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Silviculture

Influence of Neighborhood Competition on Douglas-Fir Growth Is Not Altered by Local Environmental Conditions and Climate

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Abstract

To evaluate impacts of competitive conditions in tree neighborhoods on growth responses as influenced by moisture availability and local environmental conditions, we sampled 102 codominant 40- to 70-year-old coastal Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in regions with relatively high and low moisture availability. We quantified local environmental conditions (topographic position index, heat load, and soil depth), and the annual basal area increment and climate moisture deficits during two growth periods: a five-year period prior to commercial thinning and years six to 10 after thinning. In both regions and growth periods, tree growth was higher for trees growing in local neighborhoods with lower competition. The density/growth relationships differed by region and by growth period in the moist regions, but they were not influenced by climate moisture deficit. Furthermore, including topographic position index, heat load, or soil depth did not improve model support. Our results highlight the importance of managing local competition and indicate that environmental factors such as soil depth, heat load, and topography may be less likely to warrant consideration when developing thinning prescriptions. This could allow foresters to accommodate other ecosystem services when designing density management treatments, at least within typical growing conditions.

Study Implications: Concerns about climate change have led to questions whether existing management practices, such as current thinning prescriptions, need to be modified to ensure sustainable provision of ecosystem services. Our results highlight the prominent role of local competitive conditions and indicate that fine-scale differences in topography and soils within our study region are not useful criteria for modifying thinning prescriptions to alter how trees responds to climate conditions, at least under typical growing conditions. Thus, foresters can focus their prescriptions on other aspects when developing thinning or other partial harvesting operations, such as timber production or wildlife habitat.

Keywords: climate change, density management, local competition, environmental conditions

Preparing forests for future climate conditions is a major challenge for silviculturists and key for the sustainable provision of ecosystem services (Puettmann 2011). Despite uncertainty about future climates, two aspects are generally accepted: increased temperatures and higher summer moisture deficits in many regions (Pachauri et al. 2014), including in the Pacific Northwest (PNW) of the United States (Mote and Salathé 2010). This is of special concern in the western portion of the PNW (Chmura et al. 2011), as in this area the growing season of a widespread dominant species, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), has been shown to be limited by summer moisture conditions (Littell et al. 2008), especially during years with above-average temperatures (Beedlow et al. 2013).

To mitigate the impacts of a changing climate, several long-term adaptation strategies that address a variety of forest conditions have been considered (Mote et al. 2003, Peterson et al. 2011). General agreement exists that in dense stands in the stem exclusion stage, lowering stand density can provide short-term benefits in terms of preparing forests for increased stress due to a changing climate (Spittlehouse and Stewart 2003, Chmura et al. 2011, Sohn et al. 2016). Thinning has been used for centuries as a treatment to improve growth and vigor of the remaining trees (Puettmann et al. 2009) by reducing competition and making more resources available for each of the remaining trees (Aussenac and Granier 1988, Breda et al. 1995). Numerous studies have shown a short-term increase in resistance and resilience to drought after thinning (For a review, see Sohn et al. 2016.). However, thinning responses are dynamic and change over time. Several studies with Douglas-fir showed an adjustment period right after thinning. During the first years after thinning, trees with reduced neighboring competition grew less than trees growing in a comparable post-thinning density that had not experienced a recent reduction in competition (Wang 1990, Hann et al. 2003). This initial treatment effect is likely due to the time it takes for the foliage (Hood and Sandberg 1979), crowns (Hann et al. 2003, Davis et al. 2007) and root systems (Vincent et al. 2009) to adjust to altered conditions. This adjustment period was also

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reflected in the stand water balance (Aussenac and Granier 1988) as well as water use efficiency of trees (Ruzicka et al. 2014). Compared with prethinning conditions, long-term effects of thinning include higher individual tree growth rates, but benefits in terms of resistance and resilience to drought may be reduced over time (D'Amato et al. 2013). This loss is likely, at least partially, due to the increase in leaf area (Brooks and Coulombe 2009) that leads to stand transpiration in thinned stands being similar to unthinned stands over time (Aussenac and Granier 1988). In addition, most density studies use plot or stand level conditions as predictors of average tree growth (Marshall 2002, Sohn et al. 2016); that is, they assume that topographic and environmental conditions are homogenous at plot or stand scales. However, fine scale variation in local environmental conditions (e.g., topographic position, slope steepness and aspects), which influence microclimate (McCune 2007, Ward et al. 2018) and soil depth, may well interact with competitive conditions to influence tree growth (Li and Yang 2004, Fajardo and McIntire 2007). Such fine-scale variations have typically been ignored in stand level prescriptions for even-aged stands (Puettmann et al. 2009), but may be more influential in regards to climate change and as treatments such as variable retention become of broader interest (Gustafsson et al. 2012).

To elucidate information relevant to climate change, we selected sites in two regions with temperate Mediterranean climate (Köppen 1936), but different precipitation and temperature patterns. We viewed the warmer, drier region (US Bureau of Land Management [BLM] ownership near Roseburg) as a proxy for climate-related increases in drought stress in the cooler, wetter Willamette National Forest (WNF) region (Blois et al. 2013). In addition, to expand the range of densities and growing conditions, we focused on two growth periods for each sample tree: a five-year interval without a recent history of thinnings and an interval six to 10 years after thinnings.

Our main objectives were to test (1) whether tree growth was influenced by local competition from neighboring trees in the different regions and growth periods, and (2) whether these relationships varied depending on climate conditions; that is, whether trees are more sensitive to competition during dry years. In addition, a third objective addressed whether local environmental conditions (specifically topography, slope, aspect, and soil depth) influenced tree responses to local competition and climate conditions and thus should be considered in thinning prescriptions.

Materials and Methods

Study Area

Using the "space-for-time substitution" approach (Blois et al. 2013) to investigate impacts of climate change, we evaluated tree growth in two regions with different climate regimes. The study stands were located in western (WNF) and southwestern (BLM) Oregon. Both regions have a Mediterranean-type climate with dry summers and most of the precipitation falls from October to April. The WNF stands were on the western slope of the Cascade Range within the western hemlock (*Tsuga heterophylla* [Rafinesque] Sargent) zone (Franklin and Dyrness 1973) (Figure 1). Forests in the WNF region are typically dominated by Douglas-fir, have a mean annual temperature of 8.5°C, and receive around 2,500 mm precipitation annually. In contrast, the BLM stands are within the Roseburg District near the Umpqua River Valley of southern Oregon. This region has a warmer and drier climate, with an average annual temperature of approximately 12°C and rainfall of 850 mm per year.

We selected 17 stands in each region and sampled three focal trees in each stand, resulting in a total of 102 trees. All sample stands were established after clearcutting of mature or old-growth stands 40 to 70 years ago, followed typically by broadcast burning, planting, and precommercial thinning. To ensure we had trees growing in a wide range of density conditions, we selected only stands that were commercially thinned in the last 20 years using thinning from below. This allowed us to evaluate growth under higher (prethinning) and lower (postcommercial-thinning) densities. The detailed descriptions of the study stands and trees highlight that stands in the WNF are higher in eleva-

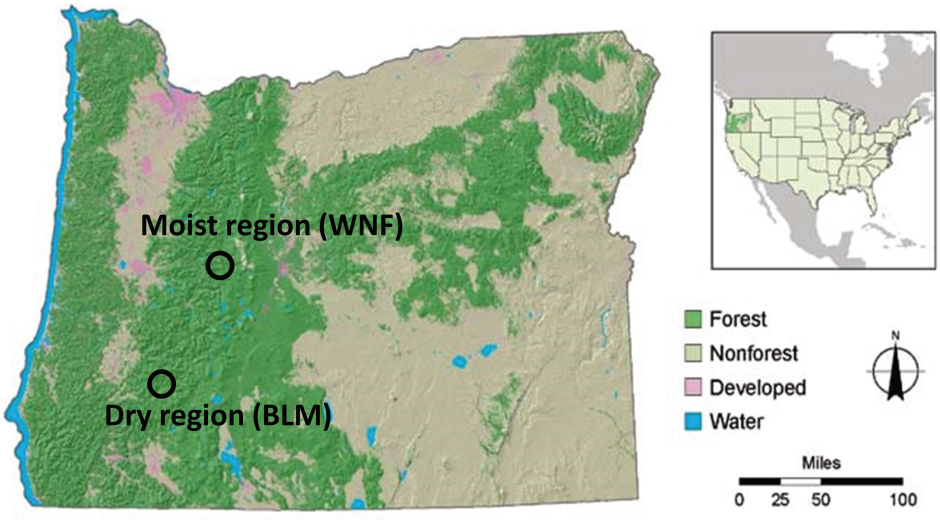

Figure 1. The black circles highlight the approximate center locations of the sample stands in the two study regions in western Oregon (moist region = Willamette National Forest [WNF] and dry region = Bureau of Land Management land near Roseburg [BLM]).

Table 1. Description (averages, with standard errors in parenthesis) of stand (upper rows) and tree (lower rows) conditions in the Willamette National Forest (WNF) and Bureau of Land Management land near Roseburg (BLM). Climatic moisture deficit (CMD) is the average of the study locations and the respective growth period. TPI is the topographic position index (Ward et al. 2018). Age is the stand age (years since clearcutting) at time of thinning. Basal area increment (BAI) is the average basal area increment for all trees and the respective growth period. H is Hegyi's (1974) competition index.

Site	Number of stands	Elevation (m)	CMD (mm) before thinning	CMD (mm) after thinning	TPI	Slope (%)	Aspect (degree)	Age (years)
WNF	17	1059 (318)	327 (87)	338 (61)	–2 (35.6)	40 (27)	191 (105)	64 (6.4)
BLM	17	533 (381)	577 (103)	545 (118)	–4.7 (21.6)	27 (19)	206 (117)	65 (14)
Site	Number of trees	DBH (cm)	Tree height (m)	BAI (mm^2) before thinning	BAI (mm^2) after thinning	Soil depth (dm)	H, remaining trees	H, removed trees
WNF	51	51.1 (12.2)	39.0 (5.4)	3464 (1539)	4025 (1288)	2.6 (1.3)	1.0 (0.4)	1.4 (0.4)
BLM	51	47.2 (9.7)	36.1 (5.3)	1288 (1224)	3565 (1645)	1 (0.3)	1.5 (1.2)	1.2 (1.2)

tion and on steeper slopes but on similar aspects as stands on the BLM sites. Although trees in both regions were of similar age at the time of thinning, differences in site quality are reflected in the trees in the WNF being approximately 10% taller on average than trees in the BLM (Table 1). Within different topographic conditions in the stands (i.e., from close to ridges to near valley bottoms), we randomly selected the sample trees. To be considered for sampling, the trees had to be codominant and healthy with no apparent damage. This criterion was used to prevent factors other than local competitive conditions and environmental and climate conditions having a major influence on tree growth.

For each focal tree, we measured diameter at breast height (DBH, 1.37m) and took two 7 mm radius increment cores at breast height. Cores were taken perpendicular to the stem and in a radial line to the pith. Core samples were stored in paper straws for transportation. In the lab, cores were mounted, sanded, and measured using Velmex equipment. Rings were cross-dated using pointer years and the cross.date function in the package dplR (Bunn 2010) for R and validated using COFECHA (Holmes 1983) software. Flagged series were checked against alternate core sample and year averages. Following measurements of alternate cores, no significant evidence was found to revise dating of flagged cores. In addition, the increment values were lined up and visually checked within a tree and among trees. After calculating the diameter inside bark for each core using Larsen and Hann (1985), basal area increment (BAI) in square millimeters was determined from growth rings for the five years prior to the thinning and years six to 10 after thinning (For more detail about these methods, see McDowell et al. 2003.). The annual BAI derived from the two cores was averaged for each tree. The first five years after thinning were avoided to minimize the impact of the postthinning adjustment period (Ruzicka et al. 2014). Postthinning density during this initial posttreatment period has been shown to be a poor indicator of tree growth (Harrington and Reukema 1983, Hann et al. 2003, Ruzicka et al. 2014). This is likely due to pronounced morphological and biophysical differences between sun and shade needles and the inability of these needles to adapt to a substantially altered environment following thinning (Boardman 1977, Tucker et al. 1987, Youngblood and Ferguson 2003). In similar stands in the study region, Ruzicka et al. (2014) showed that growth patterns start to stabilize after a mostly complete turnover of Douglas-fir needles (Maguire et al. 2002), that is, approximately five years after thinning.

Based on earlier work in the region, we assumed that trees greater than 10 meters away from the focal trees had little direct interaction with the focal trees and thus minor or no impact on focal tree growth (D'Amato and Puettmann 2004). For all trees within a 10 m radius circle of the focal trees, we measured DBH and distance from the focal trees. The diameters of all stumps within a 10 m radius of focal trees were measured at 20 cm height (diameter at stump height, DSH). For focal trees, we determined DBH five years after thinning (DBH_{T+5}) from the increment cores by subtracting the diameter increment the focal tree had grown between our measurement date and five years after thinning from the measured DBH. To estimate the DBH five years after thinning for the neighboring trees, we developed a regression equation that predicted DBH_{T+5} from the final DBH for all focal trees (adjusted $R^2 = 0.94$, $P < 0.001$).

$$DBH_{T+5} = -4.29\,(1.06) + 0.86\,(0.02) * DBH \quad (1)$$

This equation (standard errors in parentheses) was then used to predict DBH_{T+5} for all neighboring trees. The DBH five years before thinning (DBH_{T-5}) for the focal and neighboring trees was calculated using the same method as described above for DBH_{T+5} using equation 2:

$$DBH_{T-5} = -9.99\,(1.60) + 0.87\,(0.03) * DBH \quad \left(\text{Adjusted } R^2 = 0.88,\ P < 0.001\right) \quad (2)$$

To estimate the DBH_{T-5} of trees removed during the thinning operations, we estimated their DBH at the time of thinning (DBH_T) by fitting a regression equation to the Douglas-fir data in Table 1 from Thies and Cunningham (1996), who measured DBH and stump diameter for Douglas-fir of similar sizes in the region. The resulting equation predicted DBH as a function of DSH in cm (standard errors in parentheses):

$$DBH = 1.85\,(1.54) + 0.76\,(0.03) * DSH \quad \left(R^2 = 0.9043;\ P < 0.001\right) \quad (3)$$

We applied this equation to all stump diameters in the 10 m neighborhoods to estimate DBH_T of all harvested trees. Next, we used equation 1 and the procedure described above to estimate DBH_{T-5} of trees removed during thinning.

Hegyi's competition index (H; Hegyi 1974) at the beginning of each growth period was calculated for all focal trees five years after the thinnings (H_{T+5}) and five years before the thinnings (H_{T-5}), using DBHs of all residual trees after thinning for H_{T+5} and all residual plus trees removed during thinning for H_{T-5}. The equation for the second growth period was

$$H_{T+5,i} = \left[\sum_{j=1}^{n}\left(\frac{(D_j/D_i)}{L_{ij}}\right)\right] \quad (4)$$

where L_{ij} is distance between neighbor j and focal tree i, D_i is the DBH_{T+5} of focal tree i, and D_j is the DBH_{+5} of neighbor tree j. The same procedure was used to calculate $H_{T-5,i}$ using DBH_{T-5} of focal and residual trees and trees cut during the thinning operations.

Soil depth was measured with a penetrating rod in three spots within the crown radius of the focal tree to a maximum depth of 1.2 m. The three measurements were then averaged for each tree. We used ClimateNWA (Wang et al. 2012) to calculate climate conditions for all focal tree locations and measurement years. ClimateNWA uses a temperature-based evaporation level to calculate climate moisture deficit (CMD), has been calibrated for the region (For more detail see Wang et al. 2012.), and can be downscaled to specific locations (Wang et al. 2016). Topographic position index (TPI) was calculated as the difference in elevation between the location of a focal tree and the mean elevation in an annulus 150–300 m beyond that tree, that is, at a scale which has been shown to be related to microclimate in the region (Ward et al. 2018). Elevation was calculated from a 10 m digital elevation model. TPI classifies the slope position of each sample tree from valley bottoms (negative values) to ridge tops (positive values) (Ohmann et al. 2007). To account for the climate effects of slope and aspect, we calculated heat load for all focal trees using the improved version of equation 3 as described in McCune (2007).

Data Analysis

We applied a multistep modeling strategy to avoid the assumption that past growing history does not alter the influence of local growing conditions on the relationship between local competition and tree growth over a moisture gradient. In addition, to allow maximum flexibility in response between the two regions, we analyzed the study regions separately. All analyses were conducted using the R software package (R Core Team, 2017) with the lme4 (Bates et al. 2015) and nlme (Pinheiro et al. 2017, R Core Team 2017) packages. We assessed the support among the various models using the change in Akaike's information criterion (ΔAIC) (Burnham et al. 2011).

We fit a series of mixed effects models that included random effects for stands, trees within stand, and years within growth periods (the five years before and from year six to year 10 after thinning) (Table 2). Prior to working through the series of models, we fit a full model with all three random effects and compared the magnitude of the estimated random effects. We found that all estimates were approximately the same size, indicating that, for example, after accounting for the random effect of stands, there was residual variation among trees, and after accounting for residual variation among stands and among trees, there was residual variation among years. Therefore, we kept all three random effects in all models. Stands were thinned in different years; in other words, the residual variation among years does not represent a "repeated measures" type of variation. Therefore, we did not include any components in the model for repeated measures.

We investigated whether each environmental variable had any relationship with log(BAI) after accounting for competition (Table 2, top). As a set of "base" models, we fit three models that postulated different relationships between log(BAI) and H that depended on the growth period (models 2, 3, 4; Table 2) and a null model of a constant mean log(BAI) (model 1; Table 2). We fit three additional models that were each a base model plus the environmental variable (models 7, 8, 5; Table 2). We also fit two more complex models. The "full" model (model 6; Table 2) allowed effects of the environmental variable and H to vary independently in the two growth periods and a slightly less complex model that allowed the environmental variable, but not H, to vary between the growth periods (model 9; Table 2). For each environmental variable, we also fit two additional models to investigate whether the CMD was influenced by the environmental variable after allowing the effect of competition to vary between growth periods. One model included the interaction of CMD with the environmental variable and the other model included the interaction but allowed the interaction effect to vary between growth periods. These models are described in Table 2 (bottom).

We used AIC statistics to identify the best supported relationship between log(BAI) and the environmental variable. We interpreted values of AIC that did not differ by more than five AIC units between models as indicating similar support for models (Burnham et al. 2011). When multiple models had similar support, we used parsimony to identify the model with the fewest parameters as the best supported model.

Estimation of Effects

As an indicator of the practical importance of the results, we quantified the magnitude of the effects of each environmental

Table 2. Description of the various models run as part of the analysis. Model ID are identifiers used in the text and subsequent tables. Period refers to the two set of density conditions found before and after thinnings. H is Hegyi's (1974) index calculated for the appropriate growth periods (five years before and five years after thinning). Environmental variables (env. var) include climate moisture deficit (CMD), topographic position index (TPI), heat load, and soil depth.

Model ID	Period	H	Period× H	Env. var.	Period× env. var.	Model interpretation
1						No effect of covariate or competition; mean log(BAI) similar in both periods
2	X					No effect of covariate or competition; mean log(BAI) differs among periods
3	X	X				Trends with H that do not differ among periods
4	X	X	X			Base model—no effect of covariate, only of competition
5	X	X	X	X		Separate trends for H and covariate and only the H trend differs among the periods
6	X	X	X	X	X	Separate trend for H and covariate and both trends differ among the periods
7	X			X		Trends with covariates that do not differ between periods
8	X	X		X		Separate trends for H and covariate but neither trend differs among periods
9	X	X		X	X	Separate trends for H and covariate and only the covariate trend differs among the periods
Model ID	Period	H	Period× H	CMD× env. var.	CMDxenv. var. × period	
10	X	X	X	X		Interacting trend between CMD and other environmental variable (X) that does not differ between periods
11	X	X	X	X	X	Interacting trend between CMD and other environmental variable (X) that differs between periods

variable on BAI after accounting for effects of competition. For this, we used models in which we allowed the effect of competition to differ between growth periods. These models allowed us to calculate the change in BAI over the range of each environmental variable for each location (WMF, BLM) and growth period (i.e., in high-density conditions before and low-density conditions after thinning). We covered the full range of TPI, heat load, and soil depths, as these values did not change from one growth period to another. The range of CMDs differed very slightly between growth periods (Table 1); thus, we calculated the change in BAI only over the range of CMDs that was common to both growth periods.

Results

Influence of Local Competitive Conditions

Our results showed a prominent effect of local competition on tree growth. In all cases, the best supported models included an effect of the Hegyi's index (Table 3). The AIC values suggested little support for additional effects of climate or environmental variables. In addition, the confidence intervals for the change in BAI during both growth periods in most cases overlap (Table 4), supporting the conclusion of our model selection (Table 3) that local competitive conditions, as reflected in H, have a major influence on BAI. However, it is important to note the complexity of these patterns in conjunction with the high variability in individual tree growth patterns (Supplement 1, Figures 1 and 2).

Influence of Climate Conditions

The results indicate that the range of climate conditions during the growth periods in our sample stands was not sufficient to influence how basal area increment of trees responded to local competitive conditions (Table 4). Assessing the support for models in which climate moisture deficit was included and that also contained H as explanatory variables indicated that none of these models obtained higher support than the model that only included H and allowed the effect of H to differ with growth periods (Table 3, model 4), despite similar CMD values in the two growth periods (Table 1). In the WNF, all multivariable models had higher AIC values than the model with H alone (all $\Delta AIC > 5$; Table 3). For the Roseburg BLM site, several of these multivariable models had equivalent support ($\Delta AIC < 2$), but based on parsimony considerations, we concluded that none of them was better supported than the model with H alone (Table 3, model 4). Although the estimation of effects indicated that trees in similar competitive conditions were very slightly less sensitive to higher climate moisture deficit in the WNF, but not in BLM, the AIC results did not indicate support for such an effect.

Influence of Environmental Conditions

Models that included an interaction between CMD and variables representing local environmental conditions (models 10 and 11) did not receive more support than the model with H alone (Table 3). In the moist region (WNF) we found no support for the inclusion of CMD, TPI, or soil depth in explaining log(BAI) (Table 3, AICs < 5 for model 4). However, for heat load, the best supported models (models 6 and 9) indicated that heat load is associated with log(BAI) and that the relationship differed between the growth periods. In the drier region (BLM) we found no support for the inclusion of CMD,

TPI, soil depth, or heat load, as model 4 was always the best supported model. However, the impact of these variables on the absolute differences in BAI support the very limited influence of local environmental conditions. The change of BAI over the range of climate moisture deficit and the various environmental conditions (conditions common to both periods) was extremely small (Table 4).

Discussion

Influence of Local Competitive Conditions

Overall, the data confirmed that competitive conditions in tree neighborhoods are a powerful predictor of tree growth (Assmann 1961, D'Amato and Puettmann 2004). The strong impact of local competitive conditions is well supported in the literature within the region (e.g., D'Amato and Puettmann 2004, Dodson et al. 2012) and more broadly evident by the successful use of various competition indices that quantify amount, size, and/or distance between focal and neighbor trees (e.g., Biging and Dobbertin 1992, 1995). Such "local control" implies that fine-scale spatial variability in tree spacing will eventually be reflected in variability in tree sizes (Zenner et al. 1998, Dodson et al. 2012), crown shapes (Seidel et al. 2016), and stand structures and composition (Gustafsson et al. 2012, Puettmann et al. 2016).

The absolute influence of local competition may not be directly comparable between trees growing in stands that had not recently been disturbed, for example, by harvesting, and trees after a recent thinning entry. Our findings that trees growing in the same competitive conditions in the WNF grew slower in the growth period after recent thinning indicates that five years after thinning may not have been an accurate reflection of the trees adjusting to the new growing conditions. Trees may not have been able to fully use the additional growing space following thinning, although other growth studies in the region showed that, in similar stand conditions, a five-year adjustment period is sufficient for growth (Hann et al. 2003, Ruzicka et al. 2014) and water use efficiency (Ruzicka et al. 2014) to stabilize. Alternatively, the response to thinning at the higher productivity WNF sites was so rapid that any benefits of thinning in terms of resource availability was already lost by year six. For example, after fertilization, higher leaf areas have been reflected in associated higher moisture demands (Brooks and Coulombe 2009). However, based on other work in similar stands in the region (Ruzicka et al. 2014), it appears more likely that the adjustment period

Table 3. Akaike's information criterion (AIC) statistics and changes in AIC (ΔAIC) from the best supported models for a range of model structures for five different environmental variables and the two locations. Entries are comparable only among values in one region and column. H is Hegyi's (1974) index and CMD is climate moisture deficit, both calculated for the respective growth periods. TPI is topographic position index and Model IDs are described in Table 2. Bold values indicate the best supported model and models with similar support (ΔAIC < 5). Models 1, 2, 3, and 4 include only H so their values remain the same from column to column.

Willamette National Forest															
Competition (H)			CMD			TPI			Heat load			Soil depth			
Model ID	Δ AIC	AIC	Model ID	Δ AIC	AIC	Model ID	Δ AIC	AIC	Model ID	Δ AIC	AIC	Model ID	Δ AIC	AIC	
4	**0.00**	**128.90**	**4**	**0.00**	**128.90**	**4**	**0.00**	**128.90**	**6**	**0.00**	**48.94**	**6**	**0.00**	**125.61**	
3	18.67	147.57	5	16.30	145.20	6	8.75	137.65	9	2.80	51.74	4	3.29	128.90	
2	21.40	150.30	3	18.67	147.57	5	11.23	140.13	11	37.45	86.39	5	4.47	130.08	
1	79.23	208.13	6	19.51	148.41	3	18.67	147.57	4	79.96	128.90	9	13.28	138.89	
6	na	na	2	21.40	150.30	2	21.40	150.30	5	81.39	130.33	10	19.37	144.98	
5	na	na	8	35.32	164.22	10	23.49	152.39	10	81.39	130.33	3	21.96	147.57	
9	na	na	7	37.78	166.68	11	25.49	154.39	3	98.63	147.57	8	23.35	148.96	
8	na	na	9	40.49	169.39	8	29.70	158.60	8	100.28	149.22	2	24.69	150.30	
7	na	na	1	79.23	208.13	9	30.03	158.93	2	101.36	150.30	7	25.60	151.21	
11	na	na	11	na	na	7	32.21	161.11	7	102.71	151.65	11	36.54	162.15	
10	na	na	10	na	na	1	79.23	208.13	1	159.19	208.13	1	82.52	208.13	
Roseburg BLM															
Competition (H)				CMD			TPI			Heat load			Soil depth		
Model ID	Δ AIC	AIC	Model ID	Δ AIC	AIC	Model ID	Δ AIC	AIC	Model ID	Δ AIC	AIC	Model ID	Δ AIC	AIC	
4	**0.00**	**162.42**	**4**	**0.00**	**162.42**	**4**	**0.00**	**162.42**	**6**	**0.00**	**162.38**	**4**	**0.00**	**162.42**	
3	23.06	185.48	**5**	**0.14**	**162.56**	5	10.96	173.38	**4**	**0.04**	**162.42**	**5**	**2.01**	**164.43**	
2	92.24	254.66	6	17.36	179.78	6	17.93	180.35	**5**	**0.42**	**162.80**	**6**	**2.79**	**165.21**	
1	198.16	360.58	3	23.06	185.48	10	20.12	182.54	**10**	**0.42**	**162.80**	**10**	**3.06**	**165.48**	
6	na	na	8	24.22	186.64	3	23.06	185.48	11	16.81	179.19	9	18.52	180.94	
5	na	na	9	41.05	203.47	9	23.53	185.95	9	22.49	184.87	11	18.88	181.30	
9	na	na	2	92.24	254.66	8	34.15	196.57	3	23.10	185.48	3	23.06	185.48	
8	na	na	7	94.01	256.43	11	44.07	206.49	8	23.44	185.82	8	25.18	187.60	
7	na	na	1	198.16	360.58	2	92.24	254.66	2	92.28	254.66	2	92.24	254.66	
11	na	na	11	na	na	7	103.21	265.63	7	93.26	255.64	7	94.51	256.93	
10	na	na	10	na	na	1	198.16	360.58	1	198.20	360.58	1	198.16	360.58	

Table 4. Absolute change and confidence intervals (CI) of basal area increment (BAI; mm^2) over the range of environmental variables (in their respective units). Min, Max, and Range refer to the minimum, maximum, and range of the respective variables common for both growth periods, Climate moisture deficit (CMD), topographic position index (TPI), heat load, and soil depth.

	Min	Max	Range	Modelled change in BAI (growth period before thinning)	95% CI	Modelled change in BAI (growth period after thinning)	95% CI
Willamette National Forest							
CMD	501	213	288	1.024	0.917, 1.144	0.735	0.620, 0.872
TPI	–64	95	159	1.152	0.699, 1.899	1.720	0.550, 2.159
Heat load	1.01	0.41	0.06	1.684	1.107, 2.561	0.854	0.561, 1.300
Soil depth	1.2	0.3	0.9	0.674	0.470, 0.966	0.849	0.594, 1.215
Roseburg BLM							
CMD	286	799	493	0.745	0.636, 0.874	0.734	0.614, 0.876
TPI	-45	54	99	1.456	0.739, 2.870	1.090	0.550, 2.159
Heat load	0.62	1.02	0.40	1.358	0.832, 2.217	1.151	0.706, 1.875
Soil depth	0.21	1.2	0.99	0.718	0.380, 1.355	0.912	0.481, 1.726

has not been completed. The observed slower growth in the WNF following thinning was in some ways surprising, as we would have expected a quicker adjustment to altered growing conditions in the region with the higher forest productivity (WNF), for example, through a quicker increase in leaf area after thinning (Brooks and Mitchell 2011). Instead our results indicated that regional differences, such as climate (Bottero et al. 2017, Gleason et al. 2017), may be influencing tree growth responses, and the importance of additional resources after thinning may have differed between conditions where soil moisture versus light or other resources are limiting (Lee et al. 2016). For example, trees growing in more moist conditions may have been more influenced by the (at least partial) offset of added moisture by the higher crown exposure of larger trees and resulting higher evaporative demands (Hamann and Wang 2006, Bennett et al. 2015). In addition, our results were consistent with the hypothesis that the impact of thinning is higher in areas with higher moisture stress (Maguire and Kobe 2015, Sohn et al. 2016), likely due to less soil water availability in the drier region (Bréda et al. 2006, Littke et al. 2018), as reflected in higher climate moisture deficit and shallower soil depths. Genetic differences within our study stands could also have been partially responsible for these patterns (e.g., George et al. 2015).

Influence of Climate Conditions

On a global, national, (Burns and Honkala 1990) and regional (Franklin and Dyrness 1973) scale, climate conditions, especially temperature and precipitation, have been shown to be an important factor determining the presence of forests and their productivity. Also, studies have shown that tree growth in low-density stands is less affected by drought conditions than in high-density stands, but most of these results are rather short term, typically documenting growth one to three years after droughts (Sohn et al. 2016, Bottero et al. 2017). Our contrasting results, that is, the lack of an influence of climate conditions on the relationships between local competitive conditions and tree growth, may indicate that the climate conditions at our study sites during the growth periods may not have varied sufficiently to be reflected statistically in relationships between competitive conditions and growth of individual trees (Guillemot et al. 2015).

The limited impacts of climate conditions in relation to local competition may also be related to tree age. For example, Thom et al. (2019) found that growth of very young forests was sensitive to modeled climate change in boreal forests. However, by the time forests had reached the ages of trees in this study, they had lost that sensitivity. In addition, the sensitivity to climate also varies by species and results may reflect that Douglas-fir in this region, including in the WNF, is adapted to low summer precipitation (Burns and Honkala 1990). Finding similar patterns in both regions indicated that the influence of local competitive conditions may hold in the WNF, even as the climate becomes more similar to the climate in BLM; that is, as the climate gets hotter and drier (Blois et al. 2013).

Influence of Environmental Conditions

Similar to climate, soil and topographic conditions have been shown to influence tree growth at regional scales (Franklin and Dyrness 1973). For example, Douglas-fir is typically found on south-facing slopes in the northern parts of its range and

vice versa (Burns and Honkala 1990). At finer spatial scales, topographic location and soil conditions have been used as indicators of site index for red alder (Harrington 1986) and Douglas-fir in the US (Steinbrenner 1965 Monserud et al. 1990) and other places, such as Italy (Corona et al. 1998) and France (Curt et al. 2001). Such findings reflect partially that height growth, as used in site index calculations, is less influenced by competitive conditions within standard management densities (Scott et al. 1998) than diameter or basal area growth, as used in this study (Assmann 1961, Marshall 2002). In similar competitive conditions, European beech (*Fagus sylvatica*) showed a diameter growth–drought tolerance trade-off between trees growing on northwest-facing (faster growth, less drought resilience) and southwest-facing (slower growth, higher drought resilience) slopes (Diaconu et al. 2017). Similarly, modeling results showed differences in photosynthesis on north- versus south-facing slopes in areas with similar competitive conditions and precipitation levels as in our study stands (Running 1984). Also, after accounting for competition, the lack of influence of topographic position, aspect, and slope (as quantified by heat load) must be interpreted in light of the site conditions we sampled. Our results may be influenced by the limitation in the range of environmental conditions in our study areas. We limited our sample to fully stocked stands, that is, sites considered suitable for Douglas-fir management. Within these stands, we sampled codominant Douglas-fir, and areas marginal or not suitable for Douglas-fir were avoided, such as wetlands, south-facing meadows, and rock outcrops (Tesch 1981).

It appears that basal area growth was most influenced by managing local competitive conditions, and thinning prescriptions do not benefit from considering topographic and soil conditions at finer spatial scales. The consistent trends found in both regions, that the relationship between competitive conditions and tree growth is not influenced by environmental and climate conditions, indicated that the importance of managing local competition may hold in the near future, at least for the moist region, even when the climate is getting hotter and drier. Although Ruzicka et al. (2017) found an overriding effect of local density on sites reflecting a broader geographic and climate gradient within the region (western side of the Oregon Cascades), our results did not suggest that overall response patterns differed in the drier and moist study regions. In contrast, silver fir (*Abies alba*) was more sensitive to drought in lower elevation in the Vosges, but this effect was mediated by local growing conditions, specifically in mixed species stands (Lebourgeois et al. 2013). The suggestion by the authors that reduced competition in mixed stands, possibly attributable to, for example, different rooting depths, may be responsible for their results, supports our findings regarding the importance of local growing conditions.

In summary, our findings highlight that the BAI of trees was dominantly influenced by their local competitive conditions. The high importance of local competition was consistent in our two study regions and growth periods, indicating a more general relationship. Local competitive conditions also prominently influenced tree growth even when trees may still have been undergoing physiological and morphological adjustments to the more open growing conditions following thinning operations. Thus, it may not be beneficial or necessary to develop "climate smart" prescriptions by accounting for fine scale differences in topography and soil depth on sites quite suitable for tree growth. However, as indicated by recent modeling work (Horemans et al. 2021), further research is needed to determine how these relationships play out during marginal conditions that were not represented in this study, such as during extreme drought years and in areas with very poor soil conditions, such as rock outcrops.

Supplementary Materials

Supplementary information is available at *Forest Science* online.

Supplement 1 Figure S1. Basal area increment (BAI; mm^2) for the three focal trees (red, green, blue) in sample stands in the Willamette National Forest. The first set of five dots displayed growth during the first growth period (five years before the thinning). The second set of dots display the BAI in years 6 to 10 after thinning.

Supplement 1. Figure S2. Basal area increment (BAI; mm^2) for the three individual trees (red, green, blue) in sample stands on BLM land near Roseburg. The first set of five dots displayed growth during the first growth period (five years before the thinning). The second set of dots display the BAI in years 6 to 10 after thinning.

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