Microsite Influences on Variability in Douglas-Fir Seedling Development

Owen Burney, Michael G. Wing, and Robin Rose

ABSTRACT

We examined the microsite characteristics of 6,048 Douglas-fir seedlings at three regeneration sites in Washington state. Our objective was to determine the microsite characteristics that were most influential on seedling growth change over time. We analyzed microsite influences both individually and in concert with one another through regression-based techniques. Microsite parameters included soil impedance, topographic, and physical parameter measurements that were recorded at each seedling's location. Akaike's information criterion (AIC) was used to determine combinations of microsite parameters that were most strongly correlated with seedling growth. Multiparameter models explained between 15 and 39 percent of the variance in diameter growth. Prevalent terms from the strongest multiparameter models included soil penetration, log presence, stump presence, skid road presence, and topography. Individual microsite parameters for each regeneration site were also assessed for importance in explaining diameter growth using two additional methods. The first approach was to isolate the parameters that appeared in the strongest multiparameter models and to sum and contrast the AIC weights of all models in which they appeared. The second approach was to regress single parameters against seedling diameter growth. Results varied by site for both methods. AIC weight sums revealed that topographical depression and berms, the presences of logs and stumps, and soil penetration (pounds per square inch) as measured by a penetrometer were most influential, with values ranging from 0.31 (berm) to 0.82 (log). Regression analysis revealed that topographical depression, log presence, and soil penetration were significantly related to diameter growth, explaining between 6 and 29 percent of the variance in diameter growth. Combined results from the three regeneration sites suggest that preferred planting locations are near berms, in the transition zone associated with skid roads, and in soil that is neither too loose nor too compacted. Results from the Randle and Orting sites indicate that planting in topographical depressions should be avoided. Results from Orting indicate that seedlings should not be placed near logs, and Randle findings suggest not planting next to stumps.

Keywords: Seedling growth, Akaike's information criterion, modeling

Tree seedling performance varies throughout forest regeneration sites in the US Pacific Northwest. Seedling performance variability can be attributed not only to tree species characteristics but also to the microsite environments that are associated with individual seedlings. Microsite environments on regeneration sites are influenced by past activities, such as harvesting, natural disturbances, site preparation, and other management and landscape conditions. Combinations of influential factors can create microsite characteristics that fluctuate at spatial extents smaller than several square centimeters (Harper 1977, Sutton 1993).

Identifying those microsite conditions that significantly influence seedling performance can provide insight into preferred site preparation and management. Past studies have attempted to define the most influential microsite characteristics but have typically considered a limited number of measured parameters. Oswald and Neuenschwander (1993) observed that microtopography (e.g., depressions and berms) and soil texture greatly influenced seedling growth. DeLong et al. (1997) found that the presence of rotten logs, berms, and exposed seedbeds were important for the establishment of white spruce (*Picea glauca* (Moench) Voss). Norway spruce (*Picea abies*) growth has been found to be stimulated by the presence of large stumps and logging slash (Jonsson 1999). Van Lear et al. (2000) discovered that the presence of stumps created a positive influence on loblolly pine (*Pinus taeda*) due to seedling ability to colonize the stump root system. Quine et al. (1991), however, found that Sitka spruce (*Picea sitchensis*) seedlings planted next to a stump showed root growth reductions due to asymmetrical root system development in response to growth barriers imposed by stumps. In addition, root growth imbalance was not compensated for on the other side of the seedling.

Soil structure is a microsite characteristic that can be easily altered by harvesting and site preparation activities with the dominant influence being soil compaction as measured by bulk density. Soil compaction influences pore-size distribution by altering the balance between aeration porosity and available water holding capacity (Siegel-Issem et al. 2005). At low levels of compaction, the balance between aeration and water holding capacity provides an ideal growing environment, as seen with ponderosa pine (*Pinus ponderosa*) (Gomez et al. 2002). As compaction levels increase, macropores, root space, and water availability decrease and result in reduced root development and therefore reduced overall tree performance (Greacen and Sands 1980, Wert and Thomas 1981, Corns 1988, Conlin and van de Driessche 1996).

Recognition of general soil and landscape characteristics that influence seedling growth can assist reforestation planning efforts by identifying preferred regeneration areas. Choosing specifically where to plant seedlings within preferred regeneration areas should be based on knowledge of the most influential microsite parameters. Consequently, identifying preferred planting locations (microsites) that can be easily discerned in the field may help tree planters locate

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optimal planting locations and lead to increased seedling performance (Lloyd and Elder 1997, Burton et al. 2000).

We investigated the influence of microsite characteristics on tree seedling development for three tree regeneration sites using Akaike's information criterion and regression analysis techniques. We are unaware of any research efforts to study seedling microsite differences in this way. Our objective was to identify microsite parameters, either individually or in concert, that were the most influential on seedling development as characterized by growth diameter change over several years' time. We examined a variety of microsite parameters but based the majority of our parameter selections on parameters that could be quickly located and measured in the field.

Methods

Site Description

Microsite characteristics were assessed at three regeneration sites in Washington state that are identified henceforth as Belfair, Orting, and Randle. All three sites were dominated by *Pseudotsuga menziesii* prior to being harvested and are characterized by relatively level and uniform topography. Differences exist, however, between the sites in terms of precipitation, soil type, elevation, site index, and the amount of soil disturbance resulting from harvesting. All sites were replanted with stocktype 1 + 1 Douglas-fir seedlings following harvest. The seedling lots had a broad genetic base, were drawn from the study areas to reflect local conditions, and were also planted in the surrounding areas.

The Belfair site is located at an elevation of 122 m and has a glacial outwash soil that represents the poorest soil type for tree regeneration among all the sites. The Belfair site has a 50-year site index of 33 m and receives 125–177 cm of precipitation each year, mostly as rain but also from snowmelt. The Belfair site was harvested during the summer of 1996 and was subjected to compaction by heavy equipment used to pile slash and remove existing woody vegetation. Slash was piled and left on-site. Seedlings were established in February of 1997.

The Orting site is located at an elevation of approximately 520 m on the western slope of Mount Rainier and receives 165–175 cm of precipitation each year. The 50-year site index is 38 m, and the soil is a deep loam and relatively well drained. Site harvesting occurred during the summer of 1996 through whole-tree yarder skidding that minimized slash and compaction. Remaining slash was piled and burned, and seedlings were planted in February of 1997.

The Randle site is at an elevation of 610 m and has a 50-year site index of 37 m. The average rainfall per year is 130–165 cm, with long dry periods occurring during the summer months. Soils were recently influenced by the eruption of Mount St. Helens in 1980, which deposited ash deposits 15–20 cm deep on the upper soil horizon. The Randle site was harvested in 1997 through ground-based shovel logging techniques, slash was piled and burned, and seedlings were established in spring of 1998.

Study Design

The microsite characteristics data that we analyzed were collected in tandem with a study to characterize changes in seedling growth with 12 treatment combinations (Rose and Ketchum 2003). The treatment combinations consisted of two stock sizes (5–8 and 8–12 mm), two vegetation control treatments (2 and 3 years of control), and three fertilizer application treatments (no fertilizer, 1 year, and 2 years). To isolate microsite influences, we removed treatment effects from seedling growth responses. We calculated an estimated mean seedling diameter for each treatment plot through least squares regression techniques. These estimated mean values were subtracted from the observed growth diameter measurements to produce a unique residual value that represented average seedling growth without treatment effects. This treatment-free data set was used to analyze the effects that microsite characteristics had on changes on seedling growth as measured by stem diameter at 15 cm above ground line. Stem diameters included in our analysis were taken 3 years after planting at the Randle site and 4 years after planting at the Orting and Belfair sites.

Table 1. Measured microsite parameters and descriptions.

Parameters	Measurement
Tree diameter	Caliper measurement (mm) taken 15 cm above ground line
Planting location[a]	Burn piles: burned piles of slash and logging debris Logs: tree stems >30 cm in diameter not in high decay (decay class 4 and 5) Skid roads: compacted soil resulting from harvest equipment Slash: small woody debris <30 cm in diameter not piled Tree stumps: any species that is not in high decay
Soil impedance[b]	Measured at 15 and 30 cm depth with penetrometer
Topography[c]	Berm: on inclined or raised ground Depression: in area that is lower than surrounding area Flat: no apparent topography

[a] Presence or absence of objects located within 1 m radius of seedling stem.
[b] Pressure (psi) measured in 4 locations at the dripline of the seedling.
[c] Visual assessment of immediate seedling location within 1 m radius of seedling stem.

Microsite Parameters

Microsite characteristics were measured for 6,048 seedlings at the regeneration sites and included seedling diameter, localized topography, planting location, and soil impedance (Table 1). Topography and planting location measurements were taken within a 1-m radius of the tree base (Figure 1). Soil impedance was measured (pounds per square inch) at the drip line of every tree with a penetrometer. Impedance measurements were taken at two depths (15 and 30 cm) on the north and east sides of each seedling and averaged across the directional aspects. These measurements were used to create average penetration characteristics at 15- and 30-cm depths and also an overall average that incorporated all penetration measurements. No penetrometer measurements were taken at the Belfair site because the soils were mostly glacial till, making it virtually impossible to use the penetrometer.

Statistical Analyses

Data were statistically analyzed through two approaches: Akaike's information criterion (AIC) (Akaike 1974) and simple linear regression. Both statistical analyses considered seedling diameter growth change as the response parameter and are described below.

AIC Analysis

AIC was used to select the best regression model from among all measured microsite parameters for each study site. Correlations between explanatory parameters were tested prior to analysis to determine whether any parameter combination would be confounded by

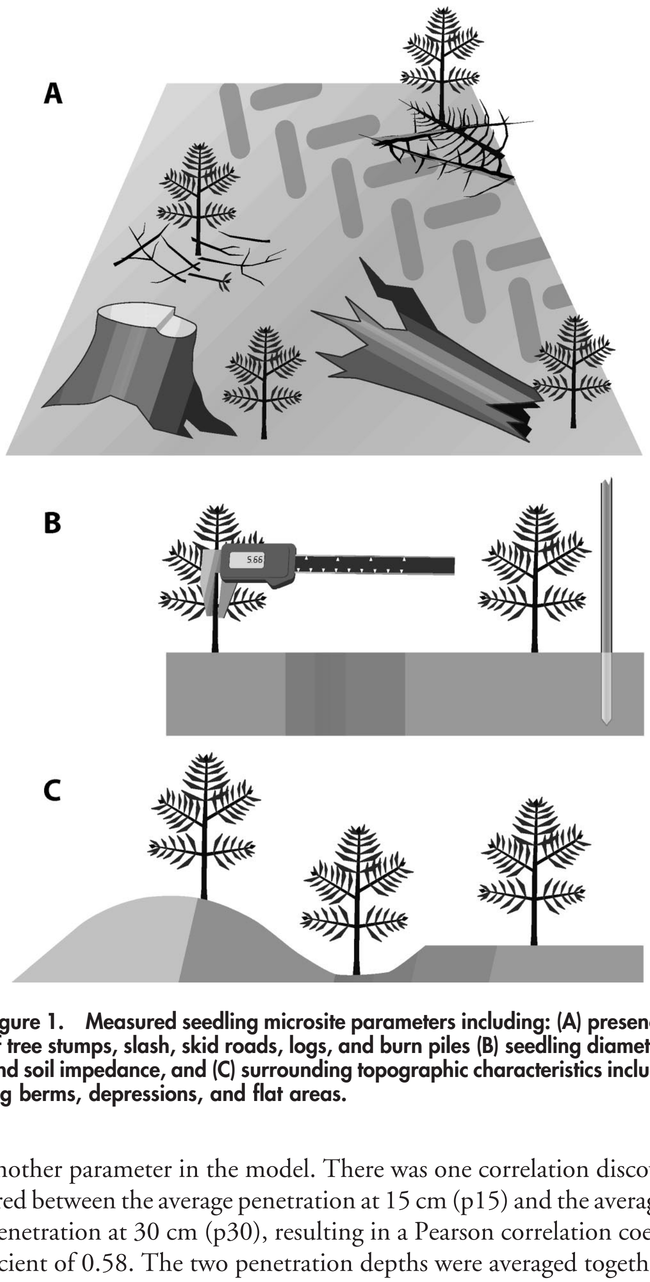

Figure 1. Measured seedling microsite parameters including: (A) presence of tree stumps, slash, skid roads, logs, and burn piles (B) seedling diameter and soil impedance, and (C) surrounding topographic characteristics including berms, depressions, and flat areas.

another parameter in the model. There was one correlation discovered between the average penetration at 15 cm (p15) and the average penetration at 30 cm (p30), resulting in a Pearson correlation coefficient of 0.58. The two penetration depths were averaged together to create an average penetration parameter (avgpen) so that correlation influence was reduced. All three penetration parameters were used in the AIC model selection process but were never included together in the same model. Another new parameter was created because of the theory that soil penetration influenced diameter growth in a quadratic response. A regression analysis on diameter growth determined which soil penetration parameter (p15, p30, or avgpen) to use in this quadratic equation. Regression results found that p15 had a significant influence on diameter growth, whereas p30 and avgpen explained less variance for all sites and produced insignificant model results for the Randle site. Consequently a quadratic soil penetration parameter ($p15^2$) was created.

AIC is based on Kullback-Leibler information theory (Kullback and Leibler 1951) and seeks to optimize parameter estimation and model selection. A maximized log-likelihood function is used to create an AIC index, which is used to rank all candidate models; a smaller AIC index indicates a better model (Anderson et al. 2000).

Model significance can be assessed by using AIC Δ and AIC weights. AIC Δ is defined as the difference (Δ) between the AIC index of each model relative to the smallest (best) AIC index value. Models with $\Delta < 2$ generally have substantial support for use in making inferences, and models with $\Delta > 2$ are less trustworthy (Burnham and Anderson 2002). AIC weights define the approximate probability that an individual model is the best out of the set of candidate models. AIC weights can also be used to assess which single parameters are most influential on the dependent variable of diameter growth. This assessment involves summing the AIC weights of all models that contain a parameter of interest; the summed weights of single parameters can then be compared (Burnham and Anderson 2002).

Originally, 70 models per site were selected for a priori comparison on the basis of biological importance and operational logic. These models were reduced to the top 29 for the Orting and Randle sites and the top 20 for the Belfair site on the basis of the original AIC ranking so that relative AIC weight comparisons could be made for multiparameter models and individual parameters. Belfair only had 20 top models because of the lack of soil penetrometer measurements taken at that site. All models were ranked by AIC index values from best to worst. A null model was also included to determine a baseline AIC index value against which all other models could be compared. Models with rankings inferior to the null model were removed from consideration as significant explanatory models. All models were tested for constant variance, linearity, and normality assumptions, and where these assumptions were not met, data transformations were applied. The removal of treatment effects and candidate models are represented by the equation:

$$\begin{aligned} Y_{ij} - (\mu + T_i + \beta_j) \\ &= \beta_0 + \beta_{1(\text{soil penetration p15, p30, or avgpen})} + \beta_{2(p15^2)} + \beta_{3(\text{flat})} \\ &\quad + \beta_{4(\text{berm})} + \beta_{5(\text{depression})} + \beta_{6(\text{stump})} \\ &\quad + \beta_{7(\text{log})} + \beta_{8(\text{skid road})} + \beta_{9(\text{burn pile})} + \beta_{10(\text{slash})} + \epsilon_{ijk}, \qquad (1) \end{aligned}$$

where $i = 12$; $j = 5$; $k = 2{,}160$ each for Belfair and Randle, 1,728 for Orting; Y_{ij} = growth diameter responses (averaged within plot); μ = overall estimated mean; T_i = treatment effect estimate; β_j = block effect estimate; β_0 = intercept; $\beta_{1(\text{soil penetration})}$ = soil penetration (p15, p30, or avgpen); $\beta_{2(p15^2)}$ = quadratic soil penetration ($p15^2$); $\beta_{3(\text{flat})}$ = flat topography, if present; $\beta_{4(\text{berm})}$ = berm topography, if present; $\beta_{5(\text{depression})}$ = depression topography, if present; $\beta_{6(\text{stump})}$ = stump topography, if present; $\beta_{7(\text{log})}$ = log topography, if present; $\beta_{8(\text{skid road})}$ = skid road topography, if present; $\beta_{9(\text{burn pile})}$ = burn pile topography, if present; $\beta_{10(\text{slash})}$ = slash topography, if present; ε_{ijk} = error between seedlings; and where $\varepsilon_{ijk} \sim N(0, \delta^2)$ and ε_{ijk} and $\varepsilon_{i'j'k'}$ are independent.

Linear Regression Analysis

Simple linear regression was used to also analyze the influence of each individual microsite parameter on seedling growth performance. Each microsite parameter was tested for normality and constant variance, with data transformations being applied when normality assumptions were not met. Similarly to the AIC analysis, a residual growth diameter free of treatment effects served as the response parameter.

Results

Single-Parameter Distributions

The number and percentage of seedlings associated with each of the microsite planting locations and topography are listed in Table

Table 2. Number and percent of seedlings associated with microsite planting topography and locations.[a]

	Total	Burn	Log	Skid	Slash	Stump	Berm	Dep	Flat
Randle									
n	2,160	40	282	317	22	193	248	79	1,833
%		2%	13%	15%	1%	9%	11%	4%	85%
Orting									
n	1,728	17	348	77	26	265	318	148	1,235
%		1%	20%	4%	2%	15%	18%	9%	71%
Belfair									
n	2,160	0	158	116	29	381	301	124	1,714
%		0%	7%	5%	1%	18%	14%	6%	79%

[a] Burn, presence of burn piles. Log, presence of logs. Skid, presence of skid roads. Slash, presence of slash debris. Stump, presence of stumps. Berm, berm microsite topography. Dep, depression microsite topography. Flat, flat microsite topography.

2. The majority (85 percent) of the 2,160 seedlings at the Randle site were found on flat topography, 15 percent on or near skid roads, 13 percent next to a log, and 9 percent next to a stump. The Orting site had 1,728 total seedlings with 71 percent on flat topography, 20 percent next to a log, 18 percent on a berm, and 15 percent next to a stump. Approximately 79 percent of the 2,160 seedlings at the Belfair site were on flat ground, 18 percent were near stumps, and 14 percent were on berms.

AIC Model Selection

Candidate models at each study site were ranked on the basis of AIC indices, Δ values, and AIC weights (Table 3). The top-ranked models from each site were used to identify the parameter or set of parameters that best explained diameter growth. On the Randle site, the first 13 models had AIC Δ values less than 2 and can be considered valid if change (Δ) among the AIC indices is used as the sole evaluative consideration. The amount of variance explained by each model, however, drops from 25 percent to 14 percent after the fourth model and no new parameters are introduced in subsequent models, suggesting that the first four models be considered. When comparing the AIC weight of the best model against the next three best models, these AIC weight ratios were 1.02, 1.02, and 1.28, respectively. The best-ranked model at the Randle site explained 22 percent of the variation in growth diameter and included soil penetration (15 cm), quadratic soil penetration, stump, and depressions. The second-best model explained 18 percent of the variation in growth diameter and included soil penetration (15 cm), quadratic soil penetration, and stump presence; and the third-ranked model explained 21 percent of the variation and included soil penetration (15 cm), skid roads, stump presence, and depressions. The fourth model was nearly identical to the third in terms of parameters but included the quadratic soil penetration parameter.

The Orting site had three top competing models based on AIC weight ratios and AIC index differences. The ratios of the best AIC ranked model compared with the second and third were 1.02 and 2.16 (Table 3). AIC index differences from this best model rose above the inference threshold ($\Delta < 2$) after the third-ranked model. The parameter model with the best AIC ranking for the Orting site included soil penetration (15 cm) and log presence and explained 35 percent of the variation in growth diameter. The second-ranked model explained 39 percent of the variance in growth diameter and included soil penetration (15 cm), quadratic soil penetration, and log presence. The third-best model included only log presence and explained 29 percent of the variation.

Since the Belfair site did not include soil penetration measurements, parameters tested in the AIC models only included planting location and microsite topography. AIC weight ratios comparing the best model against the next three models were 1.57, 2.04, and 2.15, respectively. The best-ranked AIC model selected included the flat topography and log presence parameters, which combined to explain 20 percent of the variation in growth diameter. The second-ranked model included berms and log presence and explained 19

Table 3. Akaike's information criterion (AIC) model parameters selection results for Randle, Orting, and Belfair.[a]

	Randle models	AIC				Orting models	AIC				Belfair models	AIC			
		AIC	Δ	W_i	R^2		AIC	Δ	W_i	R^2		AIC	Δ	W_i	R^2
1	p15 $p15^2$ stump dep	290.35	0.00	0.100	0.22	p15 log	262.85	0.00	0.335	0.35	Flat log	313.08	0.00	0.282	0.20
2	p15 $p15^2$ stump	290.38	0.03	0.098	0.18	p15 $p15^2$ log	262.88	0.04	0.328	0.39	Berm log	313.99	0.91	0.179	0.19
3	p15 skid stump dep	290.40	0.04	0.098	0.21	Log	264.38	1.54	0.155	0.29	Flat	314.50	1.43	0.138	0.15
4	p15 $p15^2$ skid stump dep	290.85	0.49	0.078	0.25	p15 Skid stump	267.08	4.23	0.040	0.33	Skid log Flat	314.61	1.53	0.131	0.21
5	p15 dep	290.89	0.54	0.076	0.14	p15 skid	267.70	4.85	0.030	0.28	Skid stump flat	315.58	2.50	0.081	0.20
6	Stump dep	291.15	0.80	0.067	0.13	p15 $p15^2$ skid	268.87	6.02	0.017	0.30	Berm	315.68	2.61	0.077	0.13
7	p15 $p15^2$ dep	291.17	0.81	0.067	0.17	p15 stump	268.90	6.05	0.016	0.26	Skid stump berm	317.61	4.53	0.029	0.17
8	Stump	291.60	1.25	0.053	0.09	p15 skid stump dep	268.98	6.13	0.016	0.35	Berm slash	317.91	4.83	0.025	0.13
9	p15 stump	291.62	1.27	0.053	0.13	p15 $p15^2$ skid stump	269.00	6.16	0.015	0.35	Dep log	318.82	5.74	0.016	0.12
10	Skid dep	291.83	1.48	0.048	0.12	p15 $p15^2$ stump	269.76	6.91	0.011	0.29	Log	319.40	6.32	0.012	0.07
11	Skid stump	292.02	1.67	0.043	0.12	p15 $p15^2$	269.85	7.00	0.010	0.25	Dep	320.34	7.26	0.007	0.07
12	p15 $p15^2$ skid Stump	292.27	1.92	0.038	0.19	p15	269.91	7.06	0.010	0.21	Null model	321.70	8.63	0.004	
13	Dep	292.27	1.92	0.038	0.08	p15 $p15^2$ skid stump dep	271.45	8.60	0.005	0.36					
14	p15 skid stump	292.98	2.62	0.027	0.14	p15 $p15^2$ stump dep	272.06	9.21	0.003	0.05					
15	p15 $p15^2$	293.51	3.16	0.021	0.10	p15 dep	272.41	9.56	0.003	0.21					
16	p15	293.78	3.42	0.018	0.06	Avgpen	272.48	9.64	0.003	0.16					
17	Null model	294.91	4.55	0.010		p15 $p15^2$ dep	272.49	9.64	0.003	0.25					
18						p30	276.31	13.46	0.000	0.09					
19						Null model	278.50	15.65	0.000						

[a] Rank, ranking according to AIC value. Δ, difference from best model. AIC W_i, weighted average based on Δ. Avgpen, average soil penetration. Berm, berm microsite topography. Burn, presence of burn piles. Dep, depression microsite topography. Flat, flat microsite topography. Log, presence of logs. p15, soil penetration at a depth of 15 cm (psi). $p15^2$, quadratic soil penetration (15 cm). p30, soil penetration at a depth of 30 cm (psi). Skid, presence of skid roads.

Table 4. Individual microsite regression coefficients and variance explained (adjusted R^2) in diameter growth of tree seedlings.[a]

	Randle		Orting		Belfair	
Microsite parameter	Coefficient estimate	Explained variance	Coefficient estimate	Explained variance	Coefficient estimate	Explained variance
Avgpen	0.01	2%	0.03^b	16%	N/A	N/A
Berm	1.72	0%	5.95	4%	9.70^b	13%
Burn	−10.45	3%	−26.42	2%	N/A	N/A
Dep	-12.19^b	8%	−3.44	1%	11.18^b	6%
Flat	5.28	3%	−1.58	1%	-7.52^b	15%
Log	−2.81	1%	-15.68^b	29%	17.13^b	7%
p15	0.01^b	6%	0.03^b	21%	N/A	N/A
p30	<0.01	1%	0.02^b	9%	N/A	N/A
Skid	1.91	1%	0.23	0%	1.99	0%
Slash	−20.59	2%	−28.10	4%	2.12	0%
Stump	-15.98^b	9%	1.17	0%	4.16	1%

[a] Coefficient estimates used in this table are defined as β_1 in the regression equation $Y = \beta_0 + \beta_1$ (microsite parameter). Avgpen, average of p15 and p30. Berm, berm microsite topography. Burn, presence of burn piles. Dep, depression microsite topography. Flat, flat microsite topography. Log, presence of logs. p15, soil penetration at a depth of 15 cm (psi). p30, soil penetration at a depth of 30 cm (psi). Skid, presence of skid roads. Slash, presence of slash debris. Stump, presence of stumps. N/A, not available.

[b] $P < 0.05$.

percent of the variation in growth diameter. The third-ranked AIC model included only flat topography and explained 15 percent of the variation in growth diameter. The fourth ranked model explained more variation (21 percent) than the third model and included two more parameters (stump presence and flat topography). The fifth model had an AIC index that differed by more than 2 from the top AIC model.

Single-Parameter Analysis

Individual parameters were analyzed by regression and AIC weight summations. In the regression analysis, all microsite parameters for each site were regressed individually against diameter growth to determine the parameters that explained the most variance (Table 4). Single variables explained between 0 and 9 percent of the variance in diameter growth at the Randle site. The three most significant explanatory parameters for the Randle site were stumps, depressions, and soil penetration (15 cm). The presence of stumps and depressions had a negative influence on diameter response, whereas soil penetration (15 cm) had a positive influence.

Correlations between microsite parameters and diameter growth at the Orting site were more abundant and stronger than at the other two sites. Log presence was found to be the most influential microsite parameter on diameter growth, with a negative influence. Soil penetration (15 and 30 cm) and average soil penetration were the next most influential parameters and had a positive impact on diameter.

No soil penetration measurements were taken on the Belfair site because of site conditions, but among the parameters tested, flat topography explained the most variance (15 percent) and had a negative affect on growth diameter. Berm topography (15 percent) and log presence (7 percent) were the next most influential parameters and affected growth diameter positively.

For each site, AIC weights were used to assess the relative importance of single parameters by summing the AIC weights of all the different models containing the parameter. The closer the value calculated is to 1, the more influential the single parameter is in comparison with other parameters in explaining seedling diameter growth. Parameters of interest were selected based on prevalence in the top AIC models discussed earlier. At the Randle site, AIC weights for the single parameters of depression topography, stump presence, quadratic soil penetration, and skid road presence were 0.57, 0.56, 0.41, and 0.31, respectively. The parameters chosen at the Orting site were log presence and quadratic soil penetration, with values of 0.82 and 0.39, respectively. The parameters at the Belfair site were flat topography, log presence, berm topography, and skid road presence, with values of 0.63, 0.49, 0.31, and 0.25, respectively.

Discussion

Topography

Diameter growth was influenced both positively and negatively by microsite topography, as shown by the single-parameter regression results. The negative diameter response we observed in seedlings planted in depressions at the Randle site and the positive diameter responses from seedlings planted on berms at the Belfair site were similar to the relationships observed by Burton et al. (2000). Berm topography, however, was significant as a single parameter only at the Belfair site. Berms typically have low soil bulk density, allowing roots to penetrate farther into the soil (DeLong et al. 1997) to use greater amounts of soil resources. Tabbush and Ray (1989) found that seedling planted on berms had concentrated root growth toward the center of the berm, possibly because of the ease of soil penetration and greater amount of soil water. In contrast to the Randle site, topographic depressions were positively related to diameter growth at the Belfair site. Flat topography emerged as a parameter in several of the top AIC models (Table 3) and was also found to be influential as a single parameter on diameter growth at the Belfair site, but with a negative influence (Table 4). The unexpected results for the individual topographic parameters at the Belfair site are likely caused by the predominant glacial till composing the majority of the Belfair area. Topographic depressions at the Belfair site might represent areas where the glacial till was less prevalent than in level areas.

Planting Location

The presence of stumps was a parameter in the top four AIC models for the Randle site but was not a dominant parameter in AIC models for the other sites (Table 3). Results from the single-parameter regression analysis found that stumps had a significant negative influence on diameter growth (Table 4). This is in contrast to previous research that suggests that stumps can provide natural protective shade, leading to better seedling growth and survival. Jacobs and Steinbeck (2001) found that shade can significantly increase growth and survival of Engelmann spruce (*Picea engelmannii*) seedlings. On the Randle site, shade may be less a factor in growth than the proximity of the seedling planted to the tree stump. Quine et al. (1991)

found that root growth of Sitka spruce (*Picea sitchensis*) planted next to stumps would cease growth toward the stump, deflect downward, and not compensate for root growth on the opposite side of the seedling. In our study, reduced root growth next to stumps may have been the reason for the diminished growth observed in the single-parameter regression analysis.

The presence of logs was a prevalent parameter in the top AIC models for the Orting and Belfair regeneration sites (Table 3). Approximately 20 percent of the seedlings on the Orting site were in proximity to logs (tree stems >30 cm in diameter), and as a single parameter, logs explained 29 percent of the variance in seedling diameter growth and had a negative influence (Table 4). In contrast, log presence was positively associated with diameter growth at the Belfair site but only explained 7 percent variance. Previous research (Rose 1992) suggests that planting seedlings next to logs may lead to better growth and survival because of the shade provided. It is unclear why logs negatively influenced diameter growth at the Orting site, but this may be a result of competition between seedlings and logs.

Seedlings planted in skid roads can suffer significant growth loss due to high levels of soil compaction. Our observations in this study found the opposite in which diameter growth increased for seedlings planted in skid roads. One explanation is that the presence of skid roads included not only seedlings planted in the actual road but likely also included seedlings planted directly beside the road, when planters were unable to use highly compacted road areas. This area is known as the "transition zone" and has been associated with higher growth rates than seedlings planted in the skid road (Wert and Thomas 1981). Heninger et al. (2002) found that seedlings planted directly in skid trail ruts demonstrated reduced average height growth in comparison with seedlings in surrounding areas.

Burn piles were found to have no statistically significant effect on diameter growth responses in the single-parameter analysis and did not appear as a parameter in the final AIC models. A possible explanation for this result is that less than 2 percent of all measured seedlings were in immediate proximity to burn piles. In addition, previous studies have mixed results of the influence of fire and burned landscapes on seedling growth with results reflecting fire intensity and microsite variation (e.g., topography, soil, and other forest floor conditions). Isaac (1963) found that seedlings in burned areas were twice as tall as those in unburned areas and attributed the height differences to less competing vegetation in burned areas. Stein (1986, 1989) reported that improved seedling survival and growth rates occurred in burned areas in the first 7 years following planting and found that evidence of animal browsing was reduced in burned seedling plots. Seedling performance can be negatively affected by burning (Loucks et al. 1987) when intense fire damages soil structure properties and causes excessive loss of nutrients. Minore (1986) found that the height growth of 5-year-old Douglas-fir seedlings was reduced for seedlings in burn piles in comparison with seedlings in areas that were broadcast burned.

Slash was not significantly related to diameter growth as single parameter, and the top AIC models also did not include slash as a parameter. Less than 2 percent of all seedlings at all sites were located next to slash, and this likely reflects the difficulty associated with planting near slash (Hakkila 1973). Oswald and Neuenschwander (1993) found that slash explained only 1 percent of the variation (negative impact) of growth observed in western larch seedlings (*Larix occidentalis* Nunn.).

Soil Penetration

Soil compaction has been observed by others to reduce root growth and overall seedling performance (Greacen and Sands 1980, Corns 1988, Conlin and van de Driessche 1996). The relationship of soil penetration impedance, which measures the level of soil compaction in terms of resistance (pounds per square inch), with diameter growth showed a quadratic response for the Randle and Orting sites. This quadratic response suggests that initial reductions in diameter growth are not due to compaction but rather to a lack of bulk density. As soil density increases in a given volume (bulk density), penetration impedance also increases to a threshold point where water, aeration, and nutrients become less available (Corns 1988). Overall, the soil penetration was prevalent as a single parameter and as an AIC model parameter in explaining variance in seedling diameter growth.

Conclusions

Our study objective was to analyze microsite parameters that could be quickly located and measured in the field. There are likely other microsite characteristics, such as soil nutrients and water conditions, which were not included in this study that influence growing conditions and could not be assessed in our analysis. It is also probable that natural variability in the study sites and seedling growth patterns make consistent identification of growth influences less certain. In addition, study results might have differed had greater precision been used to measure discrete distances, such as the distance to the nearest road or slash pile, rather than whether a microsite characteristic occurred in the immediate vicinity of a seedling. Nonetheless, this study provides an initial approach to studying microsite influences on seedlings on an unprecedented scale. We encourage others to further refine approaches to better understanding microsite relationships to seedling development.

Although no single microsite characteristic explained large amounts of variance, certain microsite characteristics were better at explaining tree growth than others. The microsite characteristics that were most often correlated with seedling growth differed among the three study sites and suggest that each site and its history play important roles in defining significant microsite factors. We found that some microsite characteristics do have a measurable influence on seedling growth. Study results provide some recommendations for where to plant seedlings but are linked only to sites that are of similar environmental conditions and historical influences. The combined and individual statistical results from the three regeneration sites that were analyzed in this study suggest planting locations near berms and in the transition zone associated with skid roads. Plant in soil that is neither too loose nor too compacted; this condition can be assessed by penetrating the upper soil horizon with a planting shovel. In addition, results from the Randle and Orting sites suggested that planting in topographical depressions should be avoided. Although there may be benefits to providing shade from sunlight for seedlings, results from Orting indicate that seedlings should not be placed in close proximity to logs, and Randle findings suggest a similar recommendation for planting next to stumps.

To maximize seedling growth potential, planters should consider the recommendations we provide above for establishing seedling locations. Further research is needed however, to better quantify microsite and surrounding landscape characteristics that promote seedling growth. Future research efforts on seedling growth patterns may want to consider geo-referencing individual seedling locations and surrounding features, such as slash piles and logs. Georeferencing would enable a GIS to calculate distances from seedlings to other features and provide a more precise approach to quantifying microsite influences, such as the distance to nearest skid road. Local topography, such as berms and depressions, had an influence on seedling development at all three regeneration sites. Future research might also involve developing a digital terrain model (DTM) of the surrounding landscape. Analysis of the DTM could provide an improved definition of the topography associated with individual seedlings. These suggested approaches may support research that further illustrates seedling development influences.

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