Integration of soil moisture, xylem water potential, and fall–spring herbicide treatments to achieve the maximum growth response in newly planted Douglas-fir seedlings

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Abstract: Early in the establishment of Pacific Northwest Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantations, herbaceous vegetation can decrease seedling growth through competition for soil moisture during the dry summer months. This study was designed to statistically quantify soil moisture, seedling xylem water potential (Ψ), vegetation community, and seedling growth response to six herbicide treatment regimes commonly applied over the first 2 years of establishment. When compared with the control, soil moisture and seedling Ψ increased in response to reductions in competitive cover, allowing seedlings to extend productive growing time from 28 to 80 days. As a result, seedling volume growth increased from 56 cm^3 in the untreated control to greater than 250 cm^3 for the most intensive herbicide treatment regimes. Vegetation surveys revealed that treatment regimes had the potential to provide a disturbance, which could shift community composition from native to introduced species as the relationship decreased from 10:1 to 2:1. The most intense herbicide treatment regime reduced cover below 20%, retained soil moisture >30%, maintained predawn seedling Ψ above –1.0 MPa, and decreased height to diameter ratio below 50, increasing the likelihood of successful plantation establishment.

Résumé : Tôt, lors de l'établissement des plantations de douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) dans le Pacific Northwest, la végétation herbacée peut réduire la croissance des semis à cause de la compétition pour l'humidité du sol pendant les mois secs d'été. Cette étude a été conçue pour quantifier statistiquement l'humidité du sol, le potentiel hydrique (Ψ) du xylème des semis, la communauté végétale et la réaction en croissance des semis à six régimes de traitement avec des herbicides communément appliqués pendant les deux premières années d'établissement. Comparativement au témoin, l'humidité du sol et le potentiel hydrique des semis ont augmenté en réaction à la réduction de la compétition, ce qui a permis aux semis d'allonger leur période de croissance productive de 28 à 80 jours. La croissance en volume des semis a par conséquent augmenté de 56 cm^3 dans le cas du témoin non traité à plus de 250 cm^3 dans le cas du régime le plus intensif de traitement avec des herbicides. Les inventaires de végétation ont révélé que les régimes de traitement avaient la possibilité de provoquer une perturbation qui pouvait modifier la composition végétale en favorisant le remplacement d'espèces indigènes par des espèces introduites étant donné que le rapport entre les deux groupes d'espèces est passé de 10 : 1 à 2 : 1. Le traitement le plus intensif avec des herbicides a réduit le couvert en deçà de 20 %, a conservé l'humidité du sol au-dessus de 30 %, a maintenu le potentiel hydrique de base des semis au-dessus de –1,0 MPa et a diminué le rapport entre la hauteur et le diamètre à moins de 50, augmentant ainsi les chances que l'établissement de la plantation soit un succès.

[Traduit par la Rédaction]

Introduction

Harvesting merchantable trees causes disturbance to both the forest canopy and floor, thereby, changing the growing conditions as well as the structure and composition of the remaining vegetation community. Harvest activities result in light, temperature, and moisture conditions that promote the establishment of plants other than the desired crop tree species (Dyrness 1973; Halpern 1989; Balandier et al. 2006). These plants are often considered weeds from the standpoint of tree establishment and growth (Radosevich and Holt 1984) and are capable of capitalizing on disturbed conditions by rapidly establishing themselves, persisting for long periods of time, and directly competing with tree seedlings for limited site resources (Walstad and Kuch 1987; Halpern 1989; Balandier et al. 2006).

Soil moisture availability is a prime factor limiting plant growth in areas with a Mediterranean climate like the Pacific Northwest (PNW) (Newton and Preest 1988; Powers and Reynolds 1999). Heavy competition from herbaceous vegetation during the summer months can limit soil moisture availability and reduce xylem water potential (Ψ) of planted seedlings (Petersen et al. 1988; Zutter et al. 1986; Nambiar and Sands 1993; Löf 2000). Early herbaceous vegetation control through the application of herbicides has been shown to improve seedling growth (Lauer et al. 1993; Rose and Rosner 2005; Rosner and Rose 2006), increase soil moisture

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availability (Petersen et al. 1988; Powers and Reynolds 1999), and increase seedling Ψ (Cleary 1971; Petersen et al. 1988; Nambiar and Sands 1993).

The critical period concept states that vegetation control for a specified number of years during plantation establishment will minimize reductions in seedling growth (Wagner et al. 1996; Rose et al. 1999; Wagner 2000). The application of herbicides is a common management tool that causes a temporary reduction in the amount of competitive vegetation, thereby allowing seedlings to capture site resources and maximize early growth. However, herbicidal effects are not permanent (Chen 2004); treated areas are reinvaded by vegetation, necessitating follow-up applications until seedlings become dominant on the site. Forest managers in the PNW apply site-specific herbicide regimes that may consist of a fall site preparation and a spring release during successive years as needed (Lauer et al. 1993; Balandier et al. 2006).

Vegetation management literature has not formally tested some of the links between the regimes used to establish PNW Douglas-fir plantations and the growing conditions they are intended to create. Quantifiable results are needed that demonstrate how the regimented use of herbicides minimizes seedling competition for soil moisture. The current challenge facing forest managers is the need for a better understanding of the relationships among soil moisture, seedling Ψ, the vegetation community, and Douglas-fir growth during the critical first and second years after planting. The objectives of this study were to (*i*) statistically test Douglas-fir seedling growth response to six herbaceous vegetation control regimes spanning a range of fall–spring management options, (*ii*) chronicle changes to the early-seral vegetation community resulting from herbicide use, and (*iii*) link intensively measured soil moisture and seedling Ψ parameters to the fall–spring herbicide regimes.

Materials and methods

Site description

The study site is located 8 km southwest of Oakville, Washington (46°49′15″ N, 123°16′ 34″ W), on Washington Department of Natural Resources land. The unit has a west-facing aspect and is at 135 m (440 ft.; 1 foot = 0.304 8 m) in elevation with a mean Douglas-fir site index of 41 m (135 ft.) at 50 years (WDNR 2006). The previous stand was harvested in the spring of 2005 and was composed of red alder (*Alnus rubra* Bong.) (462 trees/ha) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (3.2 trees/ha) (WDNR 2006). The average annual precipitation is 145 cm (57.4 in.; 1 in. = 25.4 mm), with only 11 cm (4.3 in.) occurring between July and September (University of Washington 2007). Soils are residuum weathered from sandstone and classified as fine-loamy, mixed, mesic Xeric Palehumults (Natural Resource Conservation Service 2007; WDNR 2006). Two soil pits were dug on the site to a depth of 1.5 m. Common to ultisols, an argillic horizon was encountered, which existed between a depth of approximately 50 and 70 cm. Plant roots encountered in these pits existed in the upper 35 cm (E.J. Dinger, unpublished data, 2006). Coarse tree roots were a notable exception, as they extended beyond the depth of the soil pit (E.J. Dinger, unpublished data, 2006).

Seedlings and treatments

Bare-root Douglas-fir (1+1) seedlings were grown at Webster Nursery (WDNR) in Olympia, Washington, from improved seed. To minimize seedling variability and maximize the potential for vigorous growth (Long and Carrier 1993), grading criteria were established based on height and stem diameter measurements taken from a random sample of 300 seedlings prior to lifting and sorting at the nursery. Based on this information, seedlings selected for this study were 35–55 cm in height and 7–9 mm in stem diameter. Herbicide treatments were selected based on information from local field foresters and were matched to the site's vegetation community. Herbicides were applied as tank mixes on five dates during the first 2 years of plantation establishment based on specific treatment regimes (Table 1).

Measurements

Because of the site's consistent aspect, one centrally located Hobo Microstation (model H21-002, Onset Computer Corporation, Bourne, Massachusetts) was installed to collect environmental data, including relative humidity, air temperature, rainfall, wind speed, and solar radiation.

On 24 March 2006, initial height and stem diameter at groundline were measured on all seedlings in the treatment plots. Seedling height and stem diameter were measured again at the end of the first and second growing seasons (15 October 2006 and 12 October 2007) to determine seasonal growth. Volume was calculated using the standard formula for the volume of a cone ($V = (\pi d^2 h)/12$), where d is the stem diameter and h is the height. Growth was calculated as the difference between the measurements taken on 24 March 2006 and those on 12 October 2007. Height to diameter ratio (HDR) was calculated as height divided by diameter.

Seven permanent 1 m radius vegetation survey subplots were established within each treatment plot using a stratified random approach. Total percent vegetation cover and percent cover by species was visually determined prior to each herbicide application and on 19 July 2006 and 16 August 2007 in all treatment plots (for a total of seven assessments). Hitchcock and Cronquist (1973) as well as Pojar and MacKinnon (2004) were used as reference material during identification and to compile information about vegetative growth habits (forb, grass-like, fern, shrub, vine/shrub, shrub/tree, and tree; see Table 2), origin (native or introduced), and lifespan duration (annual, biennial, or perennial). When plants were immature and could not be positively identified to species, they were included at the family or genus level. Forbs that were present only as cotyledons and could not be reliably identified at the time of survey were designated as an "unknown forb."

Soil volumetric moisture content (m^3 H_2O/m^3 soil) was measured using a Hydrosense time domain reflectometer (TDR) soil moisture probe with 20 cm prongs (model CS-620 Spectrum Technologies, Plainsfield, Illinois). Point estimates of soil volumetric moisture content were made immediately outside every vegetation subplot on an approximate biweekly basis from May to October in 2006 and 2007 (21 sample dates: 12 in 2006 and 9 in 2007).

Table 1. Description of the six herbicide treatment regimes (A), as well as application date, method, chemicals (both trade and common names), and rate (B).

(A) Treatment regimes.

Treatment		Description	
No.	Year 1/Year 2	Year 1 (2006)	Year 2 (2007)
1	–/–	No control	No control
2	F/–	Fall site preparation	No control
3	F/S	Fall site preparation	Spring release
4	FS/S	Fall site preparation and spring release	Spring release
5	FSG/S	Fall site preparation, spring release, glyphosate release	Spring release
6	FSG/SG	Fall site preparation, spring release, glyphosate release	Spring release, glyphosate release

(B) Herbicides applied.

			Chemicals		
Treatment	Date	Method	Trade name	Common name	Rate
Fall site preparation	20 September 2005	Broadcast	Chopper®	Imazapyr	2.3 L/ha
			Accord concentrate®	Glyphosate	3.5 L/ha
			Hasten®	Surfactant	9.4 L/ha
			Syl-Tac®	Surfactant	292.2 mL/ha
Spring release	12 April 2006	Broadcast	Atrazine 90 WSP®	Atrazine	4.9 kg/ha
			Transline®	Clopyralid	0.58 L/ha
			Garlon 4®[a]	Triclopyr	20%
			Basal oil[a]	Petroleum oil	80%
Glyphosate release	20 June 2006	Direct spot-spray	Accord concentrate®	Glyphosate	2%
			Accord concentrate®[a]	Glyphosate	75%
Spring release	30 March 2007	Broadcast	Atrazine 90 WSP®	Atrazine	4.9 kg/ha
			Transline®	Clopyralid	0.58 L/ha
Glyphosate release	29 June 2007	Direct spot-spray	Accord concentrate®	Glyphosate	2%

[a]Chemicals directly applied to stumps in all plots for control of sprouting species *Alnus rubra* and *Acer macrophyllum*. Treatment regimes (F, S, and G) were applied as a tank mix in the plots designated for chemical application.

In 2006, soil cores were taken on the 10 measurement dates from 6 June to 16 October, using an AMS core sampler with a slide hammer (AMS Inc., American Falls, Idaho). Sampling was done in all treatment plots occurring in two blocks, which ensured that all treatments had two samples on any given measurement date. Blocks 1/3 and 2/4 were sampled alternately, allowing soil cores to be taken five times from every plot on the site during the 2006 season on an approximately monthly basis. The cores were taken horizontally from a 10 cm depth. The sample was then weighed, dried for 48 h at 41 °C in a laboratory oven, and reweighed. Bulk density and volumetric soil moisture were calculated from this information. Regression analysis (Statistical Analysis Software, version 9.1, Cary, North Carolina) was used to compare the soil volumetric moisture content for a plot (x), which is the mean of the seven measurements provided by the Hydrosense TDR probe, with the soil core data (y) from the same plot on the same date. Cubic, quadratic, and linear forms were examined, and only parameters that were significant at α = 0.05 level were included in the final model. The sampling scheme provided adequate characterization of site volumetric soil moisture and produced the calibration equation $y = 0.06824 + 2.11875(x) - 3.20772(x^2)$, which had a R^2 of 0.6674. All Hydrosense TDR data was calibrated using this equation. Soil volumetric moisture content hence forward will be referred to as soil moisture.

Xylem water potential measurements were taken with a model 600 pressure chamber (PMS Instrument Company, Albany, Oregon) biweekly on the same sampling dates that soil moisture was measured. Two seedlings were randomly selected from every plot and sampled at predawn (0400–0600) and midday (1200–1400). One 8 cm length of a branch occurring in the middle-third of the seedling's crown was cut at each sampling period for analysis of Ψ. After these two samples (predawn and midday) were collected on a measurement date, seedlings were not sampled again during that season to minimize damage. A reference to decreasing Ψ indicates that seedlings went from a high potential to a low potential for movement (e.g., moving from –0.4 to –1.5 MPa), whereas the opposite situation is referred to as an increase in Ψ.

Experimental design and statistical analysis

A randomized complete-block design was used to examine the six herbaceous vegetation control treatment regimes. Each treatment was replicated four times on 24.4 m × 24.4 m plots (80 ft. × 80 ft.) and established in September 2005. The site was planted by hand on 25 February 2006 with 1536 seedlings using a 3.05 m × 3.05 m (10 ft. × 10 ft.) grid, which allowed 36 measurement trees (864) to be surrounded by a buffer row of seedlings (672) inside every plot. A perimeter fence was constructed to eliminate the potential for uneven browse damage from ungulate species.

Data were analyzed using Statistical Analysis Software,

Table 2. List of the 109 plants found on the study site grouped alphabetically according to vegetative growth habit.

Species								
Forb			Fern	Grass-like	Tree	Shrub/tree	Shrub	Vine/shrub
Adenocaulon bicolor	*Galium* spp.	*Smilacina* spp.	*Athyrium filix-femina*	Cyperaceae spp.	*Acer macrophyllum*	*Corylus cornuta*	*Berberis nervosa*	*Lonicera ciliosa*
Anaphalis margaritacea	*Galium parisiense*	*Smilacina racemosa*	*Polystichum munitum*	*Holcus lanatus*	*Alnus rubra*	*Rhamnus purshiana*	*Gaultheria shallon*	*Rubus laciniatus*
Asarium caudatum	*Galium triflorum*	*Smilacina stellata*	*Pteridium aquilinum*	*Juncus* spp.	*Prunus emarginata*	*Salix* spp.	*Oemleria cerasiformis*	*Rubus leucodermis*
Aster spp.	*Geranium molle*	*Sonchus asper*		*Lolium multiflorum*	*Pseudotsuga menziesii*	*Sambucus* spp.	*Ribes* spp.	*Rubus procerus*
Campanula spp.	*Gnaphalium* spp.	*Sonchus* spp. No. 1		*Luzula campestris*		*Sambucus racemosa*	*Rosa* spp.	*Rubus ursinus*
Cardimine nuttallii	*Hieracium albiflorum*	*Sonchus* spp. No. 2		Poaceae spp.			*Rubus parviflorus*	
Cardimine oligosperma	*Hypericum perforatum*	*Stellaria* spp.					*Rubus spectabilis*	
Cardamine spp.	*Hypochaeris radicata*	*Stachys rigida*					*Symphoricarpos albus*	
Caryophyllaceae spp.	*Hydrophyllum tenuipes*	*Thalictrum occidentale*					*Vaccinium parviflorum*	
Centaurea umbellatum	*Lactuca muralis*	*Trifolium dubium*						
Chrysanthemum leucanthemum	*Lactuca serriola*	*Trifolium* spp. No. 1						
Circaea alpina	Liliaceae spp.	*Trifolium* spp. No. 2						
Cirsium arvense	*Lotus* spp.	*Trillium ovatum*						
Cirsium vulgare	*Medicago* spp.	*Trifolium pratense*						
Conyaza canadensis	*Montia sibirica*	*Trifolium repens*						
Crepis capillaris	*Nemophila parviflora*	Unknown forb No. 1						
Dicentra formosa	*Osmorhiza chilensis*	Unknown forb No. 2						
Digitalis purpurea	*Phacelia nemoralis*	Unknown forb No. 3						
Epilobium angustifolium	*Ranunculus* spp.	Unknown forb No. 4						
Epilobium spp.	*Ranunculus uncinatus*	*Urtica dioica*						
Epilobium minitum	*Rumex acetosella*	*Vancouveria hexandra*						
Epilobium paniculatum	*Rumex crispus*	*Vicia* spp.						
Erechtites minutum	Saxifragaceae spp.	*Viola glabella*						
Fabaceae spp. No. 1	*Senecio jacobaea*	*Vicia hirsuta*						
Fabaceae spp. No. 2	*Senecio sylvaticus*	*Viola* spp.						
Galium aparine	*Senecio vulgaris*							

Note: "Unknown forb" indicates forbs that were present only as cotyledons and could not be reliably identified at the time of survey.

version 9.1 (SAS Institute Inc., Cary, North Carolina). ANOVA model assumptions of normality, linearity, and constant variance were examined on the residuals for each variable. Stem diameter and volume growth required a natural log transformation to meet ANOVA model assumptions. Unless otherwise noted, a significance level of $\alpha = 0.05$ was used on all statistical analysis. When analyses were completed by year (soil moisture and Ψ), treatments were analyzed separately even though during the first year (2006) treatments 2 and 3 as well as 5 and 6 were identical, since second-year herbicide applications had not yet been applied. ANOVA (Proc GLM) and Fisher's protected least significant difference t tests were used to test seedling growth, vegetation, soil moisture, and Ψ responses to herbicide treatments.

Statistical analysis was completed on the vegetation surveys occurring on 19 July 2006 and 16 August 2007 using treatment plot means for total vegetation cover. The composition of the vegetation community is presented through comparisons of the cover values associated with species growth habit as well as ratios of species origin and lifespan duration occurring on the 19 July 2006 and 16 August 2007 survey dates. The basis for these comparisons was developed through a two stage process. First, the mean percentage for each of the 109 plants was calculated by treatment as an average of the 28 times (seven subplots replicated four times) that a particular plant could occur in a treatment. Second, the 109 species cover means for a treatment regime on each survey date were summed based on common growth habit, species origin, or lifespan duration. The ecological response of the vegetation community to a specific treatment and its relationship to other treatments is shown by comparing these calculated cover values for growth habit (forb, shrub, tree, etc.) and the ratios for species origin (native divided by introduced) and lifespan duration (perennial divided by the sum of annual and biennial).

Volumetric soil moisture plot means were used to derive a cumulative soil moisture value by summing the means by plot across the measurement dates from May to October within each year. This resulted in two datasets (2006 and 2007) that had cumulative soil moisture values for each treatment plot. Data were analyzed separately by year.

Plot means for Ψ were calculated from the two samples taken on a particular date and time (predawn and midday). These means were then summed by treatment plot across each year (May to October), forming the cumulative Ψ values used in the analysis. Analysis was completed separately on cumulative predawn and cumulative midday Ψ values by year.

Orthogonal contrasts were designed to assess statistical differences among specific preplanned treatment comparisons. Increases in seedling growth occurring as a result of the treatments, cumulative soil moisture values in 2006 and 2007, and cumulative predawn and midday Ψ values in 2006 and 2007 were analyzed using the same set of five orthogonal contrasts. Contrast 1 tested for a general herbicide effect by comparing the no-action control with all other treatments receiving at least one application of herbicides. Contrast 2 compared treatments 2 and 3, which received minimal herbicide treatment, with the more intense treatments (4, 5, and 6). Contrast 3 compared treatment 4, which received a fall site preparation spray and two spring release applications, with treatments 5 and 6, which had additional glyphosate follow-up sprays. Contrasts 4 and 5 were designed to test for a significant difference between treatments that were similar in the first year of the study (2/3 and 5/6, respectively).

Results

While it has been well established that controlling competing vegetation improves Douglas-fir seedling growth, the data in this study shows (via biweekly measurements during two growing seasons) how critical rainfall is to seedling growth and soil moisture levels after treatment with six herbicide regimes. The most intense treatments over 2 years created the best growing environment (greater soil moisture and Ψ increased seedling volume) under limited precipitation in the first year, but did not make as much difference in the second year due to an extra 6 cm of precipitation over the summer season.

Seedling growth

After the first two seasons of establishment, seedling survival was 98.5% across all treatments on the site. Vegetation control treatment regimes significantly affected seedling height, stem diameter, and volume growth as well as HDR (Table 3 and Fig. 1). Seedling height growth after two growing seasons increased by 47%, from an average of 62.2 cm in the control plots to 91.3 cm in treatment 5 ($p < 0.0001$). Stem diameter growth of seedlings in treatments 2, 3, and 4 was between 37% and 104% greater than that of seedlings in the control plots. For treatments 5 and 6, the most intense in the study, stem diameter growth was more than twice that of seedlings in the control plots (Fig. 1).

Stem volume growth was 56.1 cm^3 for seedlings in the control. Applying treatment 2 increased volume growth by 33%, an increase to 74.8 cm^3. Treatments 3 and 4 had stem volume growth gains of 144% and 179%, respectively, over the control with a mean volume growth of 137.0 and 156.5 cm^3, respectively. There was no statistical difference between treatments 5 and 6, with volume growth increases of 296.7 and 256.2 cm^3, respectively, which is greater than a 355% improvement when compared with the control.

There was an inversely proportional relationship between the intensity of herbicide application and the HDR response ($p = 0.0013$). Seedlings in the control plots had an average HDR of 69, while the HDR of seedlings in treatments 2, 3, and 4, which received minimal to moderate amounts of vegetation control, decreased to 55. Seedlings grown under the influence of treatments 5 and 6 had high amounts of vegetation control and a mean HDR of 45.

Vegetation community

On 19 July 2006 and 16 August 2007, the various levels of herbicide use created ecological shifts in the composition of the vegetation communities through the introduction of secondary disturbances and significantly affected percent total vegetation cover ($p = <0.0001$, Table 3 and Fig. 2). Table 4 provides detailed information about the composition of these communities, demonstrating how species dominance changed in response to the treatment regimes.

Table 3. Analysis of variance for treatment effects after two growing seasons on seedling growth (height, stem diameter, volume, and height to diameter ratio in 2007), total percent vegetation cover on 19 July 2006 and 16 August 2007, and cumulative (Cum.) values of soil moisture and predawn and midday xylem water potential (Ψ).

Parameter	Source	df	Sums of squares	Mean square	*F* value	Pr > *F*[a]
Height growth	Block	3	109.6102	36.5367	0.74	0.5433
	Treatment	5	3 192.8074	638.5615	12.97	**<0.0001**
Stem diameter growth	Block	3	0.0476	0.0159	0.66	0.5881
	Treatment	5	3.4300	0.6860	28.61	**<0.0001**
Volume growth	Block	3	0.0996	0.0332	0.45	0.7239
	Treatment	5	8.5867	1.7173	23.06	**<0.0001**
Height to diameter ratio	Block	3	39.9937	13.3312	1.50	0.2541
2007	Treatment	5	1 626.1969	325.2394	36.69	**<0.0001**
Total vegetation cover						
19 July 2006	Block	3	85.2270	28.4090	0.63	0.6056
	Treatment	5	18 950.8511	3 790.1702	84.33	**<0.0001**
16 August 2007	Block	3	569.4320	189.8107	2.74	0.0803
	Treatment	5	12 938.3945	2 587.6789	37.29	**<0.0001**
Cumulative soil moisture						
2006	Block	3	0.0522	0.0174	0.86	0.4841
	Treatment	5	3.6937	0.7387	36.39	**<0.0001**
2007	Block	3	0.0171	0.0057	0.26	0.8495
	Treatment	5	1.7541	0.3508	16.32	**<0.0001**
Cumulative predawn Ψ						
2006	Block	3	1.3748	0.4583	2.06	0.1488
	Treatment	5	51.3802	10.2760	46.17	**<0.0001**
2007	Block	3	1.3342	0.4447	15.67	**<0.0001**
	Treatment	5	2.8150	0.5630	19.83	**<0.0001**
Cumulative midday Ψ						
2006	Block	3	27.2234	9.0745	32.91	**<0.0001**
	Treatment	5	32.5673	6.5135	23.63	**<0.0001**
2007	Block	3	1.2461	0.4154	3.92	**0.0300**
	Treatment	5	9.0993	1.8199	17.17	**<0.0001**

[a]The values in bold are significant at $\alpha = 0.05$.

On 19 July 2006, the control treatment had greater than 90% total vegetation cover (Fig. 2) and was dominated by native perennials with a variety of growth habits (Table 4). The fall site preparation only treatment resulted in approximately 40% total cover and shifted the vegetation community toward annual introduced forbs. Plant lifespan duration shifted as the relationship between perennials and the sum of annuals and biennials decreased to nearly a 1:1 ratio (Table 4). This also changed the ratio of native to introduced species from greater than 10:1 to a 2:1 relationship. The addition of a spring release herbicide application brought total cover below 20% (Fig. 2) minimizing the presence of introduced annuals to below 3%. The vegetation community in treatments 4, 5, and 6 was shifted back to a mixture of native perennials as the ratios ranged from 5:1 up to 71:1. The vegetation community had been greatly reduced in these plots such that the only species capable of growing were vine/shrub, fern, and a few forbs, which all had cover values below 6.5%. In addition, relatively low cover values in the denominator of these ratios were also responsible for the large observed shifts. A follow-up directed application of glyphosate further reduced total vegetation cover to below 10% in treatments 5 and 6, resulting in a similar community composition as that seen in treatment 4 (Table 4).

On 16 August 2007, the control had greater than 84% total vegetation cover and was dominated by native perennial species. The total percent vegetation cover in treatment 2 increased to 55% (Fig. 2). Introduced forb species continued to dominate these plots and were responsible for 41.8% of the cover at a nearly 1:1 native to introduced species ratio (Table 4). Despite being treated with a spring release, treatments 3, 4, and 5 responded with between 38% and 65% total vegetation cover, calling into question the efficacy of this application. Treatment 3 had a lower native to introduced species ratio at 4:1 when compared with treatments 4 and 5, which were approximately 18:1. Fast-growing perennial vine/shrub and tree species dominated treatments 4 and 5. When combined, these two components of the vegetation community were responsible for 57.8% and 36.1% of the cover, respectively (Table 4). The additional glyphosate application in treatment 6 reduced the growth of these species, resulting in less than 10% total cover (Fig. 2) of native perennial plants.

Soil moisture

In 2006, the summer drought period began approximately 15 June. For the next 92 days (until 15 September) the site received 1.2 cm of precipitation. The summer of 2007 did not have the same persistent drought conditions, with

Fig. 1. Treatment (Trt) effects on seedling growth after the initial two seasons of establishment. Back-transformed values are provided for seedling diameter and volume growth. Treatments with different letters are significantly different at $\alpha = 0.05$. Standard errors are 1 SE: height growth (3.51), seedling diameter growth (1.08), volume growth (1.15), and 2007 height to diameter ratio (1.51). An explanation of treatment regimes can be found in Table 1.

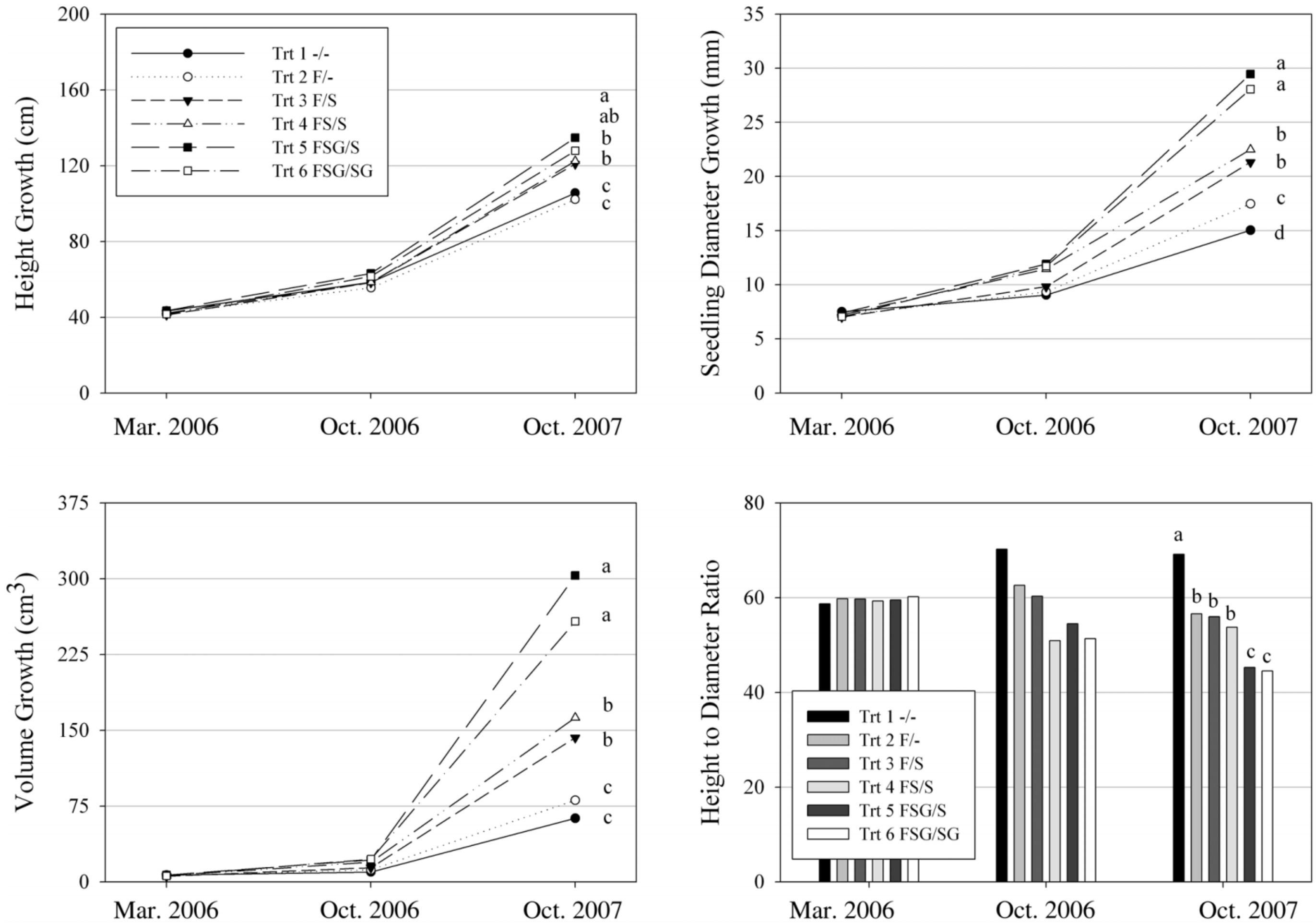

Fig. 2. Mean total percent vegetation cover by treatment across the survey dates. Treatment (Trt) means with different letters on the July 2006 (left graph) and August 2007 (right graph) survey dates are significantly different at $\alpha = 0.05$. Position of F (fall site preparation), S (spring release), and G (glyphosate follow-up) indicate approximate times when the herbicides were applied according to the treatment regimes. An explanation of treatment regimes can be found in Table 1.

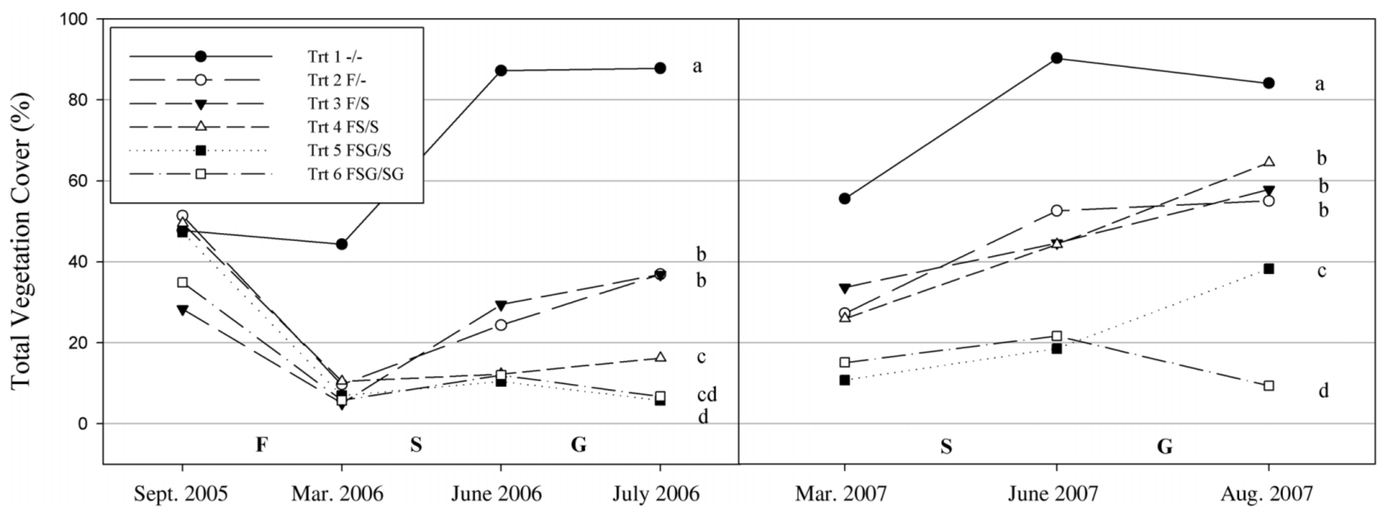

Table 4. Mean vegetation species percent cover by treatment and growth form, origin, and lifespan duration on the 19 July 2006 and 16 August 2007 survey dates.

		Mean percent cover for treatment[a]:					
		1	2	3	4	5	6
Characteristic	No. of species	–/–	F/–	F/S	FS/S	FSG/S	FSG/SG
Growth form							
19 July 2006							
Forb	77	17.1	26.0	27.9	4.7	1.3	1.9
Fern	3	23.9	5.2	3.1	4.8	2.5	3.4
Grass-like	6	2.9	1.0	0.9	0.4	0.1	0.1
Shrub	9	3.6	0.7	0.6	0.6	0.2	0.0
Shrub/tree	5	8.3	3.5	4.6	0.4	0.2	0.1
Tree	4	1.1	0.8	1.5	1.3	1.0	0.9
Vine/shrub	5	56.0	4.9	3.6	6.5	2.1	1.8
16 August 2007							
Forb	77	11.3	41.8	18.4	6.0	7.6	2.4
Fern	3	27.0	4.2	5.9	7.5	1.7	0.1
Grass-like	6	1.9	2.7	0.7	0.6	0.6	0.2
Shrub	9	4.1	1.7	2.3	1.2	0.5	0.1
Shrub/tree	5	5.7	10.5	8.7	4.6	2.7	0.4
Tree	4	2.2	7.2	18.6	16.9	13.9	3.4
Vine/shrub	5	64.1	12.6	26.5	40.9	22.2	5.0
Origin							
19 July 2006							
Native (N)	52	100.0	21.6	27.2	17.6	7.1	7.7
Introduced (I)	26	8.9	17.9	12.5	0.4	0.1	1.2
Other	31	3.9	2.8	2.5	0.6	0.2	1.3
N/I ratio		11.2	1.2	2.2	44.0	71.0	6.4
16 August 2007							
Native (N)	52	102.7	44.3	59.9	72.0	45.7	10.9
Introduced (I)	26	11.6	31.1	16.8	4.0	2.5	0.3
Other	31	2.0	5.2	4.4	1.6	1.0	0.5
N/I ratio		8.9	1.4	3.6	18.0	18.3	36.3
Lifespan duration							
19 July 2006							
Annual (A)	20	6.0	19.7	18.0	2.7	0.3	0.5
Biennial (B)	2	1.1	0.6	0.5	0.0	0.0	0.0
Perennial (P)	59	101.9	19.2	21.5	15.4	6.9	7.4
Other	28	3.9	2.6	2.3	0.5	0.2	0.3
P/(A+B) ratio		14.4	0.9	1.2	5.7	23.0	14.8
16 August 2007							
Annual (A)	20	1.2	11.8	2.5	1.9	3.1	0.6
Biennial (B)	2	0.5	5.5	0.5	0.0	0.0	0.0
Perennial (P)	59	112.6	58.4	75.5	74.9	45.1	10.6
Other	28	2.0	4.9	2.5	0.8	1.0	0.5
P/(A+B) ratio		66.2	3.4	25.2	39.4	14.5	17.7

Note: The percentage of cover for each weed species was averaged across a treatment creating a list of 109 means. Those means were then summed based on similar growth form, origin, or lifespan duration. For example, on 19 July 2006, the five species of plants classified as vine/shrubs had individual mean cover percentages that collectively were responsible for 56.0% of the vegetative cover found in the control treatments. Plants in the category "other" were not identified to a level where origin or lifespan duration could be clearly determined.

[a]Explanation of treatment regimes can be found in Table 1.

7.5 cm of precipitation falling over the same 92 day period. Seventy percent of this precipitation fell in two events, one in late June and the other in mid-August (Fig. 3).

Soil moisture was near field capacity (>0.34 m^3 H_2O/m^3 soil) until mid-June in 2006 and mid-May in 2007 (Fig. 3). After these dates, treatment regimes affected soil moisture. A rapid depletion of soil moisture in the control treatment occurred from 20 June to 7 July 2006. While the rate of deple-

Table 5. Treatment means over the initial two seasons of establishment for the cumulative values of soil moisture and predawn and midday xylem water potential (Ψ).

Treatment[a]		Cum. soil moisture (m^3 H_2O/m^3 soil)		Cum. predawn Ψ (MPa)		Cum. midday Ψ (MPa)	
No.	Year 1/Year 2	2006 (n = 12)	2007 (n = 9)	2006 (n = 12)	2007 (n = 10)	2006 (n = 12)	2007 (n = 10)
1	–/–	3.2d (0.08)	2.7c (0.07)	–9.1d (0.21)	–4.9c (0.15)	–18.9d (0.34)	–10.7c (0.23)
2	F/–	3.7c (0.02)	2.8bc (0.02)	–7.4c (0.33)	–4.5b (0.17)	–18.3cd (0.65)	–10.6c (0.19)
3	F/S	3.5c (0.06)	2.8bc (0.06)	–6.4b (0.18)	–4.4b (0.23)	–17.8c (0.67)	–10.5bc (0.27)
4	FS/S	4.1b (0.11)	3.0b (0.06)	–5.0a (0.13)	–4.3b (0.07)	–16.7b (0.80)	–10.0b (0.09)
5	FSG/S	4.2ab (0.06)	3.2a (0.08)	–5.1a (0.30)	–4.0a (0.14)	–15.8a (0.63)	–9.4a (0.19)
6	FSG/SG	4.3a (0.06)	3.4a (0.09)	–5.3a (0.33)	–3.8a (0.12)	–16.0ab (0.77)	–9.1a (0.18)

Note: Ten measurements of volumetric soil moisture were taken in 2007, but a sensor malfunction on 20 July 2007 prevented the inclusion of the data into the analysis. Cumulative values were derived by summing means for a particular measurement by plot across the sample dates within a year. Values within columns that have different letters are significantly different at α = 0.05. Standard errors are calculated by treatment over replications and are in parentheses.

[a]An explanation of treatment regimes can be found in Table 1.

tion slowed after this time, soil moisture in the control treatment continued to drop until reaching the lowest value (0.19 m^3 H_2O/m^3 soil) observed in the study on 8 September 2006. Similar treatment effects on soil moisture were observed in 2007, with the exception that depletions occurred earlier because of a dry spring and were not as pronounced because of higher summer precipitation. Soil moisture depletion in treatments 2 and 3 dropped at noticeably slower rates than the control during both years but by early to mid-August had dropped to similarly low levels as those seen in the control (<0.26 m^3 H_2O/m^3 soil in 2006 and ~0.29 m^3 H_2O/m^3 soil in 2007). Treatments with the most intensive vegetation control (4, 5, and 6) retained high levels of soil moisture (never dropping below 0.28 m^3 H_2O/m^3 soil) during the 2006 season (Fig. 3). In 2007, treatment 4 demonstrated a slower rate of soil moisture depletion until late August when it declined to levels similar to the control and treatments 2 and 3. Rains returned to the site on 15 September 2006 and 27 September 2007 replacing soil moisture in the upper profiles.

Treatment regimes significantly affected the cumulative soil moisture values during both seasons (p < 0.0001, Table 3). Cumulative soil moisture in the control plots was lower than all other treatment plots during both seasons (3.2 and 2.7 m^3 H_2O/m^3 soil in 2006 and 2007, respectively) (Table 5). Treatments 2 and 3 had similar cumulative soil moisture values during both years and were slightly higher compared with the control (treatment 2: 3.7 m^3 H_2O/m^3 soil in 2006 and 2.8 m^3 H_2O/m^3 soil in 2007; treatment 3: 3.5 m^3 H_2O/m^3 soil in 2006 and 2.8 m^3 H_2O/m^3 soil in 2007). In 2006, treatments 4, 5, and 6 showed marked improvements in cumulative soil moisture values (averaging 4.1–4.3 m^3 H_2O/m^3 soil) over the less intense treatments. This was less pronounced in 2007 (averaging 3.0–3.4 m^3 H_2O/m^3 soil) (Table 5).

Xylem water potential

Predawn Ψ measurements were greater than –0.5 MPa from May to July during both years (Fig. 3). The Ψ measurements decreased differently among the treatment regimes, beginning in early July for 2006 and in mid-August for 2007. Seedlings in the control treatment had the sharpest decrease and lowest potentials during both years (–1.5 MPa in 2006 and –0.7 MPa in 2007). In 2006, Ψ increased as vegetation cover was reduced to 20%. After this point, further reductions in total cover did not improve Ψ conditions. More consistent precipitation during the 2007 growing season alleviated the drought conditions and resulted in higher Ψ across all treatments when compared with the previous year. However, even though the magnitude of difference among the treatments was lower in 2007, Ψ patterns were similar to those observed in 2006 (Fig. 3).

Midday Ψ measurements did not begin to differentiate among the treatments until late July for 2006 and mid-August for 2007. After this point, there was a general increase in midday Ψ as the herbicide treatments became more intense (Fig. 3). Midday Ψ in the control began to decrease and reached the lowest values found in the study during both years. Seedlings in treatments 2 and 3 represented intermediate levels of Ψ in 2006, with treatments 4, 5, and 6 remaining higher than –1.7 MPa throughout the season. In 2007, midday Ψ did not differentiate among the treatments as it did in 2006. Treatments 2, 3, and 4 were similar across the 2007 measurement period. Again, treatments 5 and 6 improved midday Ψ, similar to the previous year, with levels not decreasing below –1.2 MPa (Fig. 3).

Cumulative predawn and midday Ψ values were significantly different among treatments for the first 2 years of establishment (p < 0.0001, Table 3). The seedlings in the control had the lowest cumulative predawn (–9.1 MPa) and midday (–18.9 MPa) Ψ values found (Table 5). As the herbicide treatments intensified, cumulative predawn and midday Ψ values increased during both years. Cumulative predawn Ψ values in treatments 2 and 3 were statistically different from one another in 2006 (–7.4 and –6.4 MPa, respectively) but were not statistically different at any other time. The site preparation with spring release treatments improved cumulative midday Ψ values during 2006 and 2007 over those observed in treatments 2 and 3. Cumulative predawn and midday Ψ values in treatments 5 and 6, which had the most intensive herbicide regimes, were not different from one another in either year (Table 5).

Treatment efficiency

The structure of the orthogonal contrasts provides an understanding of the incremental improvements resulting from treatment regime effects on seedling growth, cumulative

Fig. 3. Soil moisture and predawn and midday xylem water potentials by treatment regime for the 2006 and 2007 growing seasons. The period of time from 15 June to 15 September is indicated by horizontal braces. An explanation of treatment regimes can be found in Table 1.

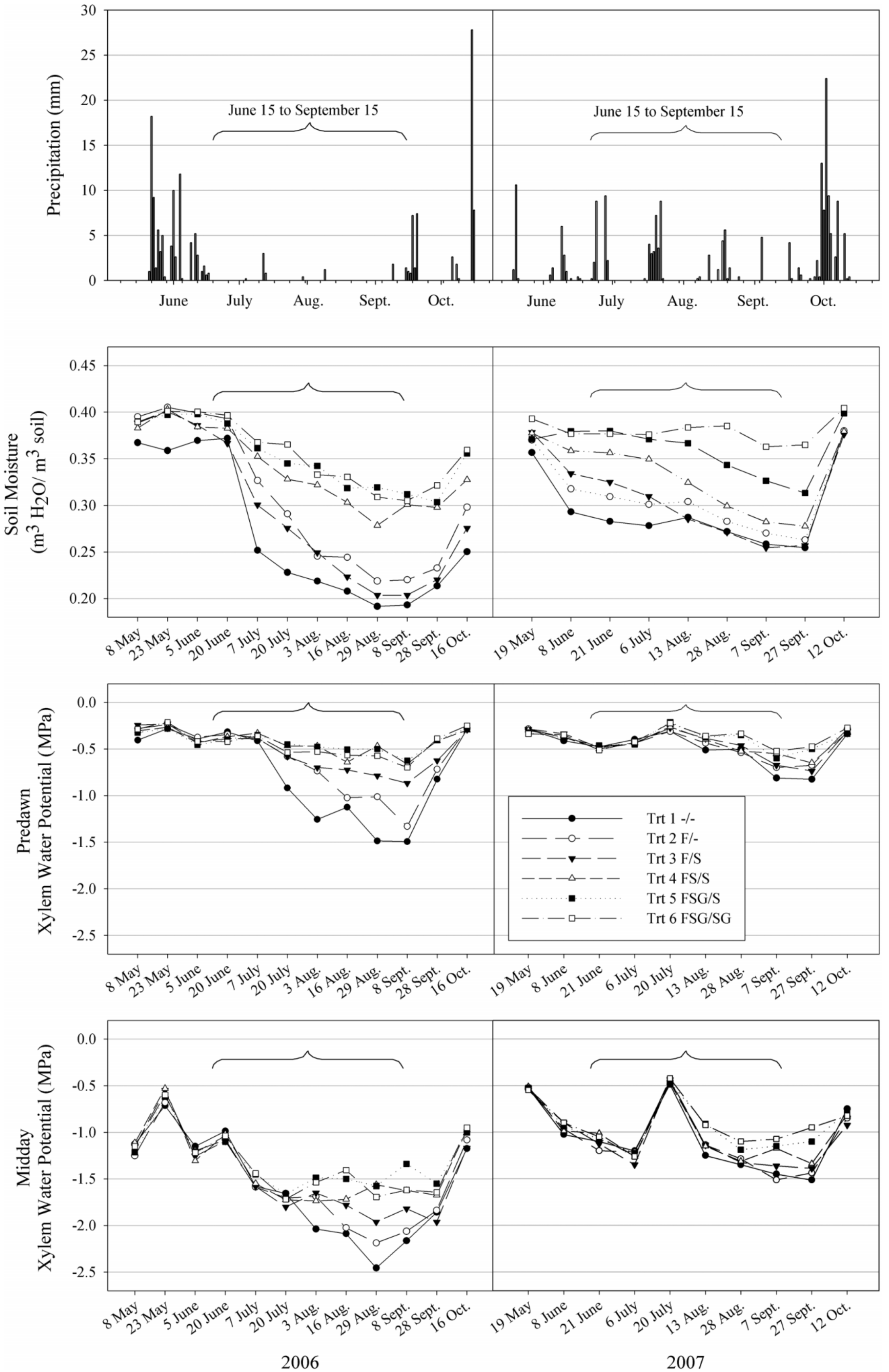

Table 6. Probability of greater F statistics for specific treatment comparisons of seedling growth and height to diameter ratio (HDR) in 2007 over the initial 2 years of establishment.

Characteristic	Comparison	df	Contrast SS	F value	Pr > F^a
Height growth	trt 1 vs. trts 2, 3, 4, 5, 6	1	997.4680	20.26	**0.000**4
	trts 2, 3 vs. trts 4, 5, 6	1	1198.5089	24.35	**0.0002**
	trt 4 vs. trts 5 and 6	1	193.4590	3.93	0.0661
	trt 2 vs. trt 3	1	749.7116	15.23	**0.0014**
	trt 5 vs. trt 6	1	53.6599	1.09	0.3130
Stem diameter growth	trt 1 vs. trts 2, 3, 4, 5, 6	1	1.8933	78.95	**<0.0001**
	trts 2, 3 vs. trts 4, 5, 6	1	1.0037	41.85	**<0.0001**
	trt 4 vs. trts 5 and 6	1	0.3166	13.20	**0.0025**
	trt 2 vs. trt 3	1	0.2118	8.83	**0.0095**
	trt 5 vs. trt 6	1	0.0047	0.19	0.6659
Volume growth	trt 1 vs. trts 2, 3, 4, 5, 6	1	3.8477	51.66	**<0.0001**
	trts 2, 3 vs. trts 4, 5, 6	1	3.1236	41.94	**<0.0001**
	trt 4 vs. trts 5 and 6	1	0.8289	11.13	**0.0045**
	trt 2 vs. trt 3	1	0.7322	9.83	**0.0068**
	trt 5 vs. trt 6	1	0.0542	0.73	0.4072
HDR (2007)	trt 1 vs. trts 2, 3, 4, 5, 6	1	1071.9793	120.92	**<0.0001**
	trts 2, 3 vs. trts 4, 5, 6	1	342.2691	38.61	**<0.0001**
	trt 4 vs. trts 5 and 6	1	209.9670	23.68	**0.0002**
	trt 2 vs. trt 3	1	0.6738	0.08	0.7866
	trt 5 vs. trt 6	1	1.3077	0.15	0.7063

[a]Values in bold are significant at $\alpha = 0.05$.

soil moisture, and cumulative seedling Ψ values (Tables 6 and 7). Results from this analysis revealed that any application of herbicides significantly improved seedling growth, cumulative soil moisture values, and cumulative Ψ values compared with the control. Three or more herbicide applications in the first 2 years of establishment (treatments 4, 5, and 6) resulted in significantly greater seedling growth, cumulative soil moisture values, and cumulative Ψ values when compared with only one or two applications of herbicides (treatments 2 and 3). Other than height, all other aspects of seedling growth as well as cumulative values of soil moisture and Ψ were most improved by treatment 5, which received four applications of herbicides (Tables 6 and 7).

Discussion

Treatment regimes effect on growing conditions

A study has not been found that provides detailed soil moisture and Ψ information for the first two seasons of the PNW Douglas-fir plantation establishment with treatment regimes designed to mimic those employed by forest managers in the region. The biweekly measurements reported here demonstrate the relationships that exist between common vegetation control regimes and the soil moisture and Douglas-fir seedling Ψ conditions created by their use. Researchers have noted that intense measurements such as these are necessary to understand how specific vegetation management regimes affect soil moisture (Zutter et al. 1986) and how seedling Ψ responds to the onset, intensity, and length of time associated with seasonal stress (Cleary 1971).

The combination of the intense soil moisture and both predawn and midday measurements demonstrates how productive growing time was affected by the treatments on both seasonal and daily temporal scales. When compared with the control, reductions in vegetation cover improved growing conditions (as measured by soil moisture and Ψ) for a longer span of time. In the control treatment, seedlings were exposed to soil moisture levels below 25% from 7 July to 28 September 2006, a period of more than 80 days (Fig. 3). Once soil moisture decreased below this level, predawn Ψ began to decline as well. Treatments 2 and 3, which received only a fall site preparation for the 2006 growing season reduced cover to approximately 40%, freeing soil moisture for an additional 28 days. By 3 August 2006, soil moisture levels had dropped below 25% and were nearer the values observed in the control treatment until the end of September (a period of 56 days). Again, predawn Ψ decreased in response to soil moisture depletion, limiting potential overnight recovery from daily stress. As the herbicide regimes intensified, total vegetation cover was reduced below 20% across the 2006 growing season, and soil moisture demonstrated relatively slow, steady rates of depletion, never declining below 28% (treatments 4, 5, and 6). Regular precipitation during 2007 minimized the depletion of soil moisture, and all treatments retained soil moisture levels above 25%.

While the ability of a soil to hold and release moisture depends on the soil texture, organic matter, and clay content, results such as those presented by Havranek and Benecke (1978) and Wittwer (1986) demonstrate how a marked decrease in Ψ can occur once soil moisture reaches a level specific to a soil type. Havranek and Benecke (1978) found that when gravimetric soil water was above 25%, Ψ, transpiration, and photosynthesis of four European conifer species grown in a controlled nursery environment were only minimally affected. After this point, further decreases in gravimetric soil water rapidly decreased soil water potential and Ψ to a level where seedling transpiration and photosynthesis eventually reached zero at 10% soil water content (Havranek

Table 7. Probability of greater *F* statistics for specific treatment comparisons of cumulative values of soil moisture and predawn and midday Ψ over the initial 2 years of establishment.

Characteristic	Comparison	df	Contrast SS	*F* value	Pr > *F*[a]
Cumulative soil moisture					
2006	trt 1 vs. trts 2, 3, 4, 5, 6	1	1.7489	86.15	**<0.0001**
	trts 2, 3 vs. trts 4, 5, 6	1	1.7802	87.69	**<0.0001**
	trt 4 vs. trts 5 and 6	1	0.0989	4.87	**0.0433**
	trt 2 vs. trt 3	1	0.0613	3.02	0.1029
	trt 5 vs. trt 6	1	0.0045	0.22	0.6460
2007	trt 1 vs. trts 2, 3, 4, 5, 6	1	0.5081	23.63	**0.0002**
	trts 2, 3 vs. trts 4, 5, 6	1	0.8929	41.52	**<0.0001**
	trt 4 vs. trts 5 and 6	1	0.2933	13.64	**0.0022**
	trt 2 vs. trt 3	1	0.0001	0.00	0.9472
	trt 5 vs. trt 6	1	0.0597	2.78	0.1164
Cumulative predawn Ψ					
2006	trt 1 vs. trts 2, 3, 4, 5, 6	1	34.9380	156.99	**<0.0001**
	trts 2, 3 vs. trts 4, 5, 6	1	14.3521	64.49	**<0.0001**
	trt 4 vs. trts 5 and 6	1	0.0876	0.39	0.5398
	trt 2 vs. trt 3	1	1.9013	8.54	**0.0105**
	trt 5 vs. trt 6	1	0.1013	0.45	0.5103
2007	trt 1 vs. trts 2, 3, 4, 5, 6	1	1.4520	51.15	**<0.0001**
	trts 2, 3 vs. trts 4, 5, 6	1	0.8168	28.77	**<0.0001**
	trt 4 vs. trts 5 and 6	1	0.4538	15.98	**0.0012**
	trt 2 vs. trt 3	1	0.0313	1.10	0.3107
	trt 5 vs. trt 6	1	0.0613	2.16	0.1625
Cumulative midday Ψ					
2006	trt 1 vs. trts 2, 3, 4, 5, 6	1	13.6519	49.52	**<0.0001**
	trts 2, 3 vs. trts 4, 5, 6	1	16.8375	61.07	**<0.0001**
	trt 4 vs. trts 5 and 6	1	1.5251	5.53	**0.0328**
	trt 2 vs. trt 3	1	0.5000	1.81	0.1981
	trt 5 vs. trt 6	1	0.0528	0.19	0.6679
2007	trt 1 vs. trts 2, 3, 4, 5, 6	1	1.8625	17.58	**0.0008**
	trts 2, 3 vs. trts 4, 5, 6	1	5.2710	49.74	**<0.0001**
	trt 4 vs. trts 5 and 6	1	1.7604	16.61	**0.0010**
	trt 2 vs. trt 3	1	0.0253	0.24	0.6321
	trt 5 vs. trt 6	1	0.1800	1.70	0.2121

[a]Values in bold are significant at $\alpha = 0.05$.

and Benecke 1978). Wittwer (1986) reported a similar phenomenon with the establishment of loblolly pine growing in southeastern Oklahoma, which experienced rapid decreases in Ψ when available soil moisture decreased to levels below 30%.

During these periods of decreased soil moisture in plots with high amounts of vegetation cover, productive growing time may have also been reduced to a few early morning hours each day. On 29 August 2006, seedlings in the control had a mean predawn Ψ of –1.5 MPa and by noon had dropped to –2.5 MPa. By comparison, seedlings in treatment 4 on the same date began at –0.6 MPa and by midday had reached approximately –1.5 MPa. Douglas-fir seedlings, under laboratory conditions, have been shown to maintain nearly 100% photosynthetic efficiency when Ψ is above –1.0 MPa (Brix 1979). Decreasing Ψ beyond this level inhibits photosynthesis until it is below 25% efficient at –2.0 MPa (Brix 1979). Extrapolating from these results (Brix 1979), seedlings in the control on 29 August 2006 had a limited amount of productive growing time, as they began the day at approximately 70% net photosynthetic efficiency and by noon had dropped to nearly 20%. Minimizing the vegetation cover with the use of treatment 4 allowed the seedlings to be 100% efficient at dawn and around 60% by noon.

After the cessation of height growth, Douglas-fir stem diameter growth will continue throughout the summer provided soil moisture is not limiting and is presumed to be indeterminate (Kramer and Kozlowski 1979). Retaining soil moisture at higher levels through four or five herbicide applications (treatments 5 and 6) served as a reservoir that allowed seedling growth to extend later into the first two seasons of establishment. Increased photosynthetically efficient growing time would presumably increase photosynthate production, which could be allocated to stem diameter and volume growth during this time period. The concept of lengthening the growing season through reductions in competing vegetation is supported by Harrington and Tappeiner (1991) who used a binary treatment regime (no control and complete control of tanoak *Lithocarpus desniflorus*) to test 5- to 7-year-old Douglas-fir sapling growth response. They found that the period for Douglas-fir stem diameter growth is 48–70 days shorter when seedlings grow with a 40%–64% competitive cover from tanoak because of the competition for soil moisture (Harrington and Tappeiner 1991).

The more intense herbicide regimes (treatments 5 and 6) tested in this study reduced the HDR of the seedlings below 50 (Fig. 1). HDR is highly sensitive to changes in stem diameter and has been used as an index of growth vigor (Cole and Newton 1987; Wagner et al. 1996; Rose et al. 1999). Reductions to the competitive vegetation cover enabled seedlings to maximize growth potential, increasing the likelihood of establishment success (Table 6). Decreasing HDR below 50 in the first 2 years of plantation establishment could allow seedlings to continue rapid growth for a period of time after herbicide applications have ceased. This may serve to lengthen herbicide effectiveness beyond chemical persistence on the site, shorten the span of time associated with the critical period of plantation establishment, and minimize the need for future herbicide release treatments.

Vegetation community response

The detailed surveys of plant species within these permanent plots have provided information, which suggests that the chemicals making up the various herbicide regimes can influence the composition of the developing vegetation community. Imazapyr (the active ingredient in Chopper) is soil persistent and can provide control for up to 6 months, whereas glyphosate (the active ingredient in Accord Concentrate) has almost no persistence due to binding on soil particles (Ahrens 1994). The application of these two chemicals in the fall of 2005 reduced the vegetation community, introducing a secondary disturbance. Presumably, these chemicals had minimal herbicidal effects on the vegetation development that occurred over the 2006 growing season, greater than 6 months after application. A lack of competition from the native perennial vegetation community and no additional herbicide applications during the 2006 season favored the colonization of plots receiving treatments 2 and 3 by introduced annual species (Table 4) (West 1968; Halpern 1989; Radosevich and Holt 1984).

The two chemicals employed in the spring release applications, Atrazine and Transline (chemical name Clopyralid), are known to have half-lives of 40–60 days (Ahrens 1994; William 1994). Applying these chemicals in the spring would immediately reduce the colonizing vegetation, and chemical persistence would help to minimize plant growth occurring after germination. Chemical effectiveness would degrade over time, but their application reduced the vegetation community long enough for the 2006 summer drought to minimize adequate germination and growing conditions. These plots were then left relatively devoid of introduced annual vegetation through the first growing season (Table 4).

The vegetation community response in plots receiving only a spring release in 2007 (treatments 3, 4, and 5) demonstrated that in addition to soil persistence, herbicide effectiveness is controlled by a host of factors, including weather, timing of application, and (or) the plant species to be controlled (William 1994). A rain event less than 24 h after application, spraying too early in the spring, the presence of species that were not as susceptible to the herbicidal effects of the chemicals at that time, or a combination of these factors potentially contributed to the lack of control observed in treatments 3, 4, and 5 during the 2007 growing season (Fig. 2 and Table 4).

On 3 August 2006, an introduced annual vegetation community with less than 40% total cover was capable of depleting soil moisture to levels similar to those observed in the control. The native perennial vegetation in the control depleted soil moisture rapidly between 20 June and 7 July 2006, but the total cover was more than twice that observed in treatments 2 and 3 (fall site preparation only). Altering the composition of the vegetation community through the use of the chemicals employed in the treatment regimes dramatically changed the competition for limited soil moisture. While relative competition is often assessed through visual estimates of vegetative cover, these results support the commonly held notion that plant species compete differently for soil moisture resources. The study of different competitive abilities of vegetation is needed, with particular attention to the resource use requirements of species common to reforestation sites. These types of results could improve the accuracy of chemical release treatments, thereby creating more precise silvicultural prescriptions.

Management and scientific implications

The results of this study clearly show how soil moisture content, seedling Ψ, and vegetation cover are integrated to either impede or enhance seedling morphological parameters. The science demonstrates how seedlings faced with different combinations of 109 competing plants can survive and grow with various degrees of success depending on specific fall–spring herbicide treatments applied during the first 2 years. Unchecked vegetation growth can rapidly decrease soil moisture, decrease Ψ, and negatively impact seedling growth. Low to moderate amounts of herbicidal control improve growing conditions and increase seedling growth in comparison to a no-action control. However, these conditions do not persist for the entire summer season and introduce a chemical disturbance that shifts species dominance of the vegetation community. Vegetation communities dominated by certain species have the potential to create soil moisture conditions that are similar to those observed in vegetation communities more than twice as dense. Only high amounts of herbicidal control retained vegetation community development below 20% and improved growing conditions across an entire season.

No other study appears to have shown such specific operationally useful outcomes for Douglas-fir after 2 years in the PNW region. The data convincingly show how even a few extra centimetres of summer rainfall can alleviate drought and improve seedling growth. It is noteworthy that treatment 6 (fall site preparation, two spring releases, and two glyphosate releases) kept soil moisture above 30% for 2 years, maintained seedling predawn Ψ ($\geq$0.75 MPa) within the commonly accepted zone for positive net photosynthesis for 2 years, and greatly improved midday Ψ for 2 years. The study further demonstrates how the treatments can prove profoundly critical when drought occurs and appear meaningless under adequate soil moisture conditions. Even more convincing is the fact that these data came from a bona fide field trial over the course of 2 years that had extremely different back-to-back environmental conditions. As the need for wood resources in the region continues, it will be imperative that forest managers weigh the risk–reward benefits of vegetation control treatments with fluctuations in environmental conditions.

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