taller growth form is used to attack a shorter growth form that is dependent on the sun. Here we report field results from a controlled, replicated experiment that tested the effectiveness of three live willow stake planting densities in reducing biomass of the reed canarygrass where it dominated a wetland area. Our goals are to investigate whether willow live-staking is effective for reducing reed canarygrass biomass, to identify the threshold of soil moisture content above which either the willow or reed canarygrass lose their competitive ability, and to determine whether planting density significantly affects the ability of willow to control reed canarygrass through shading.

2. Materials and methods

2.1. Site description

The study site was the East Basin of the Union Bay Natural Area (lat. 47°N 39.5′, long. 122°W 17.2′; Seattle, Washington, U.S.A.), a sloping wetland along the western edge of Lake Washington (Fig. 1). The basin has a generally south-southeast aspect and is on glacial till. The lower portion of the site is modified fill, which is saturated year round at the shoreline. Monotypic stands of reed canarygrass dominate the East Basin landscape, with estimated cover >95%.

The periphery of study site is characterized as abandoned, highly disturbed ground with non-native *Rubus armeniacus* (Himalayan blackberry) covering ∼50–60% of the site in dense thickets. *Phalaris arundinacea* (reed canarygrass) appears in large patches in the wetland and buffer area, with *Lythrum salicaria* (purple loosestrife), *Ranunculus repens* (creeping buttercup), and *Iris pseudacorus* (yellow-flag iris) also abundant in places. *Hedera helix* (English ivy) is found sporadically across the site, sometimes reaching 5–6 m up the stems of the taller trees. Native trees include several mature specimens of *Populus trichocarpa* (black cottonwood) in the eastern portion of the site, as well as *Alnus rubra* (red alder) in the eastern and southern portions. Less common native species include *Spiraea douglasii* ssp. *douglasii* (hardhack), *Rosa pisocarpa* (clustered wild rose), *Polystichum munitum* (western sword fern), *Fraxinus latifolia* (Oregon ash) and *Crataegus suksdorfii* (black hawthorn). *Salix lucida* ssp. *lasiandra* (Pacific willow) is found in the primarily wetland areas of the eastern and southern portions of the site, covering ∼15% of the basin. *Salix scouleriana* (Scouler willow), *Salix lasiandra* (Pacific willow), *Juncus effusus* (common rush), *Typha latifolia* (cattail) and *Carex* spp. also occur. Significant areas of bare soil occur along the seasonally fluctuating shoreline.

2.2. Plot establishment

All aboveground vegetation on the study site was removed by mowing in spring and summer of 2003 to prepare for planting live willow stakes. Three foliar applications of Roundup® were made to control vegetation regrowth in summer of 2003, and spot foliar applications of Crossbow® were made to suppress Himalayan blackberry in summer of 2003. The subsequent regrowth was mowed down and wood chip mulch was spread evenly across the area at a depth of 10–15 cm from the spring to the fall of 2003 to slow reed canarygrass regeneration.

The study site was 0.09 ha in size, and ran 72 m along the edge of Lake Washington. The site was divided into seven replicate blocks in spring 2004. Within each block, four treatments (three willow densities and an unplanted control) were applied in strips that ran from the upper edge of the site toward the lake margin. Each treatment strip was 2.57 m in width. The vertical length of each block varied from 10 to 15 m, according to the varying dimensions of the site (Table 1). The mean vertical length of all seven blocks was 12.6 m (Table 1).

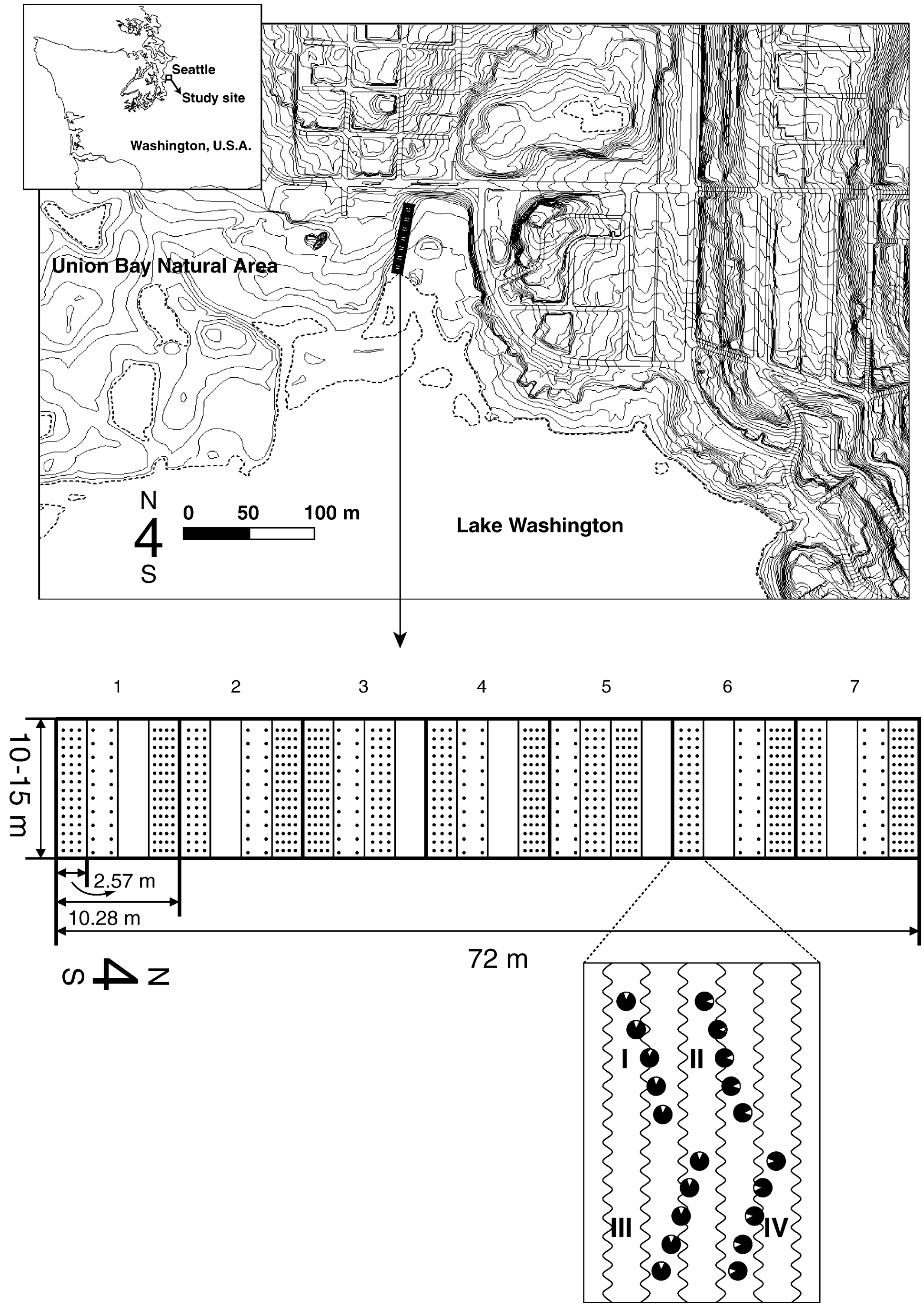

Fig. 1 – Map of the study site showing the East Basin, Union Bay Natural Area, and the planting design. The contour interval in the map is 0.6 m. Dashed and parallel lines indicate shorelines and main roads, respectively. The dots (●) within each plot of the planting layout represent willows planted 0.60 m apart (rows of four dots), 0.91 m apart (rows of three dots) and 1.21 m apart (rows of two dots). The enlarged area at the bottom of the figure shows the measurement protocol for measuring leaf area index of the willows: four diagonal transects, two viewing along the row (I and III) and two viewing across the row (II and IV). The black circles with open wedges represent 45° view caps.

The site was wetter in summer as the Lake Washington water level was raised 45.7 cm every April, after the threat of winter storm damage had passed.

The elevation within each block was measured every 4 m from the top of the site to the estimated lake edge, using an optical level (AT-G6, TOPCON, Tokyo, Japan) in March 2004. Elevations within blocks were adjusted relative to sea level using daily Lake Washington pool elevations (U.S. Army Corps of Engineers, 2004). The mean slope of the study site was $4.35 \pm 1.03°$S.E. (Table 1).

Table 1 – Site characteristics

	1	2	3	4	5	6	7	Mean
Length (m)	15.0	13.5	11.0	10.0	11.5	13.5	15.0	12.6±0.4
Slope (°)	1.89 ± 0.06	3.74 ± 0.90	5.17 ± 0.43	4.85 ± 0.50	5.40 ± 0.36	5.32 ± 0.45	4.05 ± 0.18	4.35 ± 1.03
Soil moisture content (%; 2004)	85.2 ± 5.2	112.1 ± 13.5	125.3 ± 14.6	98.7 ± 11.8	68.6 ± 5.9	68.4 ± 3.9	70.0 ± 4.6	89.8 ± 3.8
Soil moisture content (%; 2005)	109.6 ± 11.1	120.9 ± 19.6	138.2 ± 26.1	113.0 ± 18.2	64.4 ± 8.7	59.8 ± 7.2	71.5 ± 8.1	96.8 ± 6.5

Consecutive numbers in the top row are blocks from south to north on the site. Length is the mean distance from uphill to downhill edge for each block. The slope was calculated using the high and low elevation in each block (value ± S.E.). The soil moisture contents are averaged values (±S.E.) from April to October 2004 and 3 months (April, July and August) in 2005 (n = 28/month).

2.3. *Planting live stakes*

Live stakes for the experiment were cut from Scouler willows (*Salix scouleriana*) and Pacific willows (*Salix lasiandra*) in the adjacent forested wetlands. Stakes were 90 cm (3 ft) long × 1.3–2.5 cm (0.5–1 in.) in diameter. From February through March 2004, stakes were cut and immediately planted vertically (stuck) to a depth of 45 cm (half of their length). Four treatment densities were randomly assigned within each block: (1) 0.60 m (2 ft) centers, (2) 0.91 m (3 ft) centers, (3) 1.21 m (4 ft) centers and (4) controls (no plantings) (Fig. 1). These planting densities were determined from a pilot study adjacent to the study site (K. Ewing, unpublished data). The stakes were planted no closer than 1 m from the uphill and downhill edges of any treatment strip to minimize shading from adjacent vegetation. A total of 1023 willow stakes were planted, and the site was fenced to minimize disturbance.

2.4. *Soil moisture measurement*

Soil samples were collected once per month from April to October 2004 at four equidistant points along the midline of each block to determine the soil moisture gradient created by elevation changes. Soils were sampled below the layer of wood chip mulch and leaves, using a 3.6 cm diameter soil probe inserted to a depth of 10 cm. Four samples were taken in each of the seven blocks at the beginning of each month during the sampling period (n = 28). Soil moisture was measured gravimetrically (Gardner, 1986). The samples were weighed, dried to constant weight at approximately 87 °C for 21 h in a dry oven (Economy Oven, Model # 52201-286, VWR Scientific Products Corporation, West Chester, PA, U.S.A.) and reweighed to determine moisture content. The data for 7 months were pooled to obtain means for each location. Each block was divided into three classes (high, medium and low) according to the rank order of the soil moisture content data. Soil moisture contents were re-measured in the same way on April, July and August 2005 to categorize the study site into three soil moisture classes (high, medium and low) for 2005.

2.5. *Leaf area index and biomass measurement*

Performance of the willow stakes was determined by estimating leaf area index (LAI). Leaf area index was defined as projected leaf area per unit of ground area and was measured in October 2004 and August 2005 using standard indirect techniques with a plant canopy analyzer (LAI-2000, LI-COR Inc., Lincoln, NE, U.S.A.). This equipment indirectly calculates LAI from canopy light transmittance. Measurements were made on cloudy days to lower the contribution of scattered radiation and to minimize the interference from direct beam radiation. Direct sunlight on the canopy causes errors of 10–50% in LAI-2000 measurements (Welles and Norman, 1991).

One above-canopy and five below-canopy readings were obtained using the same optical sensor for each measurement. The above-canopy readings were collected in the nearest clearing and were interspersed for each measurement to allow for changing sky conditions. LAI-2000 includes a set of view caps for the lens of an optical sensor, which are snap-on opaque covers with an open wedge of 45°, 90°, 180° and 270°. A 45° view cap was used to prevent the underestimation of LAI from small plot size and sunlit foliage, and to reduce some errors from the user's silhouette (LI-COR, 1992). The measurements of willow LAI were taken at approximately 1.5 m aboveground to minimize the contribution of the understory vegetation. The measurement points were randomly selected along the centerline of each willow planting density treatment.

Leaf area indices were measured separately within high, medium, and low soil moisture areas classified by soil moisture content in each willow density treatment (n = 84: 7 replicates × 4 willow planting densities × 3 soil moisture classes). Mean LAI was determined from four replicate readings along a diagonal transect near each measurement point which were randomly selected along the centerline of each willow planting density treatment to prevent the same trees from dominating the entire set of readings for each treatment. For the first and third measurement, the view cap was oriented along the plot strips, and for the second and fourth measurement orientation was across the plot strips (Fig. 1). The each replicate reading along diagonal transects was averaged from five repetitive readings (Fig. 1). At each measurement point, 20 below-canopy readings were made.

Aboveground weed biomass was sampled in 0.25 m^2 plots at the same location where LAI measurements were made to determine treatment effectiveness (n = 84). All aboveground reed canarygrass biomass was harvested from each plot in October 2004 and August 2005. Samples were dried at 70 °C for 4 days in a drying oven (Hotpack, Philadelphia, PA, U.S.A.) and weighed.

2.6. *Data analysis*

A one-way analysis of variance (ANOVA) followed by Tukey's HSD (honestly significant difference) was conducted to compare the soil moisture content of three soil moisture classes. Linear regression analyses were conducted to examine the relationship between soil moisture content and distance from uphill edge. Two-way analyses of covariance (ANCOVA) was performed on the leaf area index (LAI) and biomass data using the General Linear Models procedure in SAS (SAS Institute, 1987) with planting density and willow age as independent variables (4 willow planting densities × 2 willow ages) and soil moisture class (converted to three factor levels: high, medium, and low) as a covariate. Two willow ages represent ages of willow stakes when willow LAIs were measured (young age: 7.5 months old; old age: 18.8 months old). Tukey's studentized range tests (honestly significant difference tests) were used to assess pair-wise differences in reed canarygrass biomass, and willow LAIs under different willow planting density treatments. Significant pair-wise differences in reed canarygrass biomass and willow LAI among the three soil moisture classes were also assessed with Tukey tests ($p < 0.05$). Graphs were drawn separately for two willow ages. All statistical tests were conducted using SAS Version 8.2 (SAS Institute, 1987).

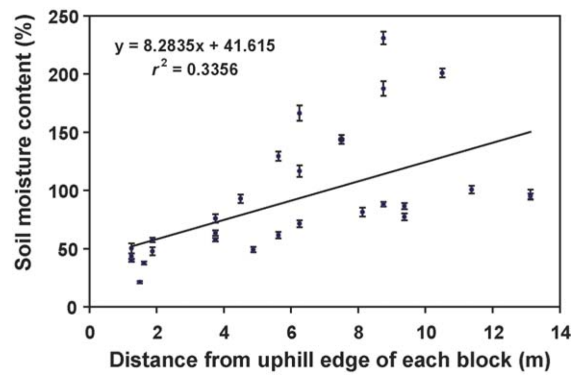

Fig. 2 – The pooled soil moisture content (%) from uphill to downhill for all blocks (m) for 2 years. Each circle is the average value of soil moisture data pooled during the sampling period. The equation in the upper left corner represents the linear regression analysis of the relationship between soil moisture content and distance from the uphill edge.

3. Results

3.1. *Classification of soil moisture*

Soil moisture content decreased as elevation from the lake edge increased (Fig. 2). A linear equation explained the relationship between soil moisture content and distance from upper edge of each block ($p < 0.05$; Fig. 2). As a result, we divided each block into three different soil moisture classes based on distance from the upper edge. The soil moisture contents of the three classes were significantly different throughout both years (Tukey's HSD test, $p < 0.05$; Table 2).

3.2. *Density, age and moisture effects*

Willow stakes developed quickly into small trees in the first year and then formed a willow canopy in the second year. Leaf area index (LAI) of willows at young willow age ranged from 0.12 to 2.99 and leaf area index at old willow age varied from 0.19 to 5.98. Mean willow LAI at the 0.60, 0.91, and 1.21 m centered planting densities was 1.33, 1.07, and 0.89 at young willow age and 2.99, 2.36 and 1.74 at old willow age, respectively. Willow LAI differed significantly at willow planting densities, willow ages and soil moisture classes (Table 3). At young willow age, willow LAI tended to increase with willow planting density, but this trend was not significant (Tukey's studentized range test, $p > 0.05$), whereas at old willow age, willow LAI was significantly higher with the 0.60 m centered planting density than with the other densities (Tukey's studentized range test, $p < 0.05$). Low soil moisture content significantly reduced willow LAI for both willow ages. Medium soil moisture also reduced willow LAI relative to high soil moisture at young willow age (Tukey's studentized range test, $p < 0.05$; Fig. 3a), but not at old willow age (Tukey's studentized range test, $p > 0.05$; Fig. 3b).

Reed canarygrass responded significantly to willow planting density and willow ages ($p < 0.001$; Table 3). Mean biomass of reed canarygrass at the 0.60, 0.91 and 1.21 m spacings was 103.4, 160.9 and 178.2 $g\,m^{-2}$ at young willow age and 138.6, 190.0 and 257.3 $g\,m^{-2}$ at old willow age, respectively (Fig. 4a and b). Reed canarygrass biomass was significantly reduced relative to the controls in the 0.60 m spacing treatment at young willow age and in both the 0.60 and 0.91 m spacing treatments at old willow age ($p < 0.05$; Fig. 4a and b). Shading by willows reduced total biomass of reed canarygrass by 44.9% at the 0.60 m density relative to the controls at young willow age (Fig. 4a) and by 68.0% at the 0.60 m density and 56.1% at the 0.91 m density at old willow age (Fig. 4b). Reed canarygrass biomass did not differ among soil moisture content classes in either willow age (Tukey's studentized range test, $p > 0.05$).

Table 2 – Three soil moisture classes estimated from data collected monthly from April to October 2004 and for 3 months (April, July and August) in 2005

Class	Soil moisture content (%, mean ± S.E.)		Distance from uphill edge to midpoint of class (m, mean ± S.E.)
	2004	2005	
High	142.8 ± 6.2 a	153.3 ± 10.5 a	2.0 ± 0.3
Medium	76.7 ± 2.6 b	81.6 ± 5.3 b	5.7 ± 0.8
Low	43.9 ± 2.0 c	49.1 ± 4.7 c	10.3 ± 0.8

Distances are from the uphill edge of the study site. The classes were derived from the rank of total mean soil moisture values from data pooled throughout the sampling period each year. Different letters following mean values indicate significant differences among classes based on Tukey's HSD (honestly significant difference) tests ($p < 0.05$).

Table 3 – Results of two-way analyses of covariance (ANCOVA) for willow leaf area index and reed canarygrass biomass with soil moisture as the covariate (willow planting densities = 0.60 m, 0.91 and 1.21 m centers; willow age = young and old; soil moisture = high, medium and low)

Source	d.f.[a]	Willows leaf area index			Reed canarygrass biomass		
		F[b]	R^2[c]	p[d]	F[b]	R^2[c]	p[d]
Willow planting density	3	7.86	8.16	***	8.70	269370.68	***
Willow age	1	44.32	46.01	***	12.83	397307.01	***
Willow planting density × willow age	3	3.09	3.21	*	3.48	107876.30	*
Soil moisture	2	8.53	8.85	***	0.49	15083.46	NS
Error	158						

NS: not significant.
[a] Degrees of freedom.
[b] F value.
[c] Mean square.
[d] Probability value.
* $p < 0.05$.
*** $p < 0.001$.

4. Discussion

4.1. *Competition between willows and reed canarygrass*

Reed canarygrass continued to invade our study site from downhill outside the study site in 2004 even after mowing and mulching. Reed canarygrass spread rapidly from rhizomes and there was some growth from transmittance of light to the soil surface and willows increase competition for soil resources with understory plants. Forman (1998) showed that the aboveground biomass of reed canarygrass was not significantly affected by shading, but belowground biomass was significantly reduced by 41, 51 and 81% by shade. Shade reduced mean total biomass of reed canarygrass by 52% in partial

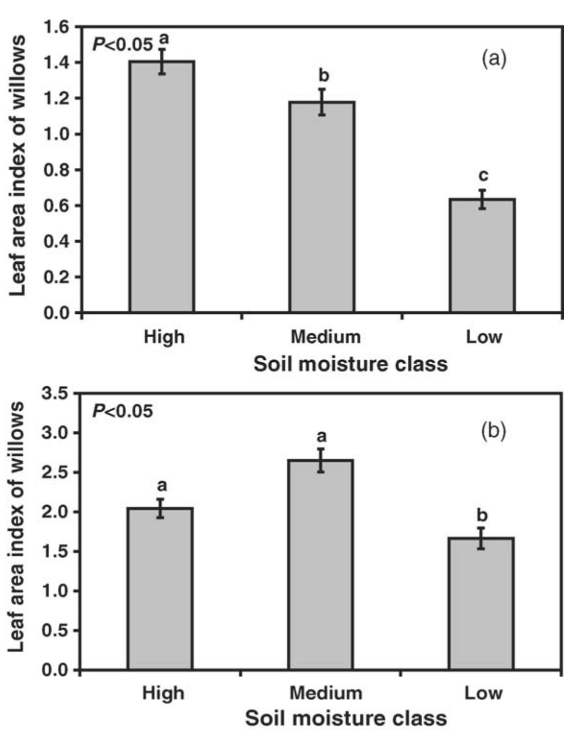

Fig. 3 – Leaf area index of willows in the different soil moisture classes at young willow age (a) and old willow age (b). The different letters indicate significant differences among means from Tukey's studentized range test (p < 0.05).

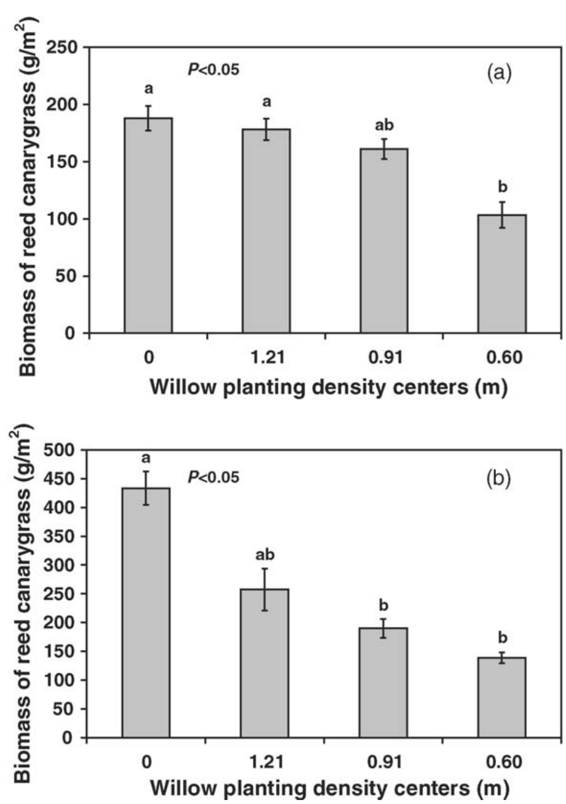

Fig. 4 – Biomass of reed canarygrass with different willow planting densities at young willow age (a) and old willow age (b). The different letters indicate significant differences among means from Tukey's studentized range test (p < 0.05).

shade and by 99% in full shade created by strips of shade cloth (Perry and Galatowitsch, 2004). Results from the 0.60 m center planting density treatment in this study showed that aboveground biomass of reed canarygrass responded significantly to willows. The planting density of 0.60 m decreased reed canarygrass mean biomass by 44.9% in the first growing season and 68.0% in the second growing season, respectively.

Common morphological responses of grasses to shade include increased leaf-area ratio, increased shoot-to-root ratio, and decreased specific leaf weight, leaf blade thickness, and shoot dry weight (Cooper and Tainton, 1968; Allard et al., 1991; Kephart et al., 1992; Kephart and Buxton, 1993). Plants subjected to shade are known to exhibit a shade avoidance reaction characterized by reductions in tiller or shoot number and stem extension (Smith et al., 1990). The increased stem length may result in thin, etiolated stems. Willow shading in our study reduced light availability, which may have led to light stress for reed canarygrass. Shading may have affected reed canarygrass biomass in this study by reducing the initiation or survival of aboveground shoots. Etiolated stems that grew outwards were shaded by the surrounding willows. However, although light competition may account for the negative effect of willows on reed canarygrass biomass, we cannot rule out the potential importance of other forms of willow interference in this study.

4.2. *Influences of soil moisture*

Soil moisture varied considerably along the slope gradient across the site (Tables 1 and 2). Reed canarygrass and willows are sensitive to soil moisture and both species are known to tolerate saturated wetlands soils (Marten, 1985; Rice and Pinkerton, 1993; Coops et al., 1996; Stromberg, 1997; Lauriault et al., 2005). Here, willow stakes became established easily in saturated downhill soils, putting out extensive root systems and shoots over two growing seasons.

Reed canarygrass produces greater aboveground biomass when growing in saturated soils (Gomm, 1978). Willow growth was suppressed at some lower plots in our study, perhaps as a result of increased reed canarygrass growth. Soil moisture did not significantly effect reed canarygrass biomass during either growing season, even though the differences among the soil moisture classes were relatively large.

We found significant positive relationships between soil moisture and willow leaf area index. Willow shading may decline in relatively dry areas. Reed canarygrass is considered to be more drought resistant than many other grass species from upland areas (Rice and Pinkerton, 1993). Pezeshki et al. (1998) reported that maximum photosynthesis and growth in *Salix nigra* (black willow) posts required ample soil moisture without flooding in the upper soil layer and adequate drainage in the top 0.6 cm of soil. Soil flooding can have adverse effects on both root initiation and subsequent root elongation in willow posts because of oxygen deficiency. Although reed canarygrass biomass did not decline significantly with soil moisture class in either year of this study, the lower willow LAI with low soil moisture suggests that reed canarygrass may have become more competitive with willows as moisture stress increased across the soil-moisture classes. However, the vigor of reed canarygrass in low soil moisture conditions may not overcome the shading effect of willows or enable it to outcompete other grasses adapted to drier areas.

4.3. *Leaf area index (LAI) of willows*

The utility of the LAI-2000 for measuring LAI in forests has been demonstrated. The LAI values observed in this study were similar to the values measured in other willow stands (Cannell et al., 1987). Willow LAI in our study increased with willow planting density and increased from 2004 to 2005, demonstrating the successful establishment of these plantings.

In another study, the maximum LAI of *Salix viminalis* was 2.4 for plants 0.5 m apart and 4.5 for plants 0.295 m apart (Cannell et al., 1987). The maximum LAI for *Salix* spp. in this study was 2.99 in 2004 and 5.98 in 2005 when willows were planted 0.6 m apart.

4.4. *Applications in other wetlands dominated by reed canarygrass*

Wetlands are diverse ecosystems in terms of topography, hydrology and vegetation. Reed canarygrass occurs in various wetlands, including marshes, wet prairies, wet meadows, fens, stream banks and swales (Hutchison, 1992). In the Pacific Northwest region of the U.S.A, reed canarygrass commonly occurs in low elevation wetlands, wet ditches, roadsides and river floodplains (Tu, 2004). Willow species are also generally associated with these habitat types. The results of our study indicate a successful technique for managing reed canarygrass in wetland sites where willows and reed canarygrass co-occur.

We demonstrated that planting live willow stakes cut from nearby plants can be an effective method to reduce aboveground biomass of reed canarygrass. The study site was representative of a transitional wetland area that contains soil moisture gradients from wet to dry. Results from this study illustrate how willow stake plantings might be used in similar wetlands with variable soil moisture content. Reed canarygrass typically forms dense stands along shores and streams in open areas at water depths no greater than 0.15 m (Lefor, 1987), and several willow species are capable of withstanding this water depth (Shields et al., 1995; Tsuyuzaki, 1997). Reed canarygrass occasionally forms large floating stems throughout open ponds with water depths of 0.9–2.7 m after being hydroseeded for erosion stabilization, and grows poorly in permanent standing open water of more than about 0.3 m (Lefor, 1987). Hence, willow planting does not need to be considered for reed canarygrass control at this depth.

4.5. *Willow planting as biological control and plant diversity*

Invasive-dominated ecosystems including exotics are the ultimate in self-organization, one of principles for ecological engineering (Kangas, 2004). Invasive species provide a serious challenge to environmental managers because of their explosive growth (Kangas, 2004; Correll, 2005). Reed canarygrass displays vigorous rhizomatous growth and prolific seed production (Kellogg et al., 2003), which facilitates the spread of this species, especially along major waterways where there may be no significant barriers to dispersal. Thus, reed canarygrass control in natural areas has been difficult to achieve (Apfelbaum and Sams, 1987). Willows plantings can be very effective in wetland environments because willows are adapted to wetlands and grow very quickly. Growth characteristics of willows and reed canarygrass are similar in terms of their fast growth and competitiveness in wetlands (Apfelbaum and Sams, 1987). Thorough site preparation to remove reed canarygrass before planting willows is required for initial establishment of willows as Antieau (2004) observed in wetland projects using other control measures. The live stake approach to reed canarygrass control may be particularly effective because it can use willows from adjacent wetlands. Additionally, our results suggest that live stakes result in significant control of reed canarygrass in only one or two growing seasons. Furthermore, live stake plantings that use genotypes from a nearby or similar environment may reduce the need for continued chemical herbicides (Hutchison, 1992) or soil-compacting mowing machinery (Paveglio and Kilbride, 2000) to obtain successful control. Our results suggest that plantings of willow live stakes can help restore wetland areas that have been overtaken by reed canarygrass.

In addition, willows can act as nurse crop for other understory plants by ameliorating high light, temperature and soil moisture (Dulohery et al., 2000; McLeod et al., 2001). Willows may benefit the wetland community within and near willows by such functions. Eight species (*Acer circinatum*, *Cornus sericea* ssp. *sericea*, *Epilobium ciliatum*, *Equisetum arvense*, *Galium aparine*, *Geranium carolinianum*, *Mycelis muralis*, *Urtica dioica* ssp. *gracilis* var. *lyallii*) other than reed canarygrass established into our study site after treatment. The lower reed canarygrass biomass may continue to increase abundance of other species. Although these are pioneer species with low cover after treatment, decline of reed canarygrass dominance by willow shading may increase plant diversity in this restored wetland ecosystem. Other wetland woody species have a possibility to control reed canarygrass by competition. More long-term studies are needed to investigate whether the willows favor other wetland species over reed canarygrass and examine whether other woody species except willows are effective to manage reed canarygrass.

5. Conclusions

Reed canarygrass growth was significantly reduced by willows grown from stakes. Willows at the 0.60 m planting density significantly diminished reed canarygrass biomass after the first growing season and willows at the 0.60 and 0.91 m planting densities significantly diminished reed canarygrass biomass after the second growing season. Based on our results, we conclude that live staking of willows at spacings of 0.60 m or 0.91 m can be an effective method for managing reed canarygrass in a wetland setting. In addition, willow leaf area index was significantly lower with low soil moisture than with moderate or high soil moisture, suggesting that reed canarygrass may become more competitive with willows as soil moisture content decreases.

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