Abstract: Environmental conditions and seedling quality interact to produce complex patterns of seedling survival and growth. Root growth potential (RGP) is one metric of seedling quality that can be rapidly measured prior to planting, but the correlation of RGP and seedling performance is not consistent across studies. Site factors including microsite objects that cast shade and competing vegetation can also influence seedling performance. We examined the effects of RGP, presence/absence of a microsite object, and competition cover on the survival and growth of three native conifers to the Inland Northwest, USA, over 5 years. We found that RGP had no effect on the survival or growth of western larch (Larix occidentalis), Douglas fir (Pseudotsuga menziesii var. glauca), and grand fir (Abies grandis) at a mesic north aspect site and a xeric south aspect site. Comparatively, the presence of a microsite increased the odds of survival by 37% for western larch and 158% for grand fir, while the absence of forb cover increased the odds of survival of western larch by 72% and of grand fir by 26%. Douglas fir was less sensitive to microsites and competition. The strong effects of neighborhood conditions around seedlings help inform silvicultural practices to enhance the establishment of western larch and grand fir, including planting seedlings near shading objects and competition control, while these practices may not be as important for Douglas fir.

Keywords: seedling quality; growth; survival; aspect; competition; site quality

1. Introduction

Quickly reforesting stands through planting often provides better control of initial species composition and density compared to natural regeneration, and also allows for the introduction of improved genetics selected for rapid growth, desirable tree form, and disease resistance. Although planting seedlings is simple in concept, a much more nuanced understanding of seedling quality and seedling–environment interactions is required to ensure seedlings survive and grow at an optimal rate. Diverse macro- and microscale biotic and abiotic factors, along with the quality of seedlings produced by nurseries, interact to influence seedling performance [1]. These factors often interact in complex ways, resulting in sub-optimal growth or high mortality that can be difficult to predict [2]. Forest regeneration can also suffer or fail as a result of uninformed management decisions including: a lack of knowledge of the ecological characteristics of different species in relation to site conditions [3] and improper selection of planting stock in the context of management goals, ecological factors, and silvicultural options [4]. The Target Plant Concept provides a framework for evaluating these various interacting factors by matching the morphological and physiological characteristics of seedlings that are quantitatively linked to field performance [1].

Many have tried to define what quality means in the context of a seedling, but the general consensus is that quality is defined by seedling performance following planting [5]. Wakeley [6] was a pioneer in identifying that seedling quality assessments should be based on both morphological and physiological characteristics. Therefore, assessments of
seedling quality should include a seedling’s response to a given environment, performance attributes (i.e., root growth potential, cold hardiness), and the measurement of specific attributes of the seedling (i.e., morphology, dormancy, nutrition), also known as material attributes [7]. Both performance and material attributes provide information on how a seedling might perform in the field.

Root growth potential (RGP) is a common test of seedling quality, as it serves as an integrated assessment of the physiological health of a seedling to grow roots in a favorable environment [5]. RGP testing is typically performed in a lab with controlled environmental conditions or in greenhouses, and therefore does not account for the range of environmental conditions a seedling is exposed to following outplanting [8]. Therefore, there has been considerable debate on the utility of RGP for predicting outplanting performance [9]. However, a seedling that is able to quickly grow new roots when planted in a new environment may overcome the stress of transplanting more quickly than a seedling with reduced root growth, as it is more quickly “coupled” with the new environment [10]. RGP has served as an indicator of seedling vigor [11], and field performance has been positively linked to RGP in conifers [7], including western larch (Larix occidentalis Nutt.) and interior Douglas fir (Pseudotsuga menziesii var. glauca (Beissn.) Franco) [12].

Site quality is highly correlated with edaphic conditions and climate. In the drought-prone areas characteristic of the Inland Northwest (USA), moisture stress is the most common cause of forest plantation failure [3]. Moisture stress can negatively impact seedling physiology and lead to higher mortality, especially under conditions of high competition [13]. Drought-prone areas can also experience extreme temperature conditions that can reduce seedling shoot and root growth [14]. In temperate mountainous regions, aspect can also influence soil moisture and soil temperature by affecting solar insolation. On sites in the northern hemisphere on moderate to steep slopes, north and east aspect sites tend to have greater soil moisture and moderate temperatures in the summer due to greater shading, while south and west aspect sites are drier and warmer due in part to greater amounts of direct radiation during the day [15]. These and other various factors interact to influence the quality of the site that can be managed by considering where to plant seedlings to protect them from extremes of soil moisture and temperature.

Stumps, large rocks, and large-diameter logs can cast shade and create microenvironments suitable to tree establishment, including lower light interception and temperature. In the northern hemisphere, these microsite features have the greatest effect for new germinants growing on the north side of the feature [16]. The larger size of planted seedlings compared to germinants suggests they may be more resistant to extreme environmental fluctuations; even so, planting seedlings on the north side of microsite features is a common reforestation practice in the northwestern USA. The benefits can vary by site quality. For example, at a site with lower water-holding capacity, seedling size was greater when 40% slash was maintained as compared to a site with three times higher water-holding capacity where there was no effect of slash retention treatment [17].

Competing vegetation influences seedling success by reducing growth; when competition is high, seedling survival can also decrease [18,19]. Since the effects of competition on seedlings is based on resource availability, resource capture, and space, competition is likely to have a greater effect on seedling survival on sites with lower productivity [20]. Tree species also respond differently to competition, where early successional species have aboveground growth traits to avoid competition, while late successional species are better able to tolerate competition [21]. When competition is high, especially from herbaceous species that primarily compete with tree seedlings belowground, early successional species may not be able to avoid competition, which may lead to increased mortality and reduced growth. Early competition, whether it induces an avoidance or tolerance strategy, can have deleterious effects on tree growth many years after establishment [22,23], suggesting early competition control is critical for the optimal performance of newly established forests.

Even with appropriate planting stock selection and favorable site conditions for successful establishment, conifer plantations still occasionally fail. The reasons for these
failures are often difficult to discern and can be due to a combination of factors. While there have been many studies examining how RGP relates to the field performance of planted seedlings and how site characteristics influence the seedling growth and survival, less is known about how the expression of RGP is influenced by site characteristics, if the effects of RGP persist multiple years after planting, and the importance of RGP versus microsite conditions with regard to seedling survival and growth. Therefore, the objective of this study was to examine the survival and growth of western larch, interior Douglas fir, and grand fir (Abies grandis (Douglas ex D. Don) Lindl.) seedlings 5 years after planting on a north aspect (i.e., cool and moist) and south aspect (i.e., hot and dry) site in northern Idaho, USA. RGP effects were examined at the population level, while the effects of competing vegetation and microsite presence/absence were examined for individual seedlings.

2. Materials and Methods

2.1. Planting Stock and Root Growth Potential

Western larch, Douglas fir, and grand fir seedlings were obtained from various private nurseries in the northwestern USA and western Canada which used proprietary nursery regimes to produce seedlings. All seedlings were 1 + 0 containerized seedlings grown in 415C Styroblock® containers (Beaver Plastics Ltd., Acheson, AB, Canada). A total of 20 Douglas fir, 14 western larch, and 4 grand fir seedlots were tested for RGP.

RGP was measured shortly after seedlings arrived at the Center for Forest Nursery and Seedling Research Seedling Quality Lab at the University of Idaho from the private nurseries. RGP was measured for 15 seedlings per unique nursery–seedlot combination with aeroponic chambers using a pulsating garden sprinkler attached to a 0.735 W utility submersible pump that sprayed the roots with water to stimulate growth over a 21-day period, similar to the mist chambers described by [8]. The air temperature in the laboratory and water temperature were kept constant at 20°C using an aquarium heater. The sprinkler was set to spray water for 1 min, followed by no water for 4 min throughout the duration of the testing. LED lights were suspended over the chambers. Each LED light fixture had 8 light modules. Each module was 4 cm wide by 123 cm long with 87 bulbs each, emitting 85:10:5 red:blue:green light (DR/W LED 120-110 V, Philips, TX, USA). LED lights were arranged to provide 125 µmol m⁻² s⁻¹ of supplemental light. The LED lights remained on for 12 h followed by 12 h of no supplemental light. At the end of each test, the number of new root tips ≥ 1 cm long were counted for each seedling and averaged among the 15 seedlings tested per seedlot. Seedling height, root collar diameter, and root volume were measured on seedlings prior to testing (Table A1).

2.2. Site Description

The study was installed on land owned by PotlatchDeltic Corp. in Latah County, Idaho, USA (elevation ~975 m) (Figure 1). The site is classified as a western redcedar (Thuja plicata Donn ex D. Don) vegetation series, which is considered to have high productivity in the region [24]. Soils of the south aspect site are classified as Brequito–Mushel complex soils, while those of the north aspect site are classified as Dworshak–Brequito complex soils. Soils at both sites are considered well-drained, with over 203 cm to a restrictive layer and parent material volcanic ash over loess over colluvium derived from metasedimentary rock [25]. Deep surficial volcanic ash deposits were present at both sites. Based on a nearby ground-based weather station in Elk River, Idaho, between 2010 and 2016, the mean annual precipitation was 588 mm, mean annual snow accumulation was 886 mm, and mean annual maximum and minimum temperatures were 36.5 °C and −18.2 °C, respectively. Prior to harvest, the stand was an 80-year-old even-aged mixed-conifer stand comprised of approximately 40% Douglas fir, 20% grand fir, 20% western larch, and 20% other species. The stand was clearcut-harvested in winter 2013 and remained fallow until seedlings were planted in spring 2016.
2.3. Study Design

The experiment consisted of 3 tree species (western larch, Douglas fir, and grand fir) planted at 2 sites with contrasting aspects (warmer, drier south aspect site and cooler, moister north aspect site). Seedlings were planted in a completely randomized block using a split-plot design with 3 blocks (Figure 2). The whole plot factor was species × RGP rating (i.e., high, moderate, or low) based on the aeroponic chamber RGP tests (Table A1). For Douglas fir and western larch, the low RGP rating included seedlots with average RGP values (average count of new roots produced in aeroponic chambers of the 15 seedlings per seedlot tested) per species less than or equal to the first quartile of all seedlots tested; the moderate rating included seedlots with average RGP values between the first and third quartile of all seedlots tested; and the high rating included seedlots with RGP values greater than or equal to the third quartile. The split-plot factor was seedlot within species × RGP rating; 2 seedlots were randomly selected among all seedlots within a RGP rating. RGP was only tested on 4 grand fir seedlots, so all 4 were included in this study. Each species × RGP rating whole-plot factor was randomized within each block. Blocks were based on slope position (i.e., upper, middle, lower slope). Each row contained 32 seedlings; the first 16 seedlings were from 1 seedlot followed by 16 seedlings from the second seedlot. Seedlings were spaced 2.4 m apart within a row, and rows were spaced 1.2 m apart.

Two weeks before planting, the sites were treated with a broadcast application of glyphosate herbicide at 2.8 kg active ingredient per hectare mixed with 2% nonionic surfactant in water to control existing vegetation. The glyphosate mixture was applied with a Model 4F CO₂ powered backpack sprayer with a 2.7 m overhead extended boom equipped with a single KLC-9 flood tip nozzle (Bellspray Inc., Opelousas, LA, USA). The sprayer was calibrated to apply 140.3 l ha⁻¹ of mix to the sites. Larger residual woody vegetation was hand-cut and moved off-site. Two months after planting, a directed application of glyphosate (5% tank concentration with 2% nonionic surfactant) was applied to the south aspect site since the initial treatment released a large amount of bracken fern (Pteridium aquilinum (L.) Kuhn). Planted seedlings were protected from herbicide contact by placing buckets over the top of the seedling. Some seedlings were incidentally damaged by herbicide and were removed from analysis.
2.4. Data Collection

Seedling height measured from the ground line to the tip of the terminal bud or base of the highest live foliage, diameter measured at ground line, and survival were measured within one month of planting, and at the end of the first, second, third, and fifth growing seasons. Vegetation cover was measured in the middle of the second growing season using a 0.25 m$^2$ square frame centered around each seedling (Table A2). Cover was estimated visually to the nearest 10% by life form (i.e., shrub, forb, and grass). The presence or absence of a microsite (i.e., large woody debris, stump, or impervious surface such as a large rock $\geq 30$ cm tall) within 61 cm of the seedling in the southern hemisphere of the seedling was recorded for each seedling in the summer of the second growing season.

2.5. Statistical Analyses

Population-level survival and volume index were analyzed using linear mixed-effects models in R version 4.0.3 [26] using the nlme package version 3.1-149 [27]. The volume index was calculated as base diameter$^2 \times$ height. Prior to calculating survival, missing seedlings were removed from the data since the reason they were missing could not be determined. Separate models were fitted for each species. Models included year of measurement and the RGP rating as discrete variables. Separate models were fit for each site (north and south aspect) since there was only 1 site for each aspect in the experiment. Interactions between all variables were tested in full models. The random effect in the model was the block within each site. Survival was converted to a proportion and transformed using the arcsine square root transformation. Models were checked for normality and heterogenous variance in the residuals. The volume index models did not meet the assumption without transformation but did when volume index was transformed with the natural logarithm. Marginal (i.e., least-square) means and standard errors of time since...
planting and RGP rating were calculated using the emmeans package version 1.5.0 in R [28] following back-transformation of predicted values.

Separate models were fitted for individual seedling survival and volume index by species that incorporated microsite presence/absence and competition cover. Seedling survival was analyzed using generalized linear mixed effects (GLMM) models with a binomial link. Time since planting, presence or absence of a microsite, and cover estimates of forbs, grasses, and shrubs were included as additive independent fixed variables. Block was included as a random effect. GLMM models were fit with the lme4 package version 1.1-26 in R [29]. Variables that were not significantly different than zero \((p \geq 0.05)\) were removed from the models until final models only contained significant variables. Predicted means and 95% confidence intervals of the predictions for the different time measurements and sites for the presence or absence of microsites were estimated with parametric bootstrapping with 250 iterations per model and holding all other predictor variables at their mean values. A similar method was used to estimate survival predictions for competition cover only for seedlings planted near microsites.

Individual volume index was analyzed using linear mixed effects models with the nlme package version 3.1-149 [27]. Similar to the individual survival models, the volume index models tested for the effects of the presence/absence of a microsite and competing vegetation cover. Volume index was transformed with the natural logarithm since models with the untransformed data were not normally distributed. The prediction function in the nlme package was used to calculate model predictions and 95% confidence intervals.

3. Results

3.1. RGP Effects on Survival and Volume Index

RGP rating as a main effect and year \(\times\) RGP rating were not significant factors for the population-level survival of the three species at either site \((p \geq 0.098)\) (Table 1). Survival remained high through the fifth growing season for western larch at the north aspect site (>95%) regardless of the RGP rating (Figure A1). In contrast, western larch showed a continual decline in survival over time at the south aspect site. By the end of the fifth growing season, western larch survival at the south aspect site ranged from 50% for the lowest RGP rating to 56% for the highest RGP rating. Compared to western larch, which showed sensitivity in survival between the sites, Douglas fir was less sensitive in terms of survival. At the north aspect site, the lowest survival was 82% for the high RGP rating and 91% for the moderate RGP rating. Survival was slightly less at the south aspect site, but still the lowest survival after 5 years was 74% for the low RGP rating. The survival response of grand fir survival was similar to that of western larch. Survival at the north aspect site was 73% and 76% for the high and low RGP ratings, respectively, while at the south aspect site grand fir survival declined over time to 36% and 37% for the high and low RGP ratings, respectively.

There were also no consistent effects of RGP rating for volume index over time among the species or at the two sites, except at the north aspect site where the main effect of RGP rating was significant for western larch \((p = 0.002)\) and grand fir \((p = 0.058)\) (Table 1). Volume index changed very little for the first 3 years after planting but increased considerably between the third and fifth year after planting (Figure A1). For western larch at the north aspect site, volume index increased by 887% for the high RGP rating between the third and fifth growing seasons, ending with a volume index of 84.5 dm\(^3\) in year five. The other RGP ratings showed similar increase of 675% and 680% for the Low and Moderate RGP rating, respectively between years three and five. A similar trend was observed for western larch at the south aspect site, although the fifth-year volume index was much lower than the north aspect site, ranging from 42.5 dm\(^3\) for the moderate RGP rating and 50.8 dm\(^3\) for the low RGP rating.
Table 1. p-Values from the population-level survival and volume index analysis of variance models by species and site.

|                  | Western Larch |          | Douglas Fir |          | Grand Fir |          |
|------------------|---------------|----------|-------------|----------|-----------|----------|
|                  | North Aspect  | South Aspect | North Aspect | South Aspect | North Aspect | South Aspect |
| Intercept        | <0.001        | <0.001   | <0.001      | <0.001   | <0.001    | <0.001   |
| Year             | <0.001        | <0.001   | <0.001      | <0.001   | <0.001    | <0.001   |
| RGP Rating       | 0.140         | 0.098    | 0.154       | 0.432    | 0.667     | 0.118    |
| Year × RGP Rating| 0.996         | 0.945    | 0.559       | 0.545    | 0.810     | 0.574    |

|                  |          |          | Population Survival |          |          |          |
|------------------|----------|----------|----------------------|----------|----------|----------|
| Intercept        | <0.001   | <0.001   | <0.001               | <0.001   | <0.001   | <0.001   |
| Year             | <0.001   | <0.001   | <0.001               | <0.001   | <0.001   | <0.001   |
| RGP Rating       | 0.002    | 0.734    | 0.486                | 0.294    | 0.058    | 0.334    |
| Year × RGP Rating| 0.567    | 0.948    | 0.426                | 0.393    | 0.337    | 0.206    |

3.2. Survival and Growth in Relation to Microsites and Competition

Shrub cover and the percent of seedlings planted near microsites was greater at the north aspect site than the south aspect site, while the south aspect site had greater forb and grass cover (Table A2).

Individual seedling survival significantly declined over time for all three species (Table 2; p ≤ 0.001). The only other statistically significant commonality among the species was that seedling survival was negatively correlated with forb cover (p ≤ 0.022). The presence of a microsite around a seedling significantly increased the odds of survival of western larch and grand fir seedlings (p ≤ 0.032), but not Douglas fir (p = 0.823), with the odds of survival increasing by 37% for western larch and 158% for grand fir in the presence of a microsite. Even though the 95% confidence intervals of western larch survival at the south aspect site overlapped between seedlings planted near microsites and seedlings without microsites, there was a general pattern of lower survival without a microsite (Figure 3). The effect of forb cover on survival was not as strong as the presence of a microsite but was still significantly related to survival. The odds of survival decreased by 2.3%, 1.2%, and 1.5% for western larch, Douglas fir, and grand fir, respectively, for each unit increase in forb cover. The largest difference in the odds of survival between the minimum and maximum forb cover for western larch was at the south aspect site, where 5 years after planting the odds of survival at the minimum forb cover of 0% was 0.72 compared to 0.26 at a forb cover of 85%. Grand fir showed a similar difference in odds of survival 5 years after planting at the south aspect site, where the odds of survival was 0.68 with 0% forb cover and 0.39 with 85% forb cover.

Similar to individual seedling survival, individual volume index was positively correlated with the presence of a microsite and negatively correlated with forb cover for all three species (Table 3). The interaction between year and site was also significant, except for Douglas fir where there were no differences in volume index between the north and south aspect sites in year 5 (p = 0.243). Predicted volume index of western larch near a microsite in year 5 at both sites was 23% greater than seedlings without a microsite (Figure 4). This can be compared to the Douglas fir, where the volume index was only 12% greater for seedlings near a microsite. Western larch had the greatest response to forb cover among the three species. At age 5, volume index was 85% greater when forbs were absent around seedlings compared to seedlings with 85% forb cover. The response of Douglas fir to forb cover was less pronounced, with a 27% gain in volume index when there was no forb competition around seedlings.
Table 2. Logistic regression results for seedling survival over a 5-year period following planting by site. Final models included the presence/absence of a microsite and forb cover around each seedling in year 2 since grass and shrub cover were not significant. The parameter estimates and their standard errors, p-value of the parameters, and the odds ratios are shown.

|                | Western Larch |         | Odds Ratio | Douglas-Fir |         | Odds Ratio | Grand Fir |         | Odds Ratio |
|----------------|---------------|---------|------------|-------------|---------|------------|-----------|---------|------------|
|                | Estimate (SE) | p-Value |            | Estimate (SE) | p-Value |            | Estimate (SE) | p-Value |            |
| Intercept      | 3.857741 (0.297606) | <0.001 | 4.875316 (0.453278) | <0.001 | 3.563970 (0.321779) | <0.001 |
| Year 2         | −0.723887 (0.215136) | <0.001 | 0.485 (−2.012527 (0.439319) | <0.001 | 1.34 (−1.630287 (0.301401) | <0.001 | 0.196 |
| Year 3         | −1.170887 (0.207769) | <0.001 | 0.181 (−2.596566 (0.428892) | <0.001 | 0.074 (−2.573727 (0.290616) | <0.001 | 0.076 |
| Year 5         | −1.494593 (0.199499) | <0.001 | 0.224 (−2.961373 (0.424310) | <0.001 | 0.052 (−3.117224 (0.289216) | <0.001 | 0.044 |
| South Aspect   | −1.705536 (0.152220) | <0.001 | 0.182 (−0.109564 (0.169058) | 0.517 | 0.896 (−0.696303 (0.153542) | <0.001 | 0.498 |
| Microsite      | 0.316336 (0.147521) | 0.032 | 1.372 (−0.034291 (0.15362) | 0.823 | 0.966 (0.947160 (0.149680) | <0.001 | 2.578 |
| Forb Cover     | −0.023711 (0.004645) | <0.001 | 0.977 (−0.011562 (0.005067) | 0.022 | 0.988 (−0.015107 (0.005179) | <0.001 | 0.985 |

Table 3. Linear regression results for seedling volume index (dm$^3$) over the first 5 years following planting by site. The volume index was transformed with the natural logarithm. Final models included the presence/absence of a microsite, forb, grass, and shrub cover around each seedling in year 2. The parameter estimates and their standard errors, p-value of the parameters, and the odds ratios are shown.

|                | Western Larch |         |            | Douglas-Fir |         |            | Grand Fir |         |            |
|----------------|---------------|---------|------------|-------------|---------|------------|-----------|---------|------------|
|                | Estimate (SE) | p-Value |            | Estimate (SE) | p-Value |            | Estimate (SE) | p-Value |            |
| Intercept      | −0.862760 (0.118435) | <0.001 |            | −1.468750 (0.097181) | <0.001 |            | −1.558550 (0.087419) | <0.001 |            |
| Initial Volume Index | 65.611930 (5.494028) | <0.001 |            | 97.232110 (6.420639) | <0.001 |            | 65.219110 (10.144961) | <0.001 |            |
| Year 2         | 1.438160 (0.059168) | <0.001 |            | 1.254720 (0.051817) | <0.001 |            | 0.695090 (0.070305) | <0.001 |            |
| Year 3         | 2.510580 (0.059881) | <0.001 |            | 2.199420 (0.052531) | <0.001 |            | 1.163490 (0.073484) | <0.001 |            |
| Year 5         | 4.608580 (0.059886) | <0.001 |            | 4.217840 (0.053589) | <0.001 |            | 2.247530 (0.072726) | <0.001 |            |
| South Aspect   | 0.186550 (0.069678) | 0.007 | 0.132060 (0.054787) | 0.016 | 0.084910 (0.070142) | 0.226 |
| South Aspect Year 2 | −0.472740 (0.095489) | <0.001 | −0.286930 (0.075745) | <0.001 | 0.311140 (0.101065) | 0.002 |
| South Aspect Year 3 | −0.580730 (0.097176) | <0.001 | −0.197220 (0.076827) | 0.010 | 0.363586 (0.107349) | <0.001 |
| South Aspect Year 5 | −0.681430 (0.096737) | <0.001 | 0.090720 (0.077748) | 0.243 | 0.473540 (0.119624) | <0.001 |
| Microsite      | 0.210570 (0.037416) | <0.001 | 0.113330 (0.029645) | <0.001 | 0.143970 (0.041362) | <0.001 |
| Forb Cover     | −0.007460 (0.001541) | <0.001 | −0.002870 (0.001080) | 0.008 | −0.007250 (0.001586) | <0.001 |
| Grass Cover    | −0.005860 (0.001868) | 0.001 | −0.004040 (0.001617) | 0.013 |            |            |
| Shrub Cover    | −0.007180 (0.001573) | <0.001 |            |            |            |            |
Figure 3. Odds of seedling survival from the end of the first growing season until the end of the fifth growing season at the north aspect and south aspect sites with or without the presence of a microsite near the seedlings (left panel) and in response to forb cover (right panel). Minimum forb cover was 0% for all 3 species. Maximum forb cover was 80% for Douglas fir and 85% for western larch and grand fir. Error bars represent 95% confidence intervals. Intervals that do not overlap are significantly different predictions at \( p \leq 0.05 \).
4. Discussion

Despite the extensive research examining the effects of RGP on seedling outplanting survival and growth, considerable disparities exist between studies that differ in tree species and geographic location [5]. Often, site factors exert greater effect on early seedling performance as was found in the current study. We found that RGP had no effect on seedling survival or growth from the year of planting through the fifth growth season, but the presence/absence of a microsite object and the amount of competing vegetation cover had significant effects. The lack of effect of RGP for grand fir could be due to the limited spread in RGP values (Table A1). These were the only four grand fir seedlots tested for RGP and their values were similar, so it is not surprising an effect was not detected. The
lack of RGP effect was more unexpected for western larch and Douglas fir, for which the average RGP values ranged more considerably among seedlots. Western larch RGP in the low RGP class was 3.5–4.8 new roots, while RGP in the high RGP class was 20.9–30.4 new roots. Douglas fir had a similar spread in RGP between the low and high RGP classes, and still no RGP effects were detected between the low and high RGP classes.

Many studies have found that RGP is an accurate predictor of field performance [11,30], yet others have found little to no effect [8,9,31]. During the early period of RGP testing development, a review by Binder et al. [31] found that RGP testing had low accuracy, low precision, and low repeatability, which can be attributed in part to variability in testing conditions and procedures. Sutton [32] failed to find any correlation between RGP and field performance until the third year after planting, and attributed this to heterogeneity in the conditions between the planting sites in their study. Brisette and Roberts [33] found no correlation between RGP and field performance of loblolly pine (*Pinus taeda* L.), which they attributed to high seedling survival given the moderate weather during the growing season. This may be the reason we could not detect an effect of RGP on survival from the first to the fifth growing season. The Palmer Drought Severity Index (PDSI) near the site during the first growing season ranged from $-1.0$ to $-1.9$, indicating a moderate year for precipitation and temperature [34].

Our results found that the presence of a microsite improved survival of western larch and grand fir, particularly at the south aspect site, which is more drought-prone than the north aspect site. Seedlings near a microsite also had greater volume index at age 5, suggesting the shading from the microsite modified the microenvironment to create more suitable conditions for seedling performance. Shade can increase survival and growth of newly planted seedlings by reducing the amount of direct solar radiation intercepted by the seeding. In a study examining the effects of retention or removal of logging slash with vegetation control, Devine and Harrington [35] found that exposed mineral soil at a 10 cm depth was $2\degree C$ greater than shaded surfaces during the peak of the summer. The daily fluctuation was also greater for exposed mineral soil compared to shaded surfaces. Lower temperatures throughout the growing season in shaded area have positive and negative effects. In regions with cool spring weather, shading can delay soil heating, which may delay seedling growth [36], while during hot, dry periods of the growing season the shading can help protect seedlings [37]. In young plantations in the Inland Northwest, surface soil temperatures can be $60\degree C$ or greater in the middle of summer [38]. Helgerson [39] found that seedling stem damage begins to occur when temperatures reach $52\degree C$. These potential extreme temperatures may help explain why western larch and grand fir seedlings performed better when planted near a microsite, as these species are more common on cooler, more mesic sites, while Douglas fir can appear on more xeric sites, and has greater heat tolerance [40].

The negative effects of forb cover on seedling survival and growth were clear for western larch and grand fir at both sites. Even though the effect of forb competition was significant for Douglas fir, the effect was much less than the other two species. Many studies have shown that the increased presence of competing vegetation negatively influences the field performance of planted conifer seedlings [41,42]. This is due in part to competition for resources. Research has helped illustrate the positive effects of vegetation control on early stand growth by increasing available soil moisture [37,43,44] and available soil nutrients [45,46], and complimentary increasing both soil moisture availability and soil nutrient availability [47]. In short, the presence of competing vegetation reduces available resources, and planted seedlings exhibit decreased field performance as a result.

Planting seedlings is a dominant method of reforestation in the Inland Northwest, USA, following timber harvesting, wildfire, and other natural disturbances. Disturbances are often large in scale and the extreme conditions following disturbance can lead to failure of natural regeneration [48]. Tree planting helps overcome the uncertainties of natural regeneration to quickly reestablish a forest. Still, seedling mortality can be high, especially in years with hot and dry weather conditions [2]. Our results help understand the effects
of seedling quality measured by RGP and microsite conditions and competing vegetation. Overall, survival, and growth were not related to RGP, which could be due to the seedlots selected for the study and the moderate weather conditions during the first 2 years of establishment. Individual seedling responses to microsites and forb competition varied by species, with western larch and grand fir exhibiting a similar strong response, while Douglas fir did not have a strong response to microsites or competing vegetation and performed similarly in the harsher south aspect site and the more mesic north aspect site. Similar differences in site sensitivity and sensitivity to competition were observed in Northeast Oregon for western larch and Douglas fir [49].

Silvics of the different species may also help understand the differences in their responses to the contrasting site conditions, presence/absence of a microsite, and forb competition. Douglas fir is one of the most widely distributed conifer species across the western United States, with the glauca variant planted in this study appearing throughout the region, often mixed with ponderosa pine (Pinus ponderosa) in dry forests [50]. Douglas fir is moderately to highly tolerant to drought [40], and therefore it is not surprising that seedling survival was high at both sites and the absence of a microsite did not affect growth or survival as strongly as western larch or grand fir. Even though western larch is considered moderately tolerant to drought [40], the species is most commonly found on more mesic north and east aspect sites in northern Idaho [51]. The preference for more mesic sites is possibly one reason survival was substantially less at the south aspect site compared to the north aspect site after 5 years. Grand fir is moderately tolerant to low light conditions and drought [40], yet is commonly found as advance regeneration beneath closed canopies. It is possible that the high light conditions of plantations are suboptimal for seedling growth and survival. Poor performance of grand fir seedlings in this study, combined with prolific natural regeneration and low economic value, suggests planting of the species may be better reserved for supplemental planting following shelterwood establishment cuts.

5. Conclusions

Our results suggest that post-planting competition control and the planting of seedlings near microsites are important silvicultural practices that should be considered to minimize mortality and increase growth of western larch and grand fir during plantation establishment, especially on south aspect sites in the Inland Northwest. These species should also be prioritized for more mesic sites. These silvicultural options may not be necessary for Douglas fir based on our results. It is important to understand that the results of this study were limited to two sites that were nearby with similar precipitation patterns and likely similar surficial soil conditions. Differences may be observed at sites that span a greater geographic gradient in the region, especially since Chen and Nelson [2] found that planting season weather and soils explained over 50% of the variation in first-year Douglas fir mortality and over 40% of the variation in western larch and Douglas fir growth within the region.

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Appendix A

Table A1. Average metrics of seedlots tested for root growth potential (RGP) that were planted in the field study. Each value indicates an average of the 15 seedlings per seedlot that were tested in the RGP chambers. The new root count was the number of new roots $\geq$ 1 cm long at the end of the test in aeroponic chambers. Height, diameter, and root volume were measured at the start of the test. Seedlot numbers refer to a split-plot experimental design with 1 seedlot within a RGP rating planting in one half of each row. They were assigned numbers to protect the proprietary data of the nurseries and landowner.

| Species       | RGP Rating | Seedlot | New Root Count | Height (cm) | Diameter (mm) | Root Volume (cm$^3$) |
|---------------|------------|---------|----------------|-------------|---------------|---------------------|
| Western larch | Low        | 1       | 3.5            | 44          | 4.15          | 4.7                 |
|               |            | 2       | 4.8            | 37.4        | 3.58          | 3.4                 |
|               | Moderate   | 1       | 11.2           | 42.1        | 5.09          | 6.8                 |
|               |            | 2       | 14.6           | 37.8        | 3.32          | 7.8                 |
|               | High       | 1       | 20.9           | 33.9        | 4.04          | 8                   |
|               |            | 2       | 34.4           | 42.1        | 3.57          | 6.8                 |
| Douglas fir   | Low        | 1       | 9.7            | 26.5        | 3.5           | 4.7                 |
|               |            | 2       | 10.2           | 31          | 3.92          | 6.6                 |
|               | Moderate   | 1       | 16.1           | 34.9        | 4.26          | 7.5                 |
|               |            | 2       | 16.5           | 27.8        | 4.15          | 6.7                 |
|               | High       | 1       | 17.5           | 33.9        | 3.75          | 5.1                 |
|               |            | 2       | 24.3           | 27.1        | 3.98          | 6.9                 |
| Grand fir     | Low        | 1       | 39.3           | 28          | 4.51          | 9.7                 |
|               |            | 2       | 40.6           | 31.9        | 4.85          | 11.9                |
|               | High       | 1       | 41.4           | 28.1        | 4.55          | 9.5                 |
|               |            | 2       | 42.4           | 24.4        | 4.65          | 12.3                |

Appendix B

Table A2. Mean ± one standard deviation of the percent cover of shrub, forb, and grass vegetation measured around individual seedlings by site, species, root growth potential (RGP) rating, and seedlot in the middle of the second growing season. The percent of seedlings with microsites identified within 61 cm of the seedling is also shown.

| Species       | RGP Rating | Seedlot | Shrub (%) | Forb (%) | Grass (%) | Microsite (%) |
|---------------|------------|---------|-----------|----------|-----------|---------------|
| North Aspect  |            |         |           |          |           |               |
| Western larch | Low        | 1       | 8.8 ± 3.6 | 10.8 ± 1.0 | 4.2 ± 2.0 | 64 ± 7        |
|               |            | 2       | 11.3 ± 1.3 | 10.6 ± 3.2 | 1.2 ± 1.1 | 67 ± 7        |
|               | Moderate   | 1       | 10.7 ± 0.8 | 14.5 ± 5.7 | 4.2 ± 3.3 | 35 ± 18       |
|               |            | 2       | 12.8 ± 2.6 | 13.4 ± 5.7 | 1.9 ± 0.8 | 52 ± 9        |
|               | High       | 1       | 8.8 ± 4.9  | 10.8 ± 1.4 | 5.8 ± 1.9 | 54 ± 15       |
|               |            | 2       | 10.0 ± 3.4 | 8.8 ± 2.5  | 1.2 ± 0.8 | 64 ± 15       |
| Douglas fir   | Low        | 1       | 13.4 ± 5.4 | 15.4 ± 1.9 | 1.6 ± 0.8 | 56 ± 22       |
|               |            | 2       | 13.1 ± 2.7 | 11.3 ± 1.1 | 1.4 ± 1.0 | 52 ± 14       |
|               | Moderate   | 1       | 9.7 ± 3.6  | 9.4 ± 5.2  | 6.8 ± 2.6 | 58 ± 13       |
|               |            | 2       | 12.0 ± 2.7 | 10.1 ± 1.5 | 2.9 ± 3.2 | 65 ± 13       |
|               | High       | 1       | 10.4 ± 1.0 | 15.1 ± 5.1 | 5.5 ± 3.6 | 50 ± 12       |
|               |            | 2       | 16.7 ± 1.5 | 10.2 ± 3.4 | 1.5 ± 0.7 | 48 ± 13       |
| Grand fir     | Low        | 1       | 16.0 ± 7.3 | 12.4 ± 4.0 | 5.6 ± 4.1 | 48 ± 13       |
|               |            | 2       | 17.7 ± 4.6 | 14.1 ± 3.6 | 2.2 ± 1.4 | 50 ± 11       |
|               | High       | 1       | 9.8 ± 2.2  | 14.0 ± 4.0 | 4.7 ± 3.2 | 58 ± 10       |
|               |            | 2       | 20.3 ± 4.8 | 14.7 ± 7.8 | 1.5 ± 1.3 | 58 ± 10       |
### Table A2. Cont.

| Species      | RGP Rating | Seedlot | Shrub (%) | Forb (%) | Grass (%) | Microsite (%) |
|--------------|------------|---------|-----------|----------|-----------|---------------|
| **South Aspect** |            |         |           |          |           |               |
| Western larch | Low        | 1       | 3.2 ± 1.7 | 15.2 ± 4.0 | 6.0 ± 2.0 | 17 ± 4        |
|              |            | 2       | 3.4 ± 2.6 | 15.4 ± 1.6 | 13.9 ± 4.6 | 17 ± 4        |
|              | Moderate    | 1       | 3.5 ± 3.1 | 12.6 ± 1.4 | 9.3 ± 2.4 | 25 ± 12       |
|              |            | 2       | 4.5 ± 2.9 | 20.0 ± 7.7 | 5.5 ± 3.2 | 12 ± 6        |
|              | High        | 1       | 3.9 ± 1.5 | 18.9 ± 4.2 | 6.1 ± 5.0 | 19 ± 1        |
|              |            | 2       | 2.9 ± 2.5 | 22.0 ± 6.6 | 4.3 ± 2.5 | 15 ± 14       |
| Douglas fir  | Low        | 1       | 2.6 ± 1.0 | 14.1 ± 4.8 | 7.4 ± 3.8 | 42 ± 16       |
|              |            | 2       | 2.3 ± 0.4 | 19.3 ± 2.5 | 6.2 ± 2.8 | 19 ± 16       |
|              | Moderate    | 1       | 3.7 ± 1.7 | 19.2 ± 5.9 | 6.1 ± 1.9 | 21 ± 4        |
|              |            | 2       | 2.6 ± 1.8 | 22.0 ± 4.7 | 8.6 ± 1.2 | 15 ± 7        |
|              | High        | 1       | 2.5 ± 0.7 | 17.5 ± 5.1 | 5.3 ± 2.2 | 15 ± 9        |
|              |            | 2       | 1.8 ± 0.4 | 21.9 ± 5.9 | 5.9 ± 2.9 | 27 ± 4        |
| Grand fir    | Low        | 1       | 4.9 ± 4.7 | 18.0 ± 8.8 | 11.3 ± 2.4 | 31 ± 11       |
|              |            | 2       | 3.3 ± 1.6 | 19.0 ± 2.6 | 7.3 ± 4.4 | 31 ± 5        |
|              | High        | 1       | 6.4 ± 4.3 | 13.5 ± 0.5 | 6.7 ± 3.3 | 29 ± 7        |
|              |            | 2       | 2.3 ± 1.8 | 21.2 ± 1.7 | 7.9 ± 1.6 | 18 ± 11       |

### Appendix C

**Figure A1.** Change in survival from the time of planting (Year 0) to the end of the fifth growing season (Year 5) by species and root growth potential (RGP) rating at the north and south aspect sites.
Figure A2. Change in volume index from the time of planting (Year 0) to the end of the fifth growing season (Year 5) by species and root growth potential (RGP) rating at the north and south aspect sites.

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