Quantifying Competitive Ability of Perennial Grasses to Inhibit Scotch Broom

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Cover photos: Upper and lower photos, by Tim Harrington, were taken 72 and 113 days after sowing seeds of Scotch broom and grasses.

Abstract

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Greenhouse pot studies were conducted to quantify the competitive abilities of three native perennial grass species to inhibit development of Scotch broom (*Cytisus scoparius* (L.) Link) seedlings: spike bentgrass (*Agrostis exarata* Trin.), blue wildrye (*Elymus glaucus* Buckley), and western fescue (*Festuca occidentalis* Hook.). In single-species stands (1) soil water content decreased with increasing grass density, (2) soil water depletion per plant differed among species as ratios of 2.4:1.3:1 for bentgrass, fescue, and wildrye, respectively, and (3) average percentage of ground cover per plant was ranked by species as bentgrass (14 percent), wildrye (8 percent), broom (8 percent), and fescue (5 percent). Regression models predicted 90, 85, and 72 percent reductions in average biomass per plant of broom when grown with approximately 250 plants/m^2 of bentgrass, wildrye, and fescue, respectively. Bentgrass and wildrye were more competitive than fescue because of their early-season depletion of soil water and rapid development of cover.

Keywords: Addition series, induced competition, soil water content, biomass.

Summary

Scotch broom (*Cytisus scoparius* (L.) Link) is a nonnative shrub that has invaded savannah and woodland sites throughout the United States, Australia, and New Zealand. Greenhouse pot studies were conducted to evaluate the competitive abilities of three native perennial grass species to inhibit development of broom seedlings: spike bentgrass (*Agrostis exarata* Trin.), blue wildrye (*Elymus glaucus* Buckley), and western fescue (*Festuca occidentalis* Hook.). In separate addition series studies, four densities of broom seedlings were grown for 140 days with and without four densities of each grass species. In single-species stands (1) soil water content decreased with increasing grass density, (2) soil water depletion per plant differed among species as ratios of 2.4:1.3:1 for bentgrass, fescue, and wildrye, respectively, and (3) average percentage of ground cover per plant was ranked by species as bentgrass (14 percent), wildrye (8 percent), broom (8 percent), and fescue (5 percent). Regression models predicted 90, 85, and 72 percent reductions in average biomass per plant of broom when grown with 250 plants/m^2 of bentgrass, wildrye, and fescue, respectively. Bentgrass and wildrye were more competitive than fescue because of their early-season depletion of soil water and development of cover. The addition series approach provided a relatively simple method for quantifying competitive abilities of plant species being considered for grassland community restoration.

Perennial grasses suppressed cover and biomass development of Scotch broom seedlings by 72 percent or more.

One potential approach for restoring existing stands of broom to native grass communities uses a low-intensity disturbance to eliminate broom (e.g., manual cutting or spot treatment of herbicides) and stimulate abundance of associated competing vegetation to prevent broom regeneration. Grass seedlings are subsequently planted into natural or created small gaps within the plant canopy. A second potential approach uses prescribed fire to simultaneously (1) control existing broom, (2) reduce the broom seed bank, (3) reduce soil nitrogen content to favor perennial grasses, and (4) create a favorable seedbed for grass sowing.

Introduction

Scotch broom (*Cytisus scoparius* (L.) Link) is a large (1 to 3 m height) leguminous shrub that has become widely distributed in Australia, New Zealand, and 19 eastern and 8 western U.S. states (USDA NRCS 2010). A native to Western Europe, the species was first introduced in California in the 1850s as an ornamental (Gilkey 1957). Scotch broom's abundant production and prolonged viability of seeds enable it to occupy sites for decades (Bossard and Rejmánek 1994, Turner 1933). Seedlings grow vigorously to form dense stands that exclude native plants and alter community structure of savannahs, woodlands, and young forests (Bossard and Rejmánek 1994, Shaben and Myers 2009, Wearne and Morgan 2004). Effective herbicide treatments exist for controlling Scotch broom (Blair and Zedaker 2005, Ketchum and Rose 2003); however, restoration of native species must follow soon after treatment to prevent reestablishment of broom and other invasive plant species.

Scotch broom has extensively invaded areas within 19 eastern and 8 western U.S. states.

Induced competition has been tested as an approach to inhibit development of invasive species while restoring native species (Endress and others 2008, Middleton and others 2010, Vasquez and others 2008). The approach relies on concepts of integrated weed management (Holt 2004) and species' dominance (Denslow and Hughes 2004). Integrated weed management combines two or more strategies for preventing, suppressing, or controlling unwanted plants, and, thus, it overcomes the dominance potential of an invasive species. Restoration of native plant species limits subsequent invasion of nonnative species by mechanisms of competition and establishment limitation (Blumenthal and others 2005).

In this research, competitive abilities of three perennial grass species to inhibit development of Scotch broom seedlings were quantified in six addition series studies conducted in a greenhouse. The research tested the hypothesis that the grass species would differ in their ability to inhibit development of broom because of differences in timing and intensity of interspecific competition. Soil water depletion and plant growth were measured periodically in single-species stands to identify species' attributes of competitive ability. Periodic development of foliar cover and final biomass were measured in two-species stands to quantify competitive outcomes.

Methods
Experimental Design and Treatments

Greenhouse studies were conducted at the Olympia Forestry Sciences Laboratory from March through August 2007 to quantify the competitive abilities of spike bentgrass (*Agrostis exarata* Trin.), blue wildrye (*Elymus glaucus* Buckley), and western fescue (*Festuca occidentalis* Hook.) to inhibit development of Scotch

broom seedlings. These perennial grass species were chosen for study because they are native to extensive areas of the Western United States and differ in growth rate and size (Hitchcock 1971). Six addition series studies were conducted: three in which Scotch broom was grown at four densities with and without four densities of each grass species, and one for each grass species grown at four densities with and without four densities of broom (a total of 68 density combinations) (table 1). An addition series is a systematic study design that compares the competitive abilities of two or more plant species grown in mixture by varying the density and proportion of each species independently (Radosevich 1987, Spitters 1983).

Grass seeds were purchased from a local vendor (Silver Falls Seed Company, Silverton, Oregon[1]), and broom seeds were collected in summer 2006 from roadside plants near Olympia, Washington. To ensure maximum rates of germination, broom seeds were soaked in deionized water for 24 hours at room temperature (21 °C) and then subjected to cold stratification for 30 days at 5 °C (Harrington 2009). Standard germination tests were conducted for each species to estimate sowing rates needed to create the desired range of seedling densities. Seeds of each species were sown in 6.1-L plastic pots (0.22-m top diameter) on 26 March. The growth medium consisted of potting soil (Sunshine mix #2, Sun-Gro Horticulture Distribution Inc., Bellevue, Washington) supplemented with additional perlite at 30 percent of the total volume. A fixed weight of growth medium was added to each pot. On 23 May, 58 days after sowing seeds, seedlings were removed from or transplanted into each pot as required to create a set of systematic densities for each addition series study. At the time of transplanting, seedlings had achieved limited development; broom seedlings still had cotyledons present and had begun to form their first set of true leaves, and the grass species were at the two- to three-leaf stage.

Plant densities in each addition series study were replicated three times in a randomized complete block design with blocking based on location within the greenhouse. Pots were watered every 3 to 7 days with an automated drip-irrigation system (model CO32, DIG Corporation, Vista, California). Fertilizer (Sunshine Technigro water soluble fertilizer, 20N 18P 18K with micronutrients, Sun-Gro Horticulture Distribution Inc., Bellevue, Washington) dissolved in water to create a nitrogen concentration of 100 ppm was applied every 2 weeks at the rate of 100 ml per pot. The objective of the irrigation and fertilizer treatments was to provide each pot the same amount of water and nutrients at a rate likely to sustain normal

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[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 1—Plant densities for addition series studies of Scotch broom grown with each of three perennial grass species

Species	Grass density	Scotch broom density					
		– – – – – – – – Plants per pot – – – – – – – –					
		0	1	2	3	4	5
Scotch broom	0		x	x	x	x	x
Spike bentgrass	1	x					
	4	x		x	x	x	x
	8	x		x	x	x	x
	12	x		x	x	x	x
	16	x		x	x	x	x
Blue wildrye	1	x					
	3	x		x	x	x	x
	5	x		x	x	x	x
	7	x		x	x	x	x
	9	x		x	x	x	x
Western fescue	1	x					
	3	x		x	x	x	x
	6	x		x	x	x	x
	9	x		x	x	x	x
	12	x		x	x	x	x

plant development. To quantify species' differences in soil water depletion, weight of each pot containing single-species stands was measured immediately prior to scheduled irrigation on 7 June, 5 July, and 10 August, corresponding to 73, 101, and 137 days after sowing, respectively. Volumetric water content was calculated after accounting for the weights of dry soil and the container; weight of plant biomass (<5 percent of total) was not included in these calculations.

Projected foliar cover (nearest 5 percent) of each species was estimated visually within the perimeter of each pot at 73, 101, and 137 days after sowing. Average canopy height (nearest centimeter) of each species also was measured on the same three dates. Broom height was calculated as the mean of individual seedling heights in each pot. On 13 August, 140 days after sowing seeds, seedlings in each pot were counted by species and their aboveground biomass was collected, dried to a constant weight at 65 °C, and weighed (nearest 0.01 g).

Statistical Analysis

All statistical analyses were conducted by using SAS (SAS Institute 2005) with a significance criterion of $\alpha = 0.05$. Average values per plant of foliar cover and aboveground biomass were calculated by species for each pot. For single-species stands having three plants per pot (four plants per pot for spike bentgrass), the three

periodic measurements of cover and height were pooled and each variable was subjected to a repeated-measures analysis of variance (ANOVA) in the MIXED procedure to test for potential differences among species, measurement dates, and their interaction. If ANOVA indicated significant ($p \leq 0.05$) effects for a given factor or factor interaction, multiple comparisons of species' least-squares means within each measurement date were conducted with Tukey's Honestly Significant Difference test with probabilities adjusted to control the type I error rate (Quinn and Keough 2002). Prior to ANOVA, an angular transformation (i.e., arc-sine, square-root) was applied to the cover values (expressed as proportions) and a logarithmic transformation was applied to the height values to homogenize their residual variances (Sokal and Rohlf 1981).

To compare rates of soil water depletion among species, relations of soil water content to density of single-species stands were tested with linear regression in the REG procedure. An angular transformation was applied to soil water content and a logarithmic transformation was applied to density to linearize the relations prior to regression. The slope of the regression can be interpreted as a relative measure of soil water depletion by a single plant of a given species. Relative ability to deplete soil water was compared among species by calculating ratios of the regression slopes to the slope of lowest value.

To quantify effects of intra- and interspecific competition on cover and biomass of a given species, data from each addition series study were subjected to stepwise linear regression in the REG procedure to fit the following logarithmic model (Kira and others 1953):

$$Y = A_0 + A_1(\ln G) + A_2(\ln B)$$

Where Y = average cover or biomass per plant (g) of the focal species,
A_{0-2} = regression coefficients to be estimated,
G = density of the associated grass species (plants per pot), and
B = density of Scotch broom (plants per pot).

An angular transformation was applied to cover and a logarithmic transformation was applied to biomass to linearize the relations prior to regression. To include treatments in the analysis for which B or G equaled zero, the value 1 was added to each density variable prior to converting it to natural logarithms. Separate regressions of cover were conducted for each measurement date to quantify species' differences in timing and intensity of competition. The regression intercept, A_0, can be interpreted as the average cover or biomass of a single, isolated plant of the focal species. The regression slopes, A_1 and A_2, can be interpreted as the competitive effects of a single grass plant and a single broom plant, respectively. Relative

competitive ability was compared among species by calculating ratios of the regression slopes to the slope of lowest value. Biomass predictions from the regression equations were adjusted with a log-bias correction (Sprugel 1983). Residuals from each ANOVA and regression were plotted against predicted values to check for nonhomogeneous variances.

Results

Species' Differences in Soil Water Depletion

At 73 days after sowing, soil water content was negatively related to density of single-species stands of spike bentgrass and blue wildrye (table 2, fig. 1). Negative relations also were observed for bentgrass and western fescue on day 101, but the relations were not significant for any species on day 137 because of increased variation in soil water content. The regression of soil water content versus Scotch broom density was not significant for any measurement date ($F_{[1,13]} \leq 0.96$; $p \geq 0.345$). Species differed in their ability to deplete soil water as ratios of the regression slopes (A_1) of 2.4:1.3:1 for bentgrass, fescue, and wildrye, respectively.

Per-plant depletion of soil water from bentgrass was about twice that from fescue or wildrye.

Species' Differences in Growth

Average foliar cover per plant in single-species stands of three plants per pot (four plants per pot for spike bentgrass) differed according to the main effects of species ($F_{[3,22]} = 3.10$; $p = 0.047$) and measurement date ($F_{[2,22]} = 53.14$; $p < 0.001$), but the interaction of species by date was not significant ($F_{[6,22]} = 0.78$; $p = 0.59$). When

Table 2—Regression models for predicting soil water content in single-species stands of spike bentgrass, blue wildrye, and western fescue at 73 and 101 days after sowing

Species	Days	Regression coefficients		R^2	$s_{y.x}$	n
		A_0	A_1			
Spike bentgrass	73	0.861	-0.098	0.51	0.10	15
	101	0.740	-0.156	0.48	0.17	15
Blue wildrye	73	0.867	-0.065	0.28	0.09	15
Western fescue	101	0.774	-0.086	0.29	0.13	14

Note: Each regression coefficient is significant ($p \leq 0.05$). Model predictions are illustrated graphically in figure 1. The regression model tested for each species was: $Y = A_0 + A_1(\ln D)$, where Y is volumetric soil water content (proportionate value transformed to arc-sine, square-root) and D is density of grass (plants per pot). $S_{y.x}$ is the standard error of the estimate.
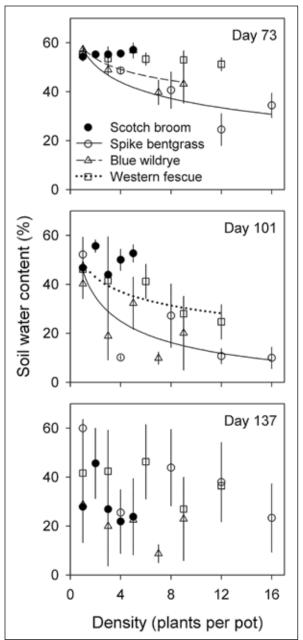
Figure 1—Average values (± SE) and regression model predictions of soil water content as affected by plant density in single-species stands of Scotch broom, spike bentgrass, blue wildrye, and western fescue at 73, 101, and 137 days after sowing. Regression statistics are given in table 2.

averaged across measurement dates, cover was ranked by species as spike bentgrass (14 percent), blue wildrye (8 percent), Scotch broom (8 percent), and western fescue (5 percent); however, only values for bentgrass and fescue differed significantly ($p = 0.029$). When averaged across species, cover differed at 73 (4 percent), 101 (9 percent), and 137 (15 percent) days after sowing ($p \leq 0.001$).

Canopy height varied according to the interaction of species by measurement date (fig. 2; $F_{[6,22]} = 7.33$; $p < 0.001$). On day 73, wildrye height (27 cm) was greater than that of fescue (12 cm) ($p = 0.002$), and on day 137, broom height (45 cm) was
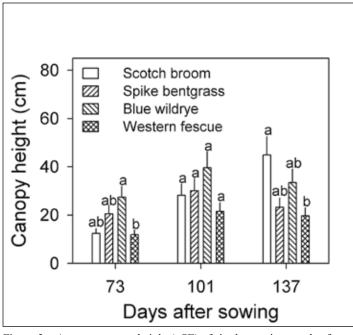
Figure 2—Average canopy height (±SE) of single-species stands of Scotch broom, spike bentgrass, blue wildrye, and western fescue at 73, 101, and 137 days after sowing. Difference in letters indicates means that differed significantly for each measurement date ($p \leq 0.05$).

greater than that of fescue (20 cm) ($p = 0.002$). Although broom started as the shortest species, it was the tallest species at completion of the research. Height of the grass species declined 2 to 7 cm from day 101 to day 137 as flowering and seed maturity occurred, causing the culms to bend.

Species' Differences in Competitive Ability

Average cover per plant of Scotch broom had negative relations with density of spike bentgrass and blue wildrye (table 3). These relations were first detected on day 73 and continued for the duration of the research. Broom cover also had negative relations with density of fescue on days 101 and 137. In general, the regression slopes (A_1) became increasingly negative over time with concomitant increases in the coefficient of determination (R^2), indicating increasing intensity of interspecific competition from the grass species. On day 137, grass species differed in their ability to competitively inhibit cover of broom as ratios of the regression slopes (A_1) of 1.3:1.2:1 for bentgrass, wildrye, and fescue, respectively. Effect of intraspecific competition from broom was detected on day 137 in the addition series studies with bentgrass and wildrye, but for fescue, the effect was only marginally significant ($F_{[1,60]} = 3.97$; $p < 0.051$); the effect from broom was greater when grown with wildrye ($A_2 = -0.148 \pm 0.05$ SE) than with bentgrass ($A_2 = -0.131 \pm 0.05$ SE).

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Table 3—Regression models for predicting average cover per plant of Scotch broom, spike bentgrass, blue wildrye, and western fescue at 73, 101, and 137 days after sowing

Focal species	Associated species	Days	Regression coefficients			R^2	$s_{y.x}$	n
			A_0	A_1	A_2			
Scotch broom	Spike bentgrass	73	0.188	-0.029	—	0.16	0.07	63
		101	0.265	-0.067	—	0.51	0.07	63
		137	0.555	-0.098	-0.131	0.53	0.11	63
Scotch broom	Blue wildrye	73	0.246	-0.064	—	0.07	0.07	63
		101	0.272	-0.059	—	0.26	0.09	63
		137	0.593	-0.092	-0.148	0.45	0.11	62
Scotch broom	Western fescue	73	—	—	—	—	—	63
		101	0.278	-0.048	—	0.20	0.09	63
		137	0.391	-0.074	—	0.24	0.13	63
Spike bentgrass	Scotch broom	73	0.413	-0.072	—	0.54	0.04	63
		101	0.592	-0.125	—	0.73	0.04	63
		137	0.680	-0.151	—	0.73	0.05	63
Blue wildrye	Scotch broom	73	0.229	-0.035	—	0.10	0.04	63
		101	0.458	-0.115	-0.024	0.57	0.05	63
		137	0.526	-0.110	-0.032	0.48	0.06	63
Western fescue	Scotch broom	73	0.181	-0.029	—	0.12	0.04	63
		101	0.339	-0.078	—	0.26	0.07	63
		137	0.527	-0.138	—	0.35	0.10	63

— = Regression coefficient not significantly different from zero ($p > 0.05$).
Note: Each regression coefficient is significant ($p \leq 0.05$). The regression model tested for each addition series study was: $Y = A_0 + A_1(\ln G) + A_2(\ln B)$, where Y is average cover per plant (proportionate value transformed with arc-sine, square-root) of the focal species and G and B are densities of grass and Scotch broom (plants per pot), respectively. The value 1 was added to each density variable before transforming to natural logarithms. $S_{y.x}$ is the standard error of the estimate.

Average cover per plant of each grass species had a negative relation with its own density (i.e., intraspecific competition effect, A_1) for each of the measurement dates (table 3). On day 137, intraspecific competition effects differed among grass species as ratios of the regression slopes (A_1) of 1.4:1.3:1 for bentgrass, fescue, and wildrye, respectively. Interspecific competition effect of broom on wildrye was detected on days 101 and 137; however, the magnitude of the effect ($A_2 = -0.024$ and -0.032) was only 21 to 29 percent of that from intraspecific competition ($A_1 = -0.115$ and -0.110). Interspecific competition effects of broom on bentgrass and fescue were not significant ($p \geq 0.103$ and $p \geq 0.072$, respectively).

Biomass values for single, isolated plants of wildrye, bentgrass, fescue, and broom averaged 20, 13, 8, and 6 g, respectively (calculations included back-transforming the regression intercept, A_0 in table 4, and applying the log-bias correction). Interspecific competition effect of grass on broom biomass differed among species as ratios of the regression slopes (A_1) of 1.8:1.5:1 for bentgrass, wild-rye, and fescue, respectively; however, intraspecific competition effect of broom

Table 4—Regression models for predicting average biomass per plant of Scotch broom, spike bentgrass, blue wildrye, and western fescue at 140 days after sowing

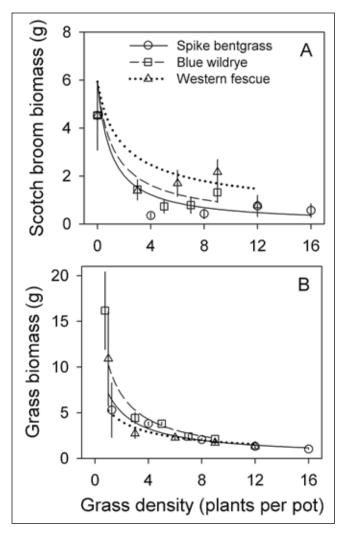| Focal species	Associated species	Regression coefficients		R^2	$s_{y.x}$	n
		A_0	A_1			
Scotch broom	Spike bentgrass	0.539	-0.984	0.31	1.58	61
Scotch broom	Blue wildrye	0.779	-0.806	0.20	1.41	63
Scotch broom	Western fescue	0.809	-0.545	0.13	1.39	63
Spike bentgrass	Scotch broom	2.487	-0.844	0.67	0.31	63
Blue wildrye	Scotch broom	2.846	-0.954	0.37	0.53	63
Western fescue	Scotch broom	1.840	-0.651	0.18	0.73	63

Note: Each regression coefficient is significant ($p \leq 0.05$). Model predictions are illustrated graphically in figure 3. The regression model tested for each addition series study was: $Y = A_0 + A_1(\ln G) + A_2(\ln B)$, where Y is average-plant aboveground biomass (grams transformed to natural logarithms) of the focal species, and G and B are densities of grass and Scotch broom (plants per pot), respectively. The value 1 was added to each density variable before transforming to natural logarithms. $S_{y.x}$ is the standard error of the estimate.
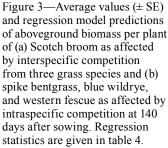
was not significant ($F_{[1,60]} \geq 0.33$; $p \geq 0.565$). The regression models predicted 90 percent, 85 percent, and 72 percent reductions in broom biomass when grown with 9 plants per pot (equivalent to approximately 250 plants/m^2) of bentgrass, wildrye, and fescue, respectively, relative to broom biomass in the absence of grass competition (fig. 3A).

Intraspecific competition effect on grass biomass differed among species as ratios of the regression slopes (A_1) of 1.5:1.3:1 for wildrye, bentgrass, and fescue, respectively (table 4, fig. 3B). However, interspecific competition effect of broom on grass biomass was not significant ($F_{[1,60]} \geq 3.22$; $p \geq 0.078$).

Discussion

The addition series studies provided a common experimental approach for quantifying and comparing the competitive abilities of several grass species to inhibit development of Scotch broom seedlings. Despite periodic irrigation every 3 to 7 days, soil water content developed a negative relation with density of each grass species. During the first 101 days of the experiment, soil water varied consistently with grass density. In the remaining 39 days of the experiment (July and early August), the frequency of irrigation was increased to meet evapotranspiration demands. Near the end of the experiment (day 137), soil water content was not significantly related to plant density. Two possible explanations may account for this declining correlation with time. First, increases in irrigation frequency may have exceeded evapotranspiration demands, resulting in similar soil water content among plant

Figure 3—Average values (± SE) and regression model predictions of aboveground biomass per plant of (a) Scotch broom as affected by interspecific competition from three grass species and (b) spike bentgrass, blue wildrye, and western fescue as affected by intraspecific competition at 140 days after sowing. Regression statistics are given in table 4.

The most competitive grass species, bentgrass, had the greatest rates of cover development and soil water depletion.

densities. Second, with maturity and flowering of the grass species, plant demand probably decreased, resulting in an accumulation of soil water for all plant densities.

For a given measurement date, the per-plant rate of soil water depletion from bentgrass (i.e., regression slope, A_1) was about twice that observed from wildrye or fescue. Average cover per plant of bentgrass (14 percent) was almost twice that of wildrye (8 percent) and almost three times that of fescue (5 percent). In addition, the absence of a significant interaction of species by measurement date for cover indicates that species' rankings in cover did not change during the study. In combination, these results suggest that differences in soil water depletion among species can be partially explained by their intrinsic rates of cover development.

Another attribute that explained differences in competitive ability among the grass species was the timing at which competitive effects were first detected.

Significant relations between soil water content and plant density were detected for bentgrass and wildrye on day 73, whereas a significant relation for fescue was not detected until day 101. Similarly, the regression analyses of plant cover indicated that competitive effects of bentgrass and wildrye on Scotch broom were detected on day 73, whereas the competitive effect for fescue was not detected until day 101. Height development of fescue also lagged behind those of the other species for the duration of the research. Despite these differences in competitive attributes, each of the three grass species competed effectively with Scotch broom to strongly inhibit development of seedlings. Reductions in broom biomass did not change appreciably as grass density exceeded four plants per pot, equivalent to 109 plants/m^2, indicating that a threshold in competition had been reached above which diminishing effects of interspecific competition were observed (fig. 3A).

An important question stimulated by the research was whether broom competition would ultimately exclude these grass species. Interspecific competition effect of broom on grass cover was only detected for wildrye. For this grass species, interspecific competition effect of broom was less than a third of intraspecific competition effect of grass, suggesting that broom is unlikely to competitively exclude grass, at least within the period of this research. Interspecific competition effect of broom on bentgrass cover was not significant perhaps because average cover per plant of bentgrass (14 percent) was almost twice that of broom (8 percent), whereas the other grass species had average covers (5 to 8 percent) similar to that of broom.

Caution should be observed when extrapolating the short-term results of this research to longer term application in restoration of perennial grasses. Because Scotch broom is a nitrogen fixer, it has the potential to alter soil chemical properties and thereby potentially shift competitive outcomes. In savannah communities of the Pacific Northwest and Australia, researchers have identified increases in soil carbon and nitrogen contents following invasion of broom, attributable to its abundant litter production and nitrogen fixation (Caldwell 2006, Fogarty and Facelli 1999, Haubensak and Parker 2004). Such soil conditions are believed to favor continued recruitment of broom (Fogarty and Facelli 1999) and place perennial grasses at a disadvantage in the plant community (Redente and others 1992, Vasquez and others 2008).

Restoring perennial grasses to broom-invaded sites involves a two-step process that first eliminates existing broom plants and then facilitates establishment of native grasses. The best method for removing broom without increasing its regeneration appears to be one that stimulates abundance of associated competing vegetation. For example, within its native range in France, broom abundance was substantially lower 3 years after cutting mature plants than after cutting was

combined with soil tillage primarily because abundance of associated competing vegetation, relative to the uncut broom stand, was increased by cutting alone and decreased by cutting plus tillage (Paynter and others 1998). On broom-invaded sites in Australia, an identical comparison of treatments resulted in no differences in broom abundance 6 years later because the treatments did not significantly change abundance of competing vegetation (Sheppard and others 2002). One approach for establishing perennial grasses without reducing abundance of associated vegetation is to plant either bare-root or containerized seedlings within natural or created small gaps in the canopy of the intact plant community (Middleton and others 2010).

Prescribed fire can be used to control existing Scotch broom plants, reduce the number of soil-stored seeds, and create a seedbed for sowing perennial grasses.

Alternatively, repeated application of prescribed fire could be used to control existing broom, restore soil nitrogen content of savannah soils to pre-invasion levels (Haubensak and others 2004), and create a seedbed in which to sow perennial grasses. Although fire may stimulate broom germination somewhat via seed scarification (Parker 2001), a single prescribed fire has been shown to reduce the initial flush of broom seedlings by as much as 68 percent (Haubensak and others 2004). Because broom is capable of germinating at relatively low temperatures (Bossard 1993, Harrington 2009), seeding of perennial grasses in autumn, as soon as possible after a prescribed fire, is likely to ensure their establishment at the same time or earlier than emergence of broom seedlings.

Conclusions

Competition from each of the grass species inhibited biomass development of Scotch broom seedlings by 72 to 90 percent. The most competitive species, spike bentgrass, was effective at depleting soil water early in the study. Bentgrass also had the greatest average cover per plant, which essentially prevented broom from developing competitive effects of its own. The least competitive species, western fescue, lagged behind the other two grass species in cover and height development and in the timing at which its competitive effects were first detected.

The addition series approach used in this research provided a relatively simple method for quantifying and comparing the competitive abilities of species being considered for restoration of plant communities. In this research, irrigation and fertilization were applied to each pot at a constant rate to provide a common test environment for quantifying competitive ability of individual species. Alternatively, the rate at which belowground resources are applied also could be manipulated to determine whether variation in resource availability affects species' competitive ability.

Acknowledgments

English Equivalents

When you know:	Multiply by:	To find:
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Square meter (m^2)	10.76	Square feet
Liters (L)	0.265	Gallons
Milliliters (ml)	0.0338	Ounces
Grams (g)	0.0022	Pounds
Degrees Celsius (°C)	1.8 °C + 32	Degrees Fahrenheit
Plants per square meter	0.0929	Plants per square foot

Literature Cited

Blair, M.P.; Zedaker, S.M. 2005. Evaluation of clopyralid, fluroxypyr, metsulfuron methyl, and triclopyr for Scotch broom control. Proceedings of the 7th annual meeting of Southeast Exotic Pest Plant Council. Birmingham, AL. http://www.se-eppc.org/2005/evaluationposter.cfm. (November 2, 2010).

Blumenthal, D.M.; Jordan, N.R.; Svenson, E.L. 2005. Effects of prairie restoration on weed invasions. Agriculture, Ecosystems, and Environment. 107: 221–230.

Bossard, C.C. 1993. Seed germination in the exotic shrub *Cytisus scoparius* (Scotch broom) in California. Madroño. 40: 47–61.

Bossard, C.C.; Rejmánek, M. 1994. Herbivory, growth, seed production, and resprouting of an exotic invasive shrub, *Cytisus scoparius*. Biological Conservation. 67: 193–200.

Caldwell, B.A. 2006. Effects of invasive scotch broom on soil properties in a Pacific coastal prairie soil. Applied Soil Ecology. 32: 149–152.

Denslow, J.S.; Hughes, R.F. 2004. Exotic plants as ecosystem dominants. Weed Technology. 18: 1283–1287.

Endress, B.A.; Parks, C.G.; Naylor, B.J.; Radosevich, S.R. 2008. Herbicide and native grass seeding effects on sulfur cinquefoil (*Potentilla recta*)-infested grasslands. Invasive Plant Science and Management. 1: 50–58.

Fogarty, G.; Facelli, J.M. 1999. Growth and competition of *Cytisus scoparius*, an invasive shrub, and Australian native shrubs. Plant Ecology. 144: 27–35.

Gilkey, H.M. 1957. Weeds of the Pacific Northwest. Corvallis, OR: Oregon State College. 441 p.

Harrington, T.B. 2009. Seed germination and seedling emergence of Scotch broom (*Cytisus scoparius*). Weed Science. 57: 620–626.

Haubensak, K.A.; D'Antonio, C.M.; Alexander, J. 2004. Effects of nitrogen-fixing shrubs in Washington and coastal California. Weed Technology. 18: 1475–1479.

Haubensak, K.A.; Parker, I.M. 2004. Soil changes accompanying invasion of the exotic shrub *Cytisus scoparius* in glacial outwash prairies of western Washington [USA]. Plant Ecology. 175: 71–79.

Hitchcock, A.S. 1971. Manual of the grasses of the United States. Volume 1. 2nd ed. (revised by A. Chase). New York: Dover Publications, Inc. 569 p.

Holt, J.S. 2004. Principles of weed management in agroecosystems and wildlands. Weed Technology. 18: 1559–1562.

Ketchum, J.S.; Rose R. 2003. Preventing establishment of exotic shrubs (*Cytisus scoparius* (L.) Link. and *Cytisus striatus* (Hill)) with soil active herbicides (hexazinone, sulfometuron, and metsulfuron). New Forests. 25: 83–92.

Kira, T.H.; Ogawa, H.; Sakizaki, N. 1953. Intraspecific competition among higher plants. I. Competition-yield-density interrelationship in regularly dispersed populations. Journal of the Institute of Polytechnics, Japan: Osaka City University. 7: 73–94.

Middleton, E.L.; Bever, J.D.; Schultz, P.A. 2010. The effect of restoration methods on the quality of the restoration and resistance to invasion by exotics. Restoration Ecology. 18: 181–187.

Parker, I.M. 2001. Safe site and seed limitation in *Cytisus scoparius* (Scotch broom): invasibility, disturbance, and the role of cryptograms in a glacial outwash prairie. Biological Invasions. 3: 323–332.

Paynter, Q.; Fowler, S.V.; Memmott, J.; Sheppard, A.W. 1998. Factors affecting the establishment of *Cytisus scoparius* in southern France: implications for managing both native and exotic populations. Journal of Applied Ecology. 35: 582–595.

Quinn, G.P.; Keough, M.J. 2002. Experimental design and data analysis for biologists. Cambridge, United Kingdom: Cambridge University Press. 537 p.

Radosevich, S.R. 1987. Methods to study interactions among crops and weeds. Weed Technology. 1: 190–198.

Redente, E.F.; Friedlander, J.E.; McLendon, T. 1992. Response of early and late seral species to nitrogen and phosphorus gradients. Plant and Soil. 140: 127–135.

SAS Institute. 2005. The SAS System for Windows, Version 9.1. Cary, NC.

Shaben, J.; Myers, J.H. 2009. Relationships between Scotch broom (*Cytisus scoparius*), soil nutrients, and plant diversity in the Garry oak savannah ecosystem. Plant Ecology. DOI: 10.1007/s11258-009-9655-7.

Sheppard, A.W.; Hodge, P.; Paynter, Q.; Rees, M. 2002. Factors affecting invasion and persistence of broom *Cytisus scoparius* in Australia. Journal of Applied Ecology. 39: 721–734.

Sokal, R.R.; Rohlf, J.F. 1981. Biometry. 2nd ed. San Francisco, CA: W.H. Freeman. 859 p.

Spitters, C.J.T. 1983. An alternative approach to the analysis of mixed cropping experiments. 1. Estimation of competition effects. Netherland Journal of Agricultural Science. 31: 1–11.

Sprugel, D.G. 1983. Correcting for bias in log-transformed allometric equations. Ecology. 64: 209–210.

Turner, J.H. 1933. The viability of seeds. Royal Botanic Gardens, Kew, England, Bulletin of Miscellaneous Information. 6: 257–269.

U.S. Department of Agriculture (USDA) Natural Resources Conservation Service. 2010. PLANTS database, Scotch broom, *Cytisus scoparius* (L.) Link. http://plants.usda.gov/java/profile?symbol=CYSC4. (November 2, 2010).

Vasquez, E.; Sheley, R.; Svejcar, T. 2008. Nitrogen enhances the competitive ability of cheatgrass (*Bromus tectorum*) relative to native grasses. Invasive Plant Science and Management. 1: 287–295.

Wearne, L.J.; Morgan, J.W. 2004. Community-level changes in Australian subalpine vegetation following invasion by the non-native shrub *Cytisus scoparius*. Journal of Vegetation Science. 15: 595–604.

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