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Initial fall-spring vegetation management regimes improve moisture conditions and maximise third-year Douglas-fir seedling growth in a Pacific Northwest plantation†

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Abstract

Competition for soil moisture can limit seedling growth and survival during the initial years of plantation establishment. Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco.) seedlings growing in the Mediterranean climate of western Washington (USA) contend with early-seral vegetation for soil moisture held in the upper soil layers. While research has documented improvements in seedling growth due to reductions in competition, this is the first study to present results showing how operationally oriented vegetation management regimes impact growing conditions for planted Douglas-fir seedlings in the Pacific Northwest. This paper presents third-year results quantifying seedling growth response to six herbicide treatment regimes applied during the first two years of plantation establishment. Soil moisture and seedling xylem water potential, measured during the initial two seasons were improved when competitive cover was maintained below 20%. In response to this low level of competition, height to diameter ratio of seedlings decreased below 50 and has remained low despite rapid colonisation of the vegetation community one year post-herbicide use. Third year (2008) stem volume growth was maximised by the most intense treatment. The volume increase was 808.8 cm^3, a 470% improvement when compared with 141.8 cm^3 in the no-action control. Herbicides restrained vegetation community growth during the years applied and, while they altered the dominance of the community, they did not eradicate any of the six plant growth habits found on the site. Results from this study demonstrate how vegetation management prescriptions can ensure successful establishment under different climatic conditions while providing a biosecurity safety net that minimises injury to plant community biodiversity.

Keywords: Douglas-fir; vegetation management; operational herbicide regime; plantation establishment.

† *Based on a paper presented at the IUFRO International Forest Biosecurity Conference, 16-20 March 2009, Rotorua, New Zealand*

Introduction

Timber-harvesting activities often create conditions appropriate for the germination and growth of early seral species (Radosevich & Holt, 1984; West & Chilcote, 1968; Chen, 2004; Dinger & Rose, 2009). This vegetation community is capable of rapid growth and can directly compete with planted seedlings for limited site resources. Depending on the level of competition for these resources, seedling growth and survival can be negatively affected (Rose et al., 1999; Newton & Preest, 1988; Zutter et al., 1986; Sands & Nambiar, 1984). This could lengthen the time associated with plantation establishment (Wagner et

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al., 1999), delay crown closure (Richardson, 1993), and decrease potential profits (Cousens, 1987). From a biosecurity standpoint, this colonising vegetation can also favour the development of plants that are difficult to control, disperse over larger areas, and displace native vegetation (Balandier et al., 2006; Halpern, 1989; Walstad & Kuch, 1987; Webster et al., 2006). The dispersion of Scotch broom (*Cytisus scoparius* (L.) Link) over the past 100 years is a prime example. It has been recognised as a problematic weed in many forestry settings (Harrington, 2009; Peterson & Prasad, 1998), has reduced growth potential of desired crop trees (Richardson et al., 1996), and exhibits tremendous potential for range expansion (Potter, 2009).

In the Mediterranean climate of the Pacific Northwest (PNW), early competition is predominantly for moisture in the upper soil layers where seedling and vegetation roots overlap (Newton & Preest, 1988; Dinger & Rose, 2009; Peterson et al., 1988). Herbicides may be used to target herbaceous plants early in stand establishment due to their ability for rapid post-disturbance invasion (Rose et al., 1999; Rosner & Rose, 2006; Chen, 2004). These treatments are designed to avoid growth losses during plantation establishment (Wagner, 2000) and may also be utilised to combat the spread of invasive and difficult-to-control plant species (Richardson, 1993).

Site-specific herbicide applications limit vegetation community development allowing seedlings to capture resources and maximise growth potential. Generally these applications are applied prior to seedling planting as fall (autumn) site preparation and during seedling dormancy as spring release treatments during years when required. While research has shown that reducing the level of competition for soil moisture resources can improve seedling growth, the link between operationally oriented vegetation management regimes in the PNW and the growing conditions they create have not been fully explored.

This paper presents the third year results from a study (Dinger & Rose, 2009) designed to evaluate how six herbicide regimes, spanning a range of management intensities, influence both seedling growth response and vegetation community development, as well as the soil moisture and xylem water potential (Ψ) conditions created through their use. Six growth habits of plants (forb, fern, graminoid, shrub, vine/shrub, and tree) were studied. This is the only study that has been found reporting quantitative results of the effect vegetation management regimes have on Pacific Northwest Douglas-fir seedling development through this type of integrated analysis. These third-year results illustrate how changes to the vegetation community affect plantation establishment through the improvement in growing conditions and how these trends can persist beyond the treatments themselves.

Materials and Methods

A study site was established on a west-facing slope at 135 m in elevation, eight km southwest of Oakville, Washington (USA) (46° 49’ 15” N and 123° 16’ 34” W). Soils are residuum from weathered sandstone and support a 50-year mean Douglas-fir site index of 41 metres. Regional climate data reveal that mean summer precipitation is 11 cm while an additional 145 cm occurs throughout the remainder of the year (University of Washington, 2007). Precipitation was recorded with a centrally located tipping-bucket gauge connected to a Hobo Microstation (Model #S-RGA-M002 and Model #H21-002, respectively; Onset Computer Corporation, Bourne, Massachusetts, USA). Seasonal variability in precipitation patterns is presented in Figure 1. From 15 June to 15 September,

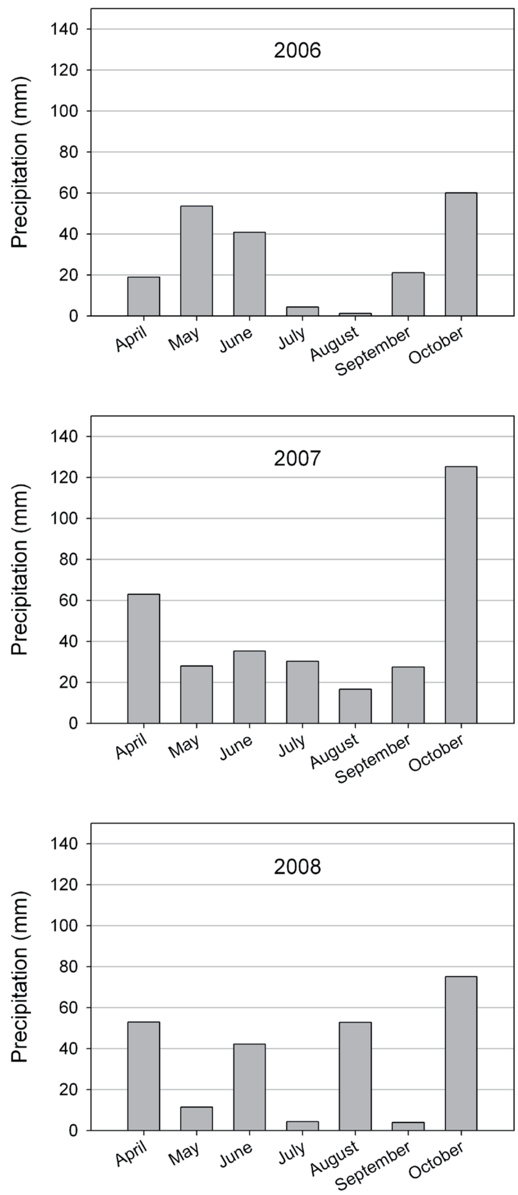

FIGURE 1: Precipitation by month across the first three growing seasons of establishment.

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TABLE 1: Description of the six vegetation management regimes. Treatment explanations are as follows: "-" no treatment; "F" fall (autumn); site preparation; "S" spring release; and "G" early-summer glyphosate application.

Treatment	2005 Fall Site Preparation	2006 Spring Release	2006 Early-Summer Release	2007 Spring Release	2007 Early-Summer Release
1. -/-	No	No	No	No	No
2. F/-	Yes	No	No	No	No
3. F/S	Yes	No	No	Yes	No
4. FS/S	Yes	Yes	No	Yes	No
5. FSG/S	Yes	Yes	Yes	Yes	No
6. FSG/SG	Yes	Yes	Yes	Yes	Yes

precipitation on the site was 1.2 cm in 2006, 7.5 cm in 2007, and 5.7 cm in 2008.

The six treatment regimes (five involving various combinations of fall, spring and/or summer treatments, plus a control; Tables 1 and 2) were replicated four times in a complete randomised block design. The site was fenced in November 2005 to eliminate the potential for browsing by ungulate species. Bareroot 1+1 Douglas-fir seedlings were planted on 25 February 2006 using a 3.1 x 3.1 m grid. This arrangement allowed 36 measurement trees to be surrounded by a buffer row inside each 24.4 x 24.4 m treatment plot.

Seedling height and stem diameter at ground line were initially assessed in March 2006 and have been measured at the end of each of the first three growing seasons (October or November). Height (cm) to diameter (cm) ratio was derived by dividing seedling height by the stem diameter. Using the standard formula for a cone, volume was calculated as $[V = (\pi d^2 h)/12]$ where d is the stem diameter and h is the height. Volume growth during 2008 was calculated as the difference between the volume in October 2007 and November 2008.

After two years of development, seedling morphological parameters were assessed on a one-tree-per-plot basis. Plot-level mean tree volume for each of the 24 treatment plots was calculated and the seedling that was +/- 10 cm^3 from this mean was carefully excavated. Roots were gently washed on site, seedlings placed individually in large plastic bags, and brought back to laboratory facilities in Corvallis, Oregon, USA. Branches were cut from the stem using garden sheers, labelled, and set aside. Hydrated stem and root volume were assessed by displacement. For each seedling, the branches and needles, stems, and roots were put in separate paper bags and placed in a laboratory oven at 68 °C for 72 hours. After drying, needles were separated from branches and all seedling component parts were weighed to determine dry mass.

Seven 1-metre-radius subplots were established in each treatment plot to assess the vegetation community (n = 168). Visual assessments of vascular plant cover were conducted in each subplot after the site was established on 8 September 2005 and on 19 July 2006, 16 August 2007, and 21 July 2008. Summed cover was calculated as the total of all species present in a subplot, providing values that often exceeded 100%. This method takes into account the possibility for overlapping vegetation in a complex community. When a plant was unable to be identified to species, genus or family level determinations were used. Forbs present only as cotyledons and unable to be accurately identified were deemed an "unknown forb." Information on plant growth habit (forb, fern, graminoid, vine/shrub, shrub, or tree) was recorded and a list of all species according to these habits is presented in Table 3. Hitchcock and Cronquist (1973) along with Pojar and MacKinnon (2004) were used as references for plant identification.

Soil moisture and xylem water potential measurements were taken on the same date following an approximate biweekly schedule from May to October during 2006 and 2007. Soil moisture was assessed vertically in the top 20 cm of the soil profile with a Hydrosense Time Domain Reflectometer (TDR) probe (Model # CS-620 Spectrum Technologies, Plainsfield, Illinois, USA). The values provided by the Hydrosense TDR probe were calibrated through regression analysis comparing the sensor values with 120 soil cores taken during 2006 (Dinger & Rose, 2009). Calibrated volumetric soil moisture values will be henceforth referred to as "soil moisture." Xylem water potential was measured with a model 600 pressure chamber (PMS Instrument

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TABLE 2 : Details of the five treatment regimes used, including date, type and rate of application, product name and common chemical name. All treatments were applied as tank mixes.

Year	Treatment Name	Treatment Date	Application Method	Product used	Product type	Manufacturer	Active Ingredient	Rate
2005	Fall Site Preparation	20 Sep	broadcast	Chopper®	Herbicide	BASF	Imazapyr	2.3 L/ha
				Accord Concentrate®	Herbicide	Dow AgroSciences	Glyphosate	3.5 L/ha
				Hasten®	Surfactant	Wilbur-Ellis Co.		9.4 L/ha
				Syl-Tac®	Surfactant	Wilbur-Ellis Co.		292.2 mL/ha
2006	Spring Release	12 Apr	broadcast	Atrazine 90 WSP®	Herbicide	Helena Chemical Co.	Atrazine	4.9 kg/ha
				Transline®	Herbicide	Dow AgroSciences	Clopyralid	0.58 L/ha
	Early-Summer Release	20 Jun	direct spot-spray	Accord Concentrate®	Herbicide	Dow AgroSciences	Glyphosate	2% solution
2007	Spring Release	30 Mar	broadcast	Atrazine 90 WSP®	Herbicide	Helena Chemical Co.	Atrazine	4.9 kg/ha
				Transline®	Herbicide	Dow AgroSciences	Clopyralid	0.58 L/ha
	Early-Summer Release	29 Jun	direct spot-spray	Accord Concentrate®	Herbicide	Dow AgroSciences	Glyphosate	2% solution

Note: The stumps of sprouting species red alder (*Alnus rubra* Bong.) and bigleaf maple (*Acer macrophyllum* Pursh) were directly treated on 12 April 2006 with triclopyr (Garlon 4® Dow AgroSciences) at 20% and petroleum oil (Brush and Basal oil®, Helena Chemical Co.) at 80% solution. A second direct application of 75% glyphosate (Accord Concentrate®) was required on 20 June 2006 to treat a small number of stumps which had sprouted again.

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TABLE 3: List of plant species found on the study site during the initial three years of establishment and presented by growth habit. The origin of plants identified to the species level was recorded as either native (N) or introduced (I) to the Pacific Northwest. When plants could not be accurately identified to the species level, origin was recorded as unknown (u).

Forbs		**Forbs**		**Fern**	
Adenocaulon bicolor Hook.	N	*Nemophila parviflora* Douglas ex Benth.	N	*Athyrium filix-femina* (L.) Roth	N
Anaphalis margaritacea (L.) Benth. & Hook.f.	N	*Osmorhia chilensis* Hook. & Arn.	N	*Polystichum munitum* (Kaulf.) C.Presl	N
Asarum caudatum Lindl.	N	*Phacelia nemoralis* Greene	N	*Pteridium aquilinum* (L.) Kuhn.	N
Aster spp.	u	*Ranunculus* spp.	u		
Campanula spp.	u	*Ranunculus uncinatus* D.Don ex G.Don	N	**Graminoid**	
Cardamine spp.	u	*Rumex acetosella* L.	I	*Brachypodium sylvaticum* (L.) P.Beauv.	I
Cardamine nuttallii Greene	N	*Rumex crispus* L.	I	Cyperaceae spp.	u
Cardamine oligosperma Nutt.	N	Saxifragaceae spp.	u	*Holcus lanatus* (L.)	I
Caryophyllaceae spp.	u	*Senecio jacobaea* L.	I	*Juncus* spp.	u
Centaurium umbellatum Gilib.	I	*Senecio sylvaticus* L.	I	*Lolium multiflorum* Lam.	I
Chrysanthemum leucanthemum L.	I	*Senecio vulgaris* L.	I	*Luzula campestris* (L.) DC.	N
Circaea alpina L.	N	*Smilacina racemosa* (L.) Desf.	N	Poaceae spp.	u
Cirsium arvense (L.) Scop.	I	*Smilacina* spp.	u		
Cirsium vulgare (Savi) Ten.	I	*Smilacina stellata* (L.) Desf.	N	**Shrub**	
Conyza canadensis (L.) Cronquist	N	*Sonchus asper* (L.) Hill	I	*Berberis nervosa* Pursh	N
Crepis capillaris (L.) Wallr.	I	*Sonchus* spp. 1	u	*Corylus cornuta* Marshall	N
Crepis setosa Haller f.	I	*Sonchus* spp. 2	u	*Gaultheria shallon* Pursh	N
Dicentra formosa (Haw.) Walp.	N	*Stachys rigida* Nutt. ex Benth.	N	*Oemleria cerasiformis* (Hook. & Arn.) J.W.Landon	N
Digitalis purpurea L.	I	*Stellaria media* (L.) Vill.	I	*Rhamnus purshiana* DC.	N
Epilobium angustifolium L.	N	*Stellaria* spp.	u	*Ribes* spp.	u
Epilobium minutum Lindl.	I	*Thalictrum occidentale* A.Gray	N	*Rosa* spp.	u
Epilobium paniculatum Nutt. ex Torr. & A.Gray	N	*Trifolium dubium* Sibth.	I	*Rubus leucodermis* Douglas ex Torr. & A.Gray	I
Epilobium spp.	u	*Trifolium pratense* L.	I	*Rubus parviflorus* Nutt.	N
Erechtites minima (Poir.) DC.	I	*Trifolium repens* L.	I	*Rubus spectabilis* Pursh	N
Fabaceae spp. 1	u	*Trifolium* spp. 1	u	*Salix* spp.	u
Fabaceae spp. 2	u	*Trifolium* spp. 2	u	*Sambucus caerulea* Raf.	N
Galium aparine L.	N	*Trillium ovatum* Pursh	N	*Sambucus racemosa* L.	N
Galium parisiense L.	I	Unknown forb spp. 1	u	*Sambucus* spp.	u
Galium spp.	u	Unknown forb spp. 2	u	*Symphoricarpos albus* (L.) S.F.Blake	N
Galium triflorum Michx.	N	Unknown forb spp. 3	u	*Vaccinium parvifolium* Sm.	N
Geranium molle L.	I	Unknown forb spp. 4	u		
Gnaphalium spp.	u	*Urtica dioica* L.	I	**Tree**	
Hieracium albiflorum Hook.	N	*Vancouveria hexandra* C.Morren & Decne.	N	*Acer macrophyllum* Pursh	N
Hydrophyllum tenuipes A.Heller	N	*Vicia hirsuta* (L.) Gray	N	*Alnus rubra* Bong.	N
Hypericum perforatum L.	I	*Vicia* spp. 1	u	*Prunus emarginata* (Douglas) Eaton	N
Hypochaeris radicata L.	I	*Vicia* spp. 2	u	*Pseudotsuga menziesii* (Mirbel) Franco.	N
Lactuca muralis (L.) Fresen.	I	*Viola glabella* Nutt.	N		
Lactuca serriola L.	I	*Viola* spp.	u	**Vine/Shrub**	
Liliaceae spp.	u			*Lonicera ciliosa* (Pursh) DC.	N
Lotus spp.	u			*Rubus laciniatus* Willd.	I
Medicago spp.	u			*Rubus discolor* Weihe & Nees	I
Montia sibirica (L.) Howell	N			*Rubus ursinus* Cham. & Schltdl.	N

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Company Albany, Oregon, USA) on two seedlings per treatment plot at both predawn (0400 to 0500) and midday (1200 to 1300) assessments.

Statistical Analysis

All data were analysed using Statistical Analysis Software version 9.1 (SAS Institute Inc. Cary, NC). Analysis of variance (generalised linear models) and Fisher's protected least significant different t-tests were used to test treatment differences on 2008 (year-3) seedling height, stem diameter, height to diameter ratio, volume growth occurring during the 2008 season, as well as vegetation community development. A natural log transformation was required to meet ANOVA model assumptions for 2008 volume growth so back-transformed values are presented. Regression analysis was used to understand the relationship between stem and root volume as well as to ascertain the relationship between above and below-ground biomass partitioning. A significance level of $\alpha = 0.05$ was used on all statistical analysis.

Results

Soil moisture and xylem water potential results are presented in Figures 2 and 3, respectively taken from Dinger and Rose (2009).

Seedling morphology

After three years of development, 2008 seedling height, stem diameter, and height to diameter ratio were significantly different among the treatments (Tables 4 and 5). Seedling height showed a 34% improvement across the treatments and ranged from 154.0 cm in Treatment 2 to approximately 205.6 cm in Treatment 5. Stem diameter incrementally improved as the treatment regimes became more intense. Utilising a fall site preparation application (Treatment 2) did not significantly improve 2008 stem diameter over the control and these treatments represent the lowest in the study (2.3 cm in the control and 2.6 cm in Treatment 2). The application of a spring release according to Treatments 3 and 4 provided moderate 2008 stem diameter responses with 3.2 and 3.4 cm, respectively. The additional glyphosate applications of Treatments 5 and 6 are responsible for stem diameters of 4.4 and 4.7 cm, respectively, an improvement of over 91% when compared to the no-action control.

The no-action control had the highest height to diameter ratio (>69) throughout the study (Figure 4). Treatments 2, 3, and 4 reduced height to diameter ratio during the two years of herbicide application, but by the end of the 2008 growing season they were approximately 60 and similar to those observed in March 2006. Treatments 5 and 6 progressively decreased height to diameter ratio to low levels (47.6 and 42.7, respectively) that have persisted one year beyond chemical application on the site.

Volume growth during the 2008 season was significantly different among the treatments (Figure 5 and Table 5). During the third growing season, seedlings in the no-action control and Treatment 2 increased in volume 141.8 and 153.6 cm^3, respectively. Combining a fall site preparation with one or two spring releases (Treatments 3 and 4) improved 2008 volume growth to 305 cm^3. The most intense herbicide regimes (Treatments 5 and 6) were necessary to maximise volume growth potential of the trees and produced values of 643.7 and 808.8 cm^3, respectively. This represents a 354% to 470% improvement in third-year volume growth when compared to the no-action control.

The plot of stem volume versus root volume after two years of development demonstrates the strong correlation between these two components of seedling morphology (Figure 6). Seventy six percent of the variation in the relationship was explained by the regression equation and at nearly a 1 to 1 ratio, seedlings had almost equal stem and root volumes. Moderate amounts of vegetation control (Treatments 2, 3, and 4) improved the volume and dry weights of each seedling morphologic component (Table 6). Treatments 5 and 6, however, enabled seedlings to maximise stem volume production to greater than 399 cm^3 in the first two years. The single largest change in seedling morphology occurred with the increase in root volume from 239.3 cm^3 in Treatment 4 to 441.3 cm^3 in Treatment 5, a difference of 202 cm^3. Dry mass of needles ranged from 35.9 g in the control to 165.9 g in Treatment 5, representing a 362% increase. The correlation between dry mass of below-ground components and the summation of all above-ground parts is presented in Figure 7. Biomass partitioning followed a 2 : 1 ratio of above to below-ground parts explaining 74% of the variation.

Vegetation Community

Summed cover (henceforth termed "cover") of the vegetation community was significantly different among the treatments (Table 7 and Figure 8). In September 2005, prior to the application of the fall site preparation, cover on the site was between 34% and 62%. The survey conducted on 19 July 2006 revealed that the treatments had impacted vegetation cover in the plots. The vegetation in the no-action control increased to over 100% while the fall site preparation treatments remained at approximately 40%. The spring release and glyphosate treatments in 2006 were responsible for decreasing cover below 20%. In 2007, cover in Treatments 2, 3, 4, and 5 increased by 40 to 60 percentage points from 2006 levels. The no-action control remained relatively stable during this season in all treatment plots between 20 and 50 percentage

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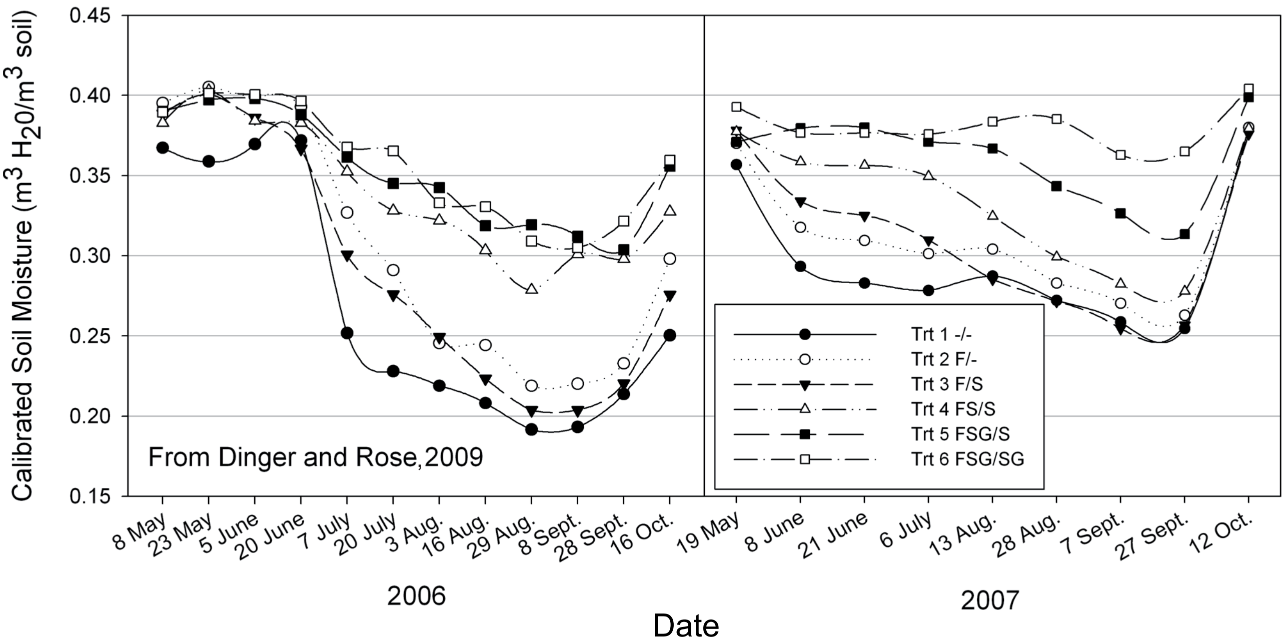

FIGURE 2 : Calibrated volumetric soil moisture by treatment regime in 2006 and 2007.

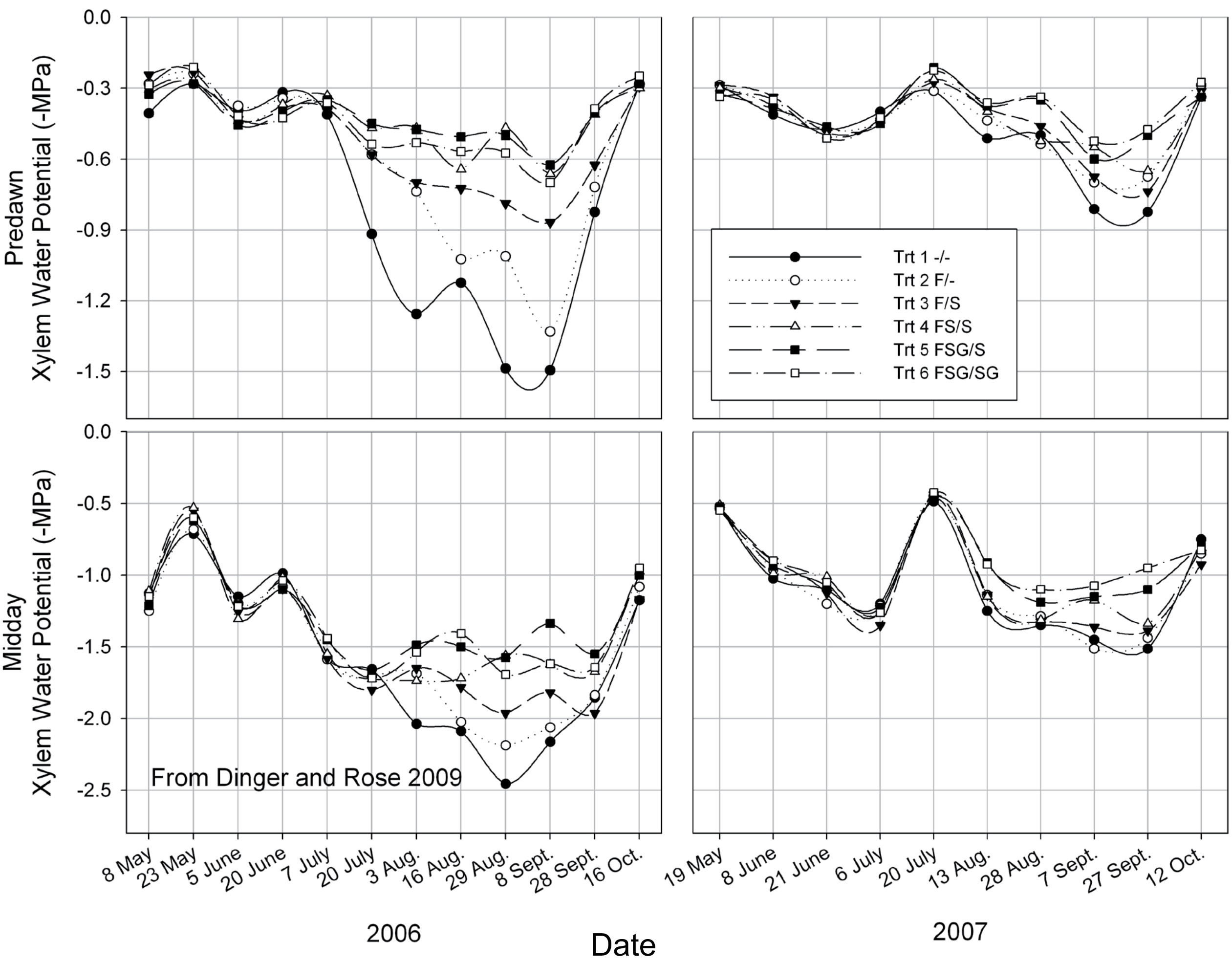

FIGURE 3 : Predawn and midday xylem water potential by treatment regime in 2006 and 2007.

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TABLE 4 : Seedling height, stem diameter, and height to diameter ratio (HDR) by treatment regime in November 2008. Units are centimetres.

Treatment	Height		Stem Diameter		HDR	
Trt 1 -/-	160.8	c	2.3	c	71.7	a
Trt 2 F/-	154.0	c	2.6	c	60.4	b
Trt 3 F/S	186.0	b	3.2	b	59.6	b
Trt 4 FS/S	188.8	b	3.4	b	58.8	b
Trt 5 FSG/S	205.6	a	4.4	a	47.6	c
Trt 6 FSG/SG	199.4	ab	4.7	a	42.7	d

Values within columns that have different letters are statistically different at α = 0.05. Standard errors are 1 SE (height 5.21; stem diameter 0.15; height to diameter ratio 1.60).

points from the prior year with almost 120% cover. Treatment 6 restrained vegetation community development below 20% for a second year. Cover was significantly different among the treatments one year after herbicide application (Table 7). Vegetation cover during 2008 increased in all treatment plots between 20 and 50 percentage points from the prior year.

The control has been dominated by vine/shrub, fern, forbs, and shrubs for three years (Figure 9). Applying a fall site preparation (Treatment 2) initially reduced the abundance of vine/shrub, fern, and shrub species below 10%. However, this treatment favoured the development of a forb-dominated community which has continued to persist until 21 July 2008. Treatments 4, 5, and 6 maintained the abundance of all six growth habits below 10% during the 2006 growing season. In 2007, the spring release application limited the development of forbs to 20% in Treatments 3, 4, and 5 but did little to control the other growth habits. During 2008, all growth habits increased in abundance or remained relatively stable in each of the treatment regimes. Forbs demonstrated a rapid increase in Treatment 6 as they went from 2% to 37% in one year. The cover of the vine/shrub component of the vegetation community in all treatment plots showed only slight changes from 2007 to 2008. The abundance of tree species has increased in all treatment plots and has become a dominant part of the vegetation community in Treatments 3, 4, and 5 with nearly 30% cover.

Discussion

Seedling growth

Early maintenance of soil moisture reserves through the application of intense vegetation management regimes has enabled Douglas-fir seedlings to maximise growth potential despite a lack of summer precipitation in 2006. Results such as these may become increasingly important as precipitation patterns fluctuate in response to environmental changes. Successful establishment of forest stands may require the use of approaches which promote seedling survival and growth under uncertain and variable climatic scenarios. Approaches such as these could serve the purpose of mitigating against harsh years when resources are most limiting.

Douglas-fir seedlings with height to diameter ratios below 50, such as those occurring in Treatments 5 and 6, have been able to sustain large increases in growth despite the increase in vegetation community during 2008. These data demonstrate that low height

TABLE 5 : Analysis of variance results for treatment effects on 2008 seedling height, stem diameter, and height to diameter ratio as well as 2008 volume growth.

Parameter	Source	DF	Sums of squares	Mean square	F value	Pr>F
Height	block	3	450.6161	150.2054	1.38	0.2865
	treatment	5	8 628.1594	1 725.6319	15.88	<0.0001*
Stem Diameter	block	3	0.1325	0.0442	0.71	0.5595
	treatment	5	18.6462	3.7292	60.15	<0.0001*
Height to Diameter Ratio	block	3	36.5645	12.1882	1.19	0.3471
	treatment	5	2 112.4401	422.4880	41.25	<0.0001*
2008 Volume Growth	block	3	0.1766	0.0589	0.69	0.5696
	treatment	5	10.2119	2.0424	24.10	<0.0001*

Values with an asterisk are significant at α = 0.05.

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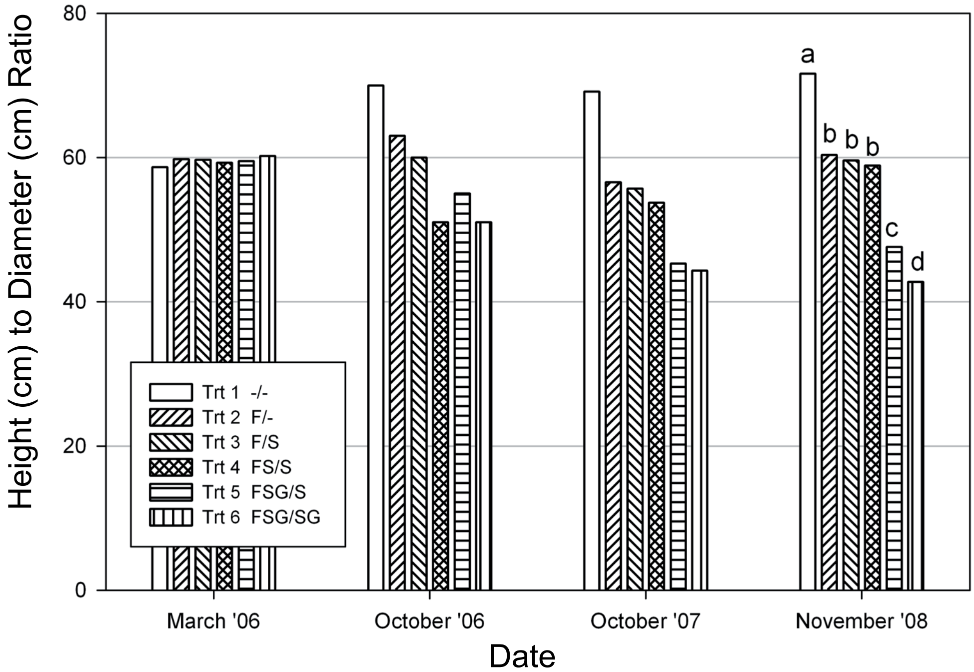

FIGURE 4: Height (cm) to diameter (cm) ratio by treatment regime during the initial three years of establishment. November 2008 treatment means with different letters are significantly different at α = 0.05.

to diameter ratios can persist beyond chemical application suggesting that intense herbicide treatments early in plantation establishment can shorten the amount of time associated with the critical period (Wagner et al., 1999), minimise the need for future herbicide applications, and exceed legal reforestation requirements set forth by state laws in Washington and Oregon (USA). These requirements stipulate that

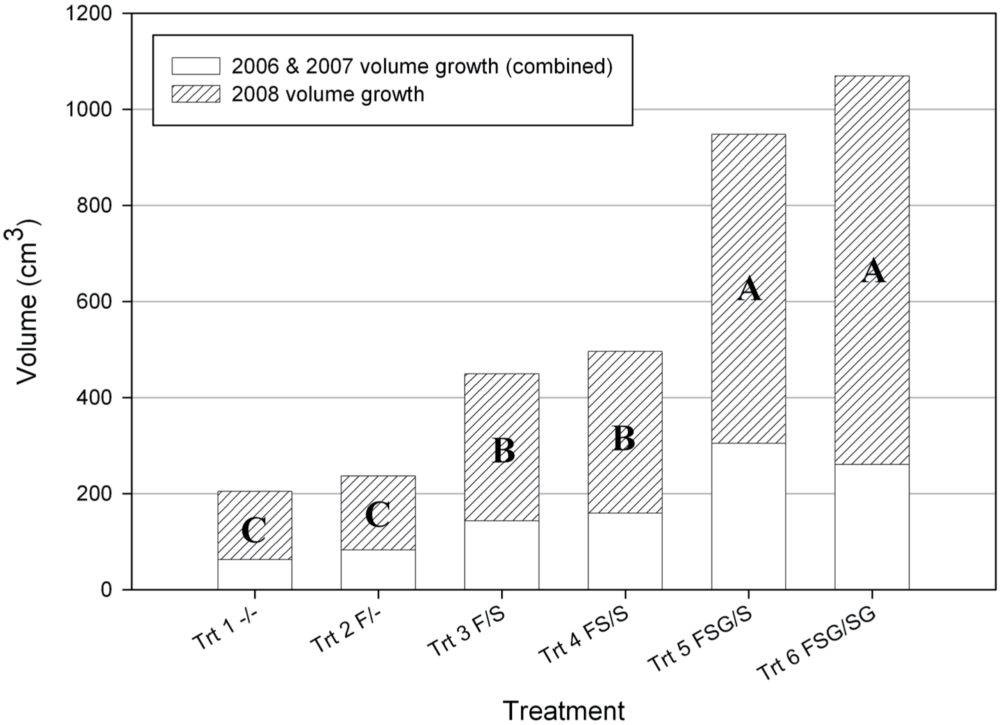

FIGURE 5: Volume growth accruing in 2008 was analysed by treatment regime. Treatments with different letters are statistically different at α = 0.05 (shaded area). A log-transformation was required to meet ANOVA model assumptions. Back-transformed values are presented. Years 2006 and 2007 were combined for each treatment to illustrate the starting point for 2008 volume growth (unshaded area).

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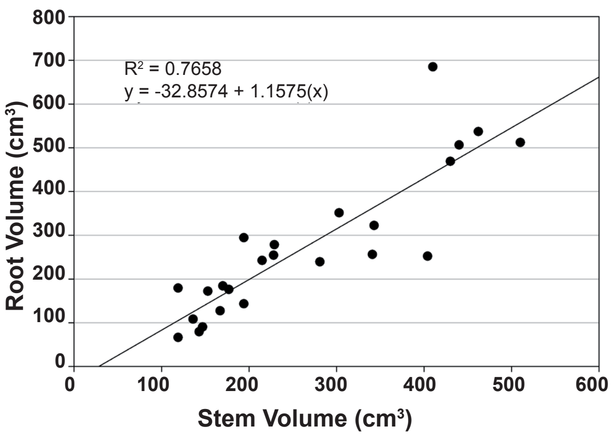

FIGURE 6: Regression analysis results of the relationship between year-2 shoot and root volume of the mean seedling growing in each treatment plot.

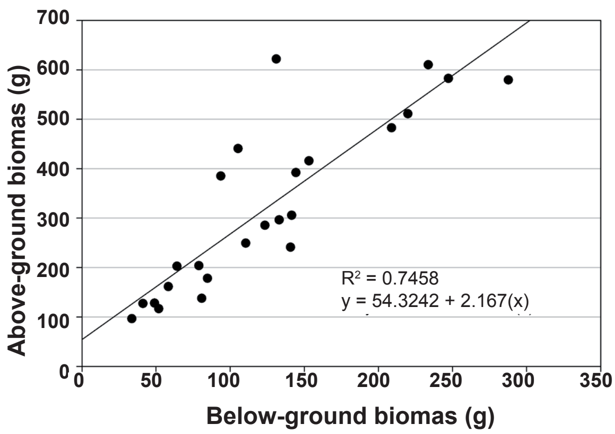

FIGURE 7: Regression analysis results of the relationship between below and above-ground biomass of the second year mean seedling growing in each treatment plot.

a minimum number of seedlings per hectare must be healthy and taller than neighbouring vegetation (termed "free to grow") within six years of harvesting the previous stand (Logan, 2002). Restraining cover of the vegetation community below 20% for two years has enabled the regeneration of this next stand to reach "free to grow" status in less than three years, exceeding the legal mandate while providing a biosecurity safety net.

Maintenance of adequate soil moisture availability enabled tree seedlings to develop root systems capable of supporting the production of large amounts of above-ground biomass. Overnight recovery to xylem water potential values above -1.0 MPa has been shown to allow Douglas-fir seedlings to grow at 100% net photosynthetic efficiency (Brix, 1979). Lengthening the amount of time adequate resources are available has also been shown to increase the productive assimilation of carbohydrates on both daily and seasonal scales (Dinger & Rose, 2009; Harrington & Tappeiner, 1991; Newton & Preest, 1988; Petersen et al., 1988; Felming et al., 1996). These carbohydrates could then be allocated to various parts of tree seedlings. It was found in a controlled greenhouse study under favourable soil moisture conditions that new root growth of Douglas-fir seedlings was linked to the production of current photosynthate when light intensity was adequate to support high rates of net photosynthesis (van den Driessche, 1987). Increased root development accompanied by greater photosynthetic area would presumably increase the potential for carbohydrate production. This may help to explain the morphologic differences observed

TABLE 6 : Seedling morphology results from excavating the mean tree per plot after two years of development. Results presented by treatment regime (n = 4). Seedling height and diameter units are centimetres, volume by displacement units are cubic centimetres, and dry weight units are grams.

Treatment	Seedling		Stem		Branch	Needle	Root	
	Height	Diameter	Vol.	Dry Wt.	Dry Wt.	Dry Wt.	Vol.	Dry Wt.
-/-	115.8	1.8	136.3	58.3	22.8	35.9	85.8	43.9
F/-	110.3	2.1	163.5	72.2	53.6	67.4	180.0	89.2
F/S	124.3	2.3	198.3	86.7	55.1	82.4	216.8	98.6
FS/S	129.8	2.7	255.3	113.2	103.8	137.3	239.3	116.0
FSG/S	135.5	3.5	399.3	181.8	177.3	165.9	441.3	195.3
FSG/SG	135.8	3.5	426.3	191.9	172.1	160.0	467.3	211.3

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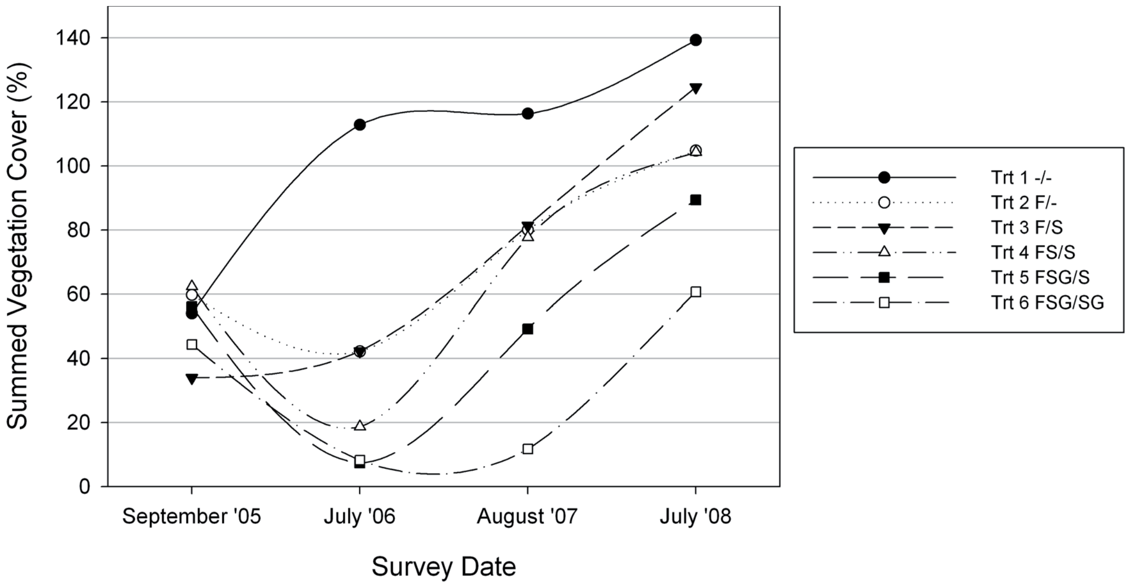

FIGURE 8: Summed vegetation cover by treatment regime across the four survey dates.

in Treatments 5 and 6 (Table 6) when soil moisture was retained at higher levels through more intensive vegetation control regimes (Figure 2).

The converse is also true in that seedlings experiencing low soil moisture and xylem water potential in plots with high amounts of competitive cover were incapable of extending root systems that could support the increased production of carbohydrates. McGrath and Duryea (1994) showed that decreasing diameter of slash pine (*Pinus elliottii* Engelm.) seedlings in Florida (USA) corresponded with smaller root systems that were incapable of adapting to decreases in xylem water potential which decreased growth and survival. Tinus (1996) demonstrated that when interior Douglas-fir seedling roots grown in Arizona (USA) were exposed to desiccating conditions and then placed in root mist chambers, stresses greater than -2.2 MPa during the desiccation period caused seedlings to have limited root growth upon return to favourable growing conditions. Despite being capable of rapidly increasing xylem water potential after severe stress (increasing from -3.8 MPa to -0.3 MPa in a 24 hour period), it was found that seedlings did not produce new roots (Tinus, 1996).

Second year seedling biomass partitioning coupled with third year growth results demonstrate the feedback loop that continues to widen the gap between seedlings which had low amounts of competition for soil moisture and those that did not. The stresses induced in treatment plots with high amounts of competitive

TABLE 7 : Analysis of variance table for treatment effects on summed vegetation cover by survey date.

Parameter	Source	DF	Sums of squares	Mean square	F value	Pr>F
Sept 2005	block	3	325.6204	108.5401	0.30	0.8266
	treatment	5	2 289.4398	457.8880	1.26	0.3330
July 2006	block	3	184.8980	61.6327	0.80	0.5140
	treatment	5	31 316.1122	6 263.2225	81.10	<0.0001*
August 2007	block	3	801.4583	267.1528	2.14	0.1382
	treatment	5	25 064.2594	5 012.8519	40.11	<0.0001*
July 2008	block	3	249.2143	83.0714	1.02	0.4125
	treatment	5	15 035.6497	3 007.1299	36.84	<0.0001*

Values with an asterisk are significant at $\alpha = 0.05$.

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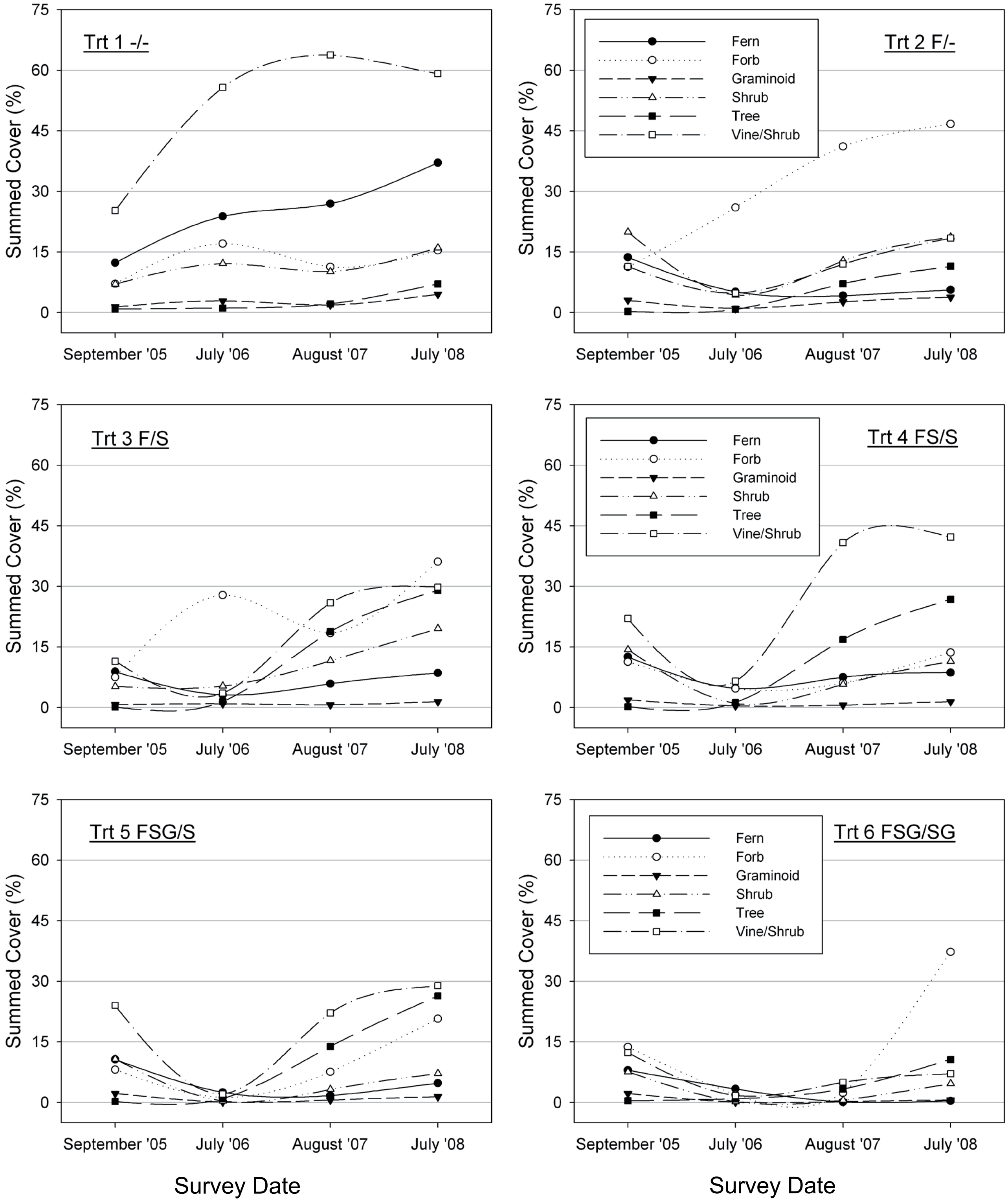

FIGURE 9: Summed vegetation cover partitioned by six growth habits according to treatment regimes across the four survey dates.

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cover during 2006 did not respond with rapid growth when those stresses were relieved under the higher soil moisture conditions observed in 2007. These results further support evidence that *a priori* moisture conditions will impact seedling growth in subsequent years (Newton & Preest, 1988).

Vegetation Community

Despite the use of herbicides under the various treatment regimes tested, all six growth habits of plants (forb, fern, graminiod, shrub, vine/shrub, and tree) were present in all of the treatments as of 21 July 2008. Herbicide use did not completely eradicate any of these growth forms. Seed/spore dispersal, remnant below-ground vegetative parts, refugia within treatment plots, partial or complete resistance to herbicidal effects, or a combination of these are likely responsible for the observed reinvasion of treated plots by these six growth habits. This finding is important due to biodiversity concerns across large landscapes which include intensively managed forests.

In the southeastern United States of America, it has been reported that one year after herbaceous vegetation control in a loblolly pine (*Pinus taeda* L.) plantation there were no significant treatment differences in number of plant species and biomass of palatable ungulate forage when a no-action control and two methods of herbicide application were compared (Blake et al., 1987). Lindgren and Sullivan (2001) compared different release treatments applied to stands up to 12 years old in an interior British Columbia, Canada plantation and found that while cover was reduced during the year of application, species diversity was unaffected and structural diversity was increased. Longer-term vegetation management studies have reported that while plant abundance and floristic diversity were altered during the years of chemical application, treatment regimes had no significant effect on cover, species richness, or diversity eleven years after site preparation applications on four sites in central Georgia, USA (Miller et al., 1999) and fourteen years after glyphosate application in southeastern British Columbia, Canada (Comeau & Harper, 2009). The results presented here further support this growing body of literature by uniquely illustrating the response of a coastal Pacific Northwest vegetation community to various intensities of herbicidal control.

The fall site preparation included broad spectrum herbicides that control many different plant species (Ahrens et al., 1994). Without continued control in the spring of 2006, these treatments opened germination sites for ruderal forb species (Treatments 2 and 3) (West & Chilcote, 1968; Dyrness, 1973). This community has continued to persist in Treatment 2 and has hindered seedling growth similar to the no-action control. Both the commercial herbicides Atrazine® and Clopyralid®, which were used in the spring release, are labelled for the control of herbaceous plants (Ahrens et al., 1994) and restrained the development of this portion of the vegetation community during both years these chemicals were applied. The additional early-summer application of glyphosate in mid-June 2006 and 2007 limited the growth of all species. Once those treatments ceased, the open conditions of Treatment 6 were quickly colonised by forb species similar to that observed two years prior in the fall site preparation only treatments. However, providing a competitive advantage for two years in these plots enabled seedlings to continue rapid growth despite increasing vegetation cover.

It is important to recognise that the perimeter fence is another aspect that has influenced the vegetation communities in treatment plots. This fence was constructed to prevent uneven browsing from ungulate species that could occur on the Douglas-fir seedlings in the study (Brandeis et al., 2002). The exclosure also eliminated browsing of the developing vegetation community. *Prunus emarginata* (Douglas Eaton), *Sambucus racemosa* (L.), and *Rubus spectabalis* (Pursh) are palatable to ungulates in this region (Harrington & Tappeiner, 2007) and these have flourished in the absence of browsing. This fact has partially contributed to the abundance of certain species within treatment plots on the site.

By changing the dominant vegetation, the herbicides utilised in the different treatment regimes have also changed the nature of competition during the first three years. Height of the vegetation community was not measured but the species list included in Table 3 coupled with the abundance of the various growth habits in Figure 9 show how certain treatments favour layered shrub and tree dominated plant communities. This community is capable of competing for light in addition to soil moisture and it is expected to continue affecting seedling growth potential (Cole & Newton, 1986; Cole & Newton, 1987; Newton et al., 1993; Chan & Walstad, 1987). Results presented here illustrate the mechanisms by which common regimes designed to limit vegetation growth can alter the dominance of the community through their application and impact seedling growth. We have been unable to find any other study in the Pacific Northwest linking these kinds of operationally oriented regimes from the beginning of the establishment period to the vegetation communities they create and the persistence of those habitat types beyond chemical use.

Conclusions

The impact of reducing competing vegetation through the application of herbicides has had a clear effect on seedling growth. In the context of short budgetary cycles and pressure to reduce rotation lengths, these kinds

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of short-term results become increasingly important in the selection of effective treatments. Uncertain future climatic scenarios underscore the necessity of forest establishment research that demonstrates the success and growth of seedlings under naturally occurring droughty and well-watered conditions. Improving the growing conditions for two years with intensive vegetation control has enabled seedlings to continue vigorous growth beyond chemical persistence on this site. Biodiversity of plant species other than the intended crop are also important on managed lands and while these data demonstrate that herbicides dramatically affect plants during the year applied, they did not eradicate any of the plant growth forms present on the site. When applied judiciously, vegetation management regimes common to the establishment of intensively-managed Pacific Northwest Douglas-fir plantations can restrain vegetation community growth, improve planted seedling growth, and maintain diverse vegetation communities on multi-year timescales.

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