AN ABSTRACT OF THE THESIS OF

L. Madelene Elfstrom for the degree of Master of Science in Sustainable Forest Management presented on March 9, 2022.

Title: Effects of Thinning on Tradeoffs Between Drought Resistance, Drought Resilience, and Wood Production in mature Douglas-fir in Western Oregon

Abstract approved: ____

Matthew D. Powers

Recent climate projections predict more frequent and severe drought conditions in western Oregon which is a threat to forest health, productivity, and structure. Land managers are increasingly concerned with how to create forest drought resistance: a tree or stand's ability to maintain its growth rates during a drought, and resilience: a tree or stand's ability to return to pre-drought growth rates after the end of a drought. Thinning has been found in several studies to increase drought resistance and resilience but these effects can vary with thinning intensity and over time, and heavy thinning treatments designed to reduce drought stress may reduce stand productivity. This work expands on existing knowledge by examining how thinning intensity, spatial arrangement and time since treatment impact tradeoffs between drought resistance, drought resilience, and timber production.

I collected stand data and tree cores on the Mature Forest Study (MFS), a long-term thinning study on Oregon State University's McDonald-Dunn Research Forest in the eastern foothills of the Oregon Coast Range. The MFS includes four different thinning intensity treatments, in two spatial arrangements (uniform thinning and thinning with gaps) that were implemented in 1993. I used annual growth data from these tree cores to investigate drought responses during and following drought events in 2001 and 2015-2016. I processed tree cores and calculated basal area increment to calculate resistance and resilience scores.

My initial hypothesis was that the treatments with the lowest residual densities would have the greatest drought resistance and resilience. During the 2001 drought, both resistance and resilience were significantly higher in the lower density treatments. By the 2015-2016 drought, the only treatment that was significantly different in drought response was the medium density treatment which had higher resistance than all other densities. The spatial arrangement of the trees generally did not have a significant effect on drought resistance and resilience or periodic volume growth. Drought event was by far the biggest influence on tree drought response, with trees showing significantly lower resistance and resilience during the 2015-2016 drought than in the 2001 drought across all density and spatial arrangement combinations. I also calculated two-way tradeoff variables between drought resistance, resilience, periodic annual volume increment, and standing volume. There were no significant tradeoffs associated with stand density or spatial arrangement between drought resistance and resilience or between standing volume and any other variable during either drought event. Density treatment did have a significant effect on the periodic annual volume increment – resistance tradeoff from the second drought, due to higher resistance scores in lower density stands and a nonsignificant trend towards higher volume increments in the higher density treatments. These results imply that in the short to medium term, thinning can have a positive effect on drought resistance and resilience while thinning treatments that maximize drought resistance and resilience appear to have fairly limited tradeoffs with the economic concerns of PAI or standing volume.

Effects of Thinning on Tradeoffs Between Drought Resistance, Drought Resilience, and Wood Production in mature Douglas-fir in Western Oregon

by
L. Madelene Elfstrom

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented March 9, 2022
Commencement June 2022

Master of Science thesis of L. Madelene Elfstrom presented on March 9, 2022

APPROVED:

Major Professor, representing Sustainable Forest Management

Head of the Department of Forest Engineering Resources and Management

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

L. Madelene Elfstrom, Author

ACKNOWLEDGEMENTS

Thank you so much to my advisor, Matt Powers, for his faith in me as a student and the countless hours of conversations that spanned land management, forestry, society, academia, and cross-country skiing, among many other topics. Without his thoughtful guidance, I would not have gained such a well-rounded understanding of forestry. He conceived of this project, funded it, and, with constant input helped me understand all the ins and outs of research and writing, even with the challenges of Covid and my taking a fulltime job halfway across the country.

Covid changed the world a few terms into my time at OSU and with it the location of this research. Stephen Fitzgerald, Liz Cole and the McDonald-Dunn Research Forest were integral in helping us shift the research to a new location in a week. Thank you to my field technician, Anna Rose Peterson, for her cheerful, straightforward help throughout the field season. Her experience in forest inventory was invaluable. Andrew Merschel welcomed me into the dendrochronology lab and shared his knowledge of measuring and cross-dating tree cores.

The analysis of this research would not have been possible without the careful input and guidance of Ariel Muldoon. She met with me up until her last day OSU to make sure I understood the analysis and the minutia of coding it. Thank you to my committee, Arijit Sinha, Tammy Cushing and Stephen Fitzgerald, for their input and mentorship.

Thank you to my family who instilled in me a love of the woods and adventure from an early age. Spread across three countries and time zones, you supported and believed in me through long conversations about my research at all hours. Y’all have always celebrated each little step along this journey, encouraged and challenged me to be my best and put my everything into the projects I take on.

Starting graduate school after years in the workforce was a daunting challenge and I cannot imagine doing it with a different cohort. Thank you for studying, laughing, grumbling, and sharing your passion with me about different aspects of forestry. Once we could no longer sit inside and study together, we found ways to connect, motivate and lift each other up through long bike rides, mushroom forays, walks and zoom study sessions.

CONTRIBUTION OF AUTHORS

Dr. Matt Powers was instrumental in the conception and design of this study including research questions and interpretations. Anna Rose Peterson helped with the data collection. L. Madelene Elfstrom wrote the thesis with edits by Dr. Matt Powers.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

LIST OF TABLES

1. General Introduction

The Pacific Northwest contains some of the United States' most productive forest ecosystems which has its own suite of complex management concerns. In particular, the coastal regions of the Northwest have a long history of logging that continues today. Increasing concerns about endangered species, such as the northern spotted owl (*Strix occidentalis caurina*), in the 1990s led to the implementation of the Northwest Forest Plan on federal lands in the Pacific Northwest. The management goals of the Northwest Forest Plan include increasing old-growth forest characteristics and species biodiversity in addition to managing for timber production (Thomas et al. 2006). As a result, recent research has addressed how to accelerate the development of forests which can provide timber and ecosystem services through more old-growth forest structure and composition, such as a multi-story canopy and an established understory shrub layer. In this already difficult balancing act of management goals, climate change has emerged as a threat to the health and productivity of forests globally and locally. Land managers will need to consider the implications of climate change into their plans.

Much of the forestlands surrounding the Willamette Valley were originally oak woodlands maintained by frequent low severity fire. Following the forced removal of the Kalapuya people and the subsequent absence of fire, much of the present day Douglas-fir (*Pseudotsuga menziesii*) dominated forests began to develop (Interdisciplinary Planning Team 2005). White settlers transformed the Pacific Northwest's forests into monocultures but following the concerns about the northern spotted owl and a general loss of biodiversity in the 1990s, the Northwest Forest Plan was created (Puettmann et al. 2016). Since then, increasing research has focused how to accelerate the development of forests that can provide timber and ecosystem services through more “old-growth” like structure characteristics such as a multi-story canopy and an established understory shrub layer.

One approach to providing a wider array of ecosystem services is through accelerating the development of old-growth characteristics in stands that are also being managed for commercial wood production. There is evidence that thinning, which includes variable density thinning (VDT), can help young, even-aged stands develop old-growth characteristics while still meeting objectives of timber production and ecosystem services (Tappeiner et al. 1997; Bailey and Tappeiner 1998; Puettmann et al. 2016; Brodie and Harrington 2020). Additionally, more open stands can produce higher levels of biodiversity at the forest floor level, but recovery is often slow due to mechanical damage and short-lived due to canopy re-closure (Wilson and Puettmann 2007).

However, in this already difficult balancing act of management goals, climate change has emerged as a threat to the health and productivity of forests both globally and locally. As climates shift, we can expect increased pests, diseases, droughts, wildfires, higher temperatures, and other extremes (Dale et al. 2001; Rehfeldt et al. 2006; Bentz et al. 2010; Little et al. 2016). In the past, land managers could make decisions based on historical forest and climate conditions (Spittlehouse and Stewart 2003). However, due to increased uncertainty land managers will need to consider the implications of climate change in their natural resource-based decision-making. Predicted climate models can provide guidance in the creation of our management plans (Holmes et al. 2009; Nagel et al. 2017).

Predicted increases of drought and air temperature in the Pacific Northwest are of special concern for forest management because they have the potential to impact timber production and the provisioning of ecosystem services (Halofsky and Hibbs 2009; Littell et al. 2010; Chesson et al. 2016). Some predictions include an air temperature increase of 2° C over the next 30 years reaching 3° C by the 2080s (Mote and Salathé 2010). Additionally, there is evidence that precipitation will increase in the winter and decrease in the summer but ultimately remain the same overall quantity compared to historic values in the Pacific Northwest. Decreased rainfall during the growing season is particularly concerning as water availability is the primary limitation of Douglas-fir growth, one of the dominant tree species in this region and primary timber production species (Weiskittel et al. 2012; Littell et al. 2014). Drought stress occurs when water availability is limited such that trees either cavitate or close their stomata and become carbon starved, either way they are not able to perform basic physiological processes (McDowell et al. 2008). Coupled with lower rainfall quantities, higher temperatures will increase moisture stress in trees due to increased evaporative demand (Littell et al. 2008; Trouvé et al. 2014; Montwé et al. 2015; Restaino et al. 2016; Ford et al. 2017).

Today, land managers and researchers acknowledge that climate change is a threat to forests. Given the balancing act that already exists in silvicultural systems designed for managing for biodiversity and timber production, incorporating planning for climate change has the potential to cause tradeoffs with the aforementioned management values. We need to carefully assess these tradeoffs to incorporate climate mitigations into our forest management.

Recent research has focused on understanding which site characteristics will be most affected by these changes and how the genetics of local trees interact with this. On the Colville National Forest (NF), it was found that Douglas-fir on drier sites were more affected (i.e.: less resistant) by droughts than those on wetter sites (Carnwath and Nelson 2017). This relationship that xeric forests experiencing the effects of drought more acutely than wetter forests is widely accepted (Fritts 1976). Beyond the trees in their local environment, research has addressed how moving genotypes can impact tree growth in future predicted climates. In a study based in the Canadian Coastal Range, a Douglas-fir genotype from the Willamette Valley, a relatively dry ecoregion in the Pacific Northwest, had the largest reduction in volumetric growth during a drought compared to genotypes from wetter environments (Montwé et al. 2015). These results contradicted the generally-accepted hypothesis that genotypes from more xeric local conditions handle drought better and suggest that Douglas-fir forests in drier ecoregions like the Willamette Valley may be particularly susceptible to increasing drought activity.

The recognition that forests in some ecoregions of the Pacific Northwest may be particularly susceptible to projected increases in drought stress emphasizes the need to incorporate drought resistance and resilience into the already complex set of management goals for these lands. Stand density reductions have been repeatedly suggested as an effective mechanism for reducing drought stress (D'Amato et al. 2013; Bottero et al. 2017), and stand density gradients have been linked to differences in drought resistance and resilience across a range of studies. In Northern California, mixed conifer forests exhibited higher drought resistance in stands that were thinned for fuels mitigation but as a drought continued, drought resistance dropped in both the thinned and un-thinned stands (Vernon et al. 2018). In a study looking at ponderosa pine (*Pinus ponderosa*) and red pine (*Pinus resinosa*) across a latitude and aridity gradient, lower density forests exhibited increased drought resistance and resilience compared to those with higher density (Briggs and Kantavichai 2018). Heavier thinning was consistently found to be effective in improving drought resistance and resilience. Additionally, in areas prone to summer droughts, thinning allowed for reduced competition later in the growing season, allowing for the development of more latewood. These results are similar to those of Jimenez et al. (2019) that studied growth patterns in *Pinus halepensis* on the Iberian Peninsula. They found evidence that even five years after thinning, these treatments allowed trees to grow for a longer period each year (effectively lengthening the growing year) and provided resilience to droughts. In Arizona, thinning was shown to increase pre-dawn water potential in both ponderosa pines established before and after white settlement of the area (Skov et al. 2004).

Although heavier thinning generally promotes increased drought resistance and resilience in the short term, results from some long-term studies suggest that repeated thinning treatments that maintain stands at very low densities may promote a long-term shift towards reduced drought resistance and resilience (McDowell et al. 2006; D'Amato et al. 2013; Briggs and Kantavichai 2018). Additionally, thinning too heavily can reduce stand-scale wood production (Curtis 2006; D'Amato et al. 2010; Newton and Cole 2015), suggesting the potential for tradeoffs between maximizing drought resistance and resilience and maximizing timber yields. In addition to potential tradeoffs between drought resistance, resilience and timber yields, conventional, uniform thinning approaches may not be optimal for creating the complex stand structures desired for the conservation of old-growth associated species. Variable density thinning (VDT) can help accomplish the goal of creating a more heterogenous forest structure to provide habitat for old-growth associated species along with commercial wood production (Roberts and Harrington 2008; Comfort et al. 2010; Dodson et al. 2014; Kuehne et al. 2015; Puettmann et al. 2016; Willis et al. 2018). As a thinning system meant to be finely tuned to the existing landscape and forest, VDT is an intermediate step that incorporates gaps and unharvested leave islands (i.e., “skips”) into a thinned matrix to promote horizontal and vertical variability in a stand.

VDT can balance multiple objectives, such as promoting species biodiversity and structural variability while still being economically feasible (Puettmann et al. 2016). In places where roads and infrastructure already exist it could easily replace uniform thinning. Not only does VDT accelerate the development of old-growth like characteristics in the canopy, but one study in Western Oregon found that VDT increased diameter growth in smaller Douglas-fir trees and also a greater diversity of tree diameters and heights (Puettmann et al. 2016). More aggressive thinning treatments can produce greater rates of residual tree growth although the eventual canopy closure led to declines in these growth rates later (Dodson et al. 2012; Briggs and Kantavichai 2018). Growth of residual trees is also generally greater near gaps than in the thinned matrix (Roberts and Harrington 2008; Powers et al. 2009) . Growth is a general indicator of a healthy tree or stand. By reducing stand density, VDT has the potential to increase drought resistance and resilience, with greater potential benefits to residual trees in lower density neighborhood environments such as around gaps.

Although thinning treatments are likely to have differing impacts on drought resistance, resilience, wood growth, and wildlife habitat depending on the residual density and spatial arrangement of residual trees, the interacting effects of thinning intensity and spatial pattern (i.e., uniform thinning vs thinning with gaps) on tradeoffs between any combination of these factors have not been heavily studied. My thesis explores tradeoffs between drought response (resistance and resilience) and metrics of wood production (periodic annual increment (PAI) and total standing volume).

I used the Mature Forest Study (MFS), a long-term thinning study that encompasses a range of thinning treatments, to evaluate the impacts of thinning intensity and spatial pattern on tradeoffs between drought resistance, resilience and wood production. The MFS is located on the Oregon State University's McDonald-Dunn Forest which lies on the east side of Oregon's Coast Range, just north of Corvallis, OR, in an area that that is likely to be heavily impacted by the effects of increasing droughts and temperatures. Thinnings on this site were implemented in 1993 and tree cores and stand data was collected in 2020, giving me the ability to evaluate basal area increment (BAI) growth patterns during and after drought events in both 2001 and 2015-2016.

Through analysis of this data, my thesis evaluates the questions of: 1) how stand density and spatial arrangement (gap versus uniform thinning) affect individual trees' drought resistance and resilience, 2) how does the timing and intensity of post-thinning drought affect drought resistance and resilience, and 3) how do stand density and spatial arrangement impact stand level tradeoffs between drought resistance, drought resilience, and wood production as measured in PAI and standing volume. Looking into these questions has the potential to provide land managers with information as they balance forest management goals under a changing climate.

1.1 Works Cited

Agne MC, Beedlow PA, Shaw DC, Woodruff DR, Lee EH, Cline SP, Comeleo RL. 2018. Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. For Ecol Manage. 409:317–332. doi:https://doi.org/10.1016/j.foreco.2017.11.004. https://www.sciencedirect.com/science/article/pii/S0378112717306928.

Allen CD, Breshears DD, McDowell NG. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere. 6(8):1–55. doi:10.1890/ES15-00203.1.

Bailey JD, Tappeiner JC. 1998. Effects of thinning on structural development in 40- to 100-year, old Douglas-fir stands in western Oregon. For Ecol Manage. 108(1–2):99–113. doi:10.1016/S0378-1127(98)00216-3.

Bauhus J, Puettmann K, Messier C. 2009. Silviculture for old-growth attributes. For Ecol Manage. 258(4):525–537. doi:10.1016/j.foreco.2009.01.053.

Bentz BJ, Rgnire J, Fettig CJ, Hansen EM, Hayes JL, Hicke JA, Kelsey RG, Negron JF, Seybold SJ. 2010. Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. Bioscience. 60(8):602–613. doi:10.1525/bio.2010.60.8.6.

Bottero A, D'Amato AW, Palik BJ, Bradford JB, Fraver S, Battaglia MA, Asherin LA. 2017. Density-dependent vulnerability of forest ecosystems to drought. J Appl Ecol. 54(6):1605–1614. doi:10.1111/1365-2664.12847.

Brackett M. 1973. Notes on TARIF tree volume computation. Olympia.

Brackett M. 1977. Notes on TARIF tree volume computation. Olympia.

Bradford JB, D'Amato AW. 2012. Recognizing trade-offs in multi-objective land management. Front Ecol Environ. 10(4):210–216. doi:10.1890/110031.

Brandeis TJ, Newton M, Cole EC. 2002. Biotic injuries on conifer seedlings planted in forest understory environments. New For. 24(1):1–14. doi:10.1023/A:1020553021748.

Briggs DG, Kantavichai R. 2018. Effects of thinning on ring mass growth along stem of douglas fir in four coastal pacific northwest sites. For Sci. 64(2):139–148. doi:10.1093/forsci/fxx003.

Brodie LC, Harrington CA. 2020. Guide to variable-density thinning using skips and gaps.

USDA For Serv - Gen Tech Rep PNW-GTR. 2020(GTR-989):1–37.

Carnwath G, Nelson C. 2017. Effects of biotic and abiotic factors on resistance versus resilience of Douglas fir to drought. PLoS One. 12(10):1–19. doi:10.1371/journal.pone.0185604.

Chesson P, Gebauer RLE, Schwinning S, Huntly N, Ernest MSK, Sher A, Novoplansky A, Weltzin JF, Schwinning S, Huntly N, et al. 2016. International Association for Ecology Resource Pulses , Species Interactions , and Diversity Maintenance in Arid and Semi-Arid Environments Published by : Springer in cooperation with International Association for Ecology Stable URL : http://www.jstor.org. (May). doi:10.1007/s00442-004-1551-l.

Chmura DJ, Anderson PD, Howe GT, Harrington CA, Halofsky JE, Peterson DL, Shaw DC, Brad St.Clair J. 2011. Forest responses to climate change in the northwestern United States: Ecophysiological foundations for adaptive management. For Ecol Manage. 261(7):1121–1142. doi:10.1016/j.foreco.2010.12.040. http://dx.doi.org/10.1016/j.foreco.2010.12.040.

Cole E, Newton M. 2009. Tenth-year survival and size of underplanted seedlings in the Oregon coast range. Can J For Res. 39(3):580–595. doi:10.1139/X08-198.

Cole E, Newton M, Bailey JD. 2017. Understory vegetation dynamics 15 years post-thinning in 50-year-old Douglas-fir and Douglas-fir/western hemlock stands in western Oregon, USA. For Ecol Manage. 384:358–370. doi:10.1016/j.foreco.2016.11.003. http://dx.doi.org/10.1016/j.foreco.2016.11.003.

Comfort EJ, Roberts SD, Harrington CA. 2010. Midcanopy growth following thinning in young-growth conifer forests on the Olympic Peninsula, western Washington. For Ecol Manag 259 1606-1614. 259:1606–1614. https://www.fs.fed.us/pnw/pubs/journals//pnw_2010_comfort001.pdf.

Curtis RO. 2006. Volume Growth Trends in a Douglas-Fir Levels-of-Growing-Stock Study. West J Appl For. 21(2):79–86. doi:10.1093/wjaf/21.2.79.

D’Amato AW, Bradford JB, Fraver S, Palik BJ. 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. Ecol Appl. 23(8):1735–1742. doi:10.1890/13-0677.1.

D’Amato AW, Jokela EJ, O’Hara KL, Long JN. 2017. Silviculture in the United States: An Amazing Period of Change over the Past 30 Years. J For. 116(January):55–67. doi:10.5849/jof-2016-035.

D’Amato AW, Palik BJ, Kern CC. 2010. Growth, yield, and structure of extended rotation Pinus resinosa stands in Minnesota, USA. Can J For Res. 40(5):1000–1010. doi:10.1139/X10-041. https://doi.org/10.1139/X10-041.

Dale V, Joyce LA, Mcnulty S, Neilson R, Ayres M, Flannigan M, Hanson P, Irland L, Lugo A, Peterson CJ, et al. 2001. Climate Change and Forest Disturbances. Bioscience. 51:723.

DARYCHUK N, HAWKINS BJ, STOEHR M. 2012. Trade-offs between growth and cold and drought hardiness in submaritime Douglas-fir. Can J For Res. 42(8):1530–1541. doi:10.1139/x2012-092.

Davis LR, Puettmann KJ, Tucker GF. 2007. Overstory response to alternative thinning treatments in young Douglas-fir forests of Western Oregon. Northwest Sci. 81(1):1–14. doi:10.3955/0029-344X-81.1.1.

Dodson EK, Ares A, Puettmann KJ. 2012. Early responses to thinning treatments designed to accelerate late successional forest structure in young coniferous stands of Western Oregon, USA. Can J For Res. 42(2):345–355. doi:10.1139/X11-188.

Dodson EK, Burton JI, Puettmann KJ. 2014. Multiscale controls on natural regeneration dynamics after partial overstory removal in douglas-fir forests in Western Oregon, USA. For Sci. 60(5):953–961. doi:10.5849/forsci.13-011.

Fernández-de-Uña L, McDowell NG, Cañellas I, Gea-Izquierdo G. 2016. Disentangling the effect of competition, CO2 and climate on intrinsic water-use efficiency and tree growth. J Ecol. 104(3):678–690. doi:https://doi.org/10.1111/1365-2745.12544. https://doi.org/10.1111/1365-2745.12544.

Finley K, Zhang J. 2019. Climate effect on ponderosa pine radial growth varies with tree density and shrub removal. Forests. 10(6). doi:10.3390/f10060477.

Ford KR, Breckheimer IK, Franklin JF, Freund JA, Kroiss SJ, Larson AJ, Theobald EJ, HilleRisLambers J. 2017. Competition alters tree growth responses to climate at individual and stand scales. Can J For Res. 47(1):53–62. doi:10.1139/cjfr-2016-0188.

Franklin JF, Johnson KN. 2012. A Restoration Framework for Federal Forests in the Pacific Northwest. J For. 110(8):429–439. doi:10.5849/jof.10-006. https://doi.org/10.5849/jof.10-006.

Fritts HC. 1976. Tree rings and climate. Caldwell, NJ: Blackburn.

Halofsky JE, Andrews-Key SA, Edwards JE, Johnston MH, Nelson HW, Peterson DL, Schmitt KM, Swanston CW, Williamson TB. 2018. Adapting forest management to climate change: The state of science and applications in Canada and the United States. For Ecol Manage. 421:84–97. doi:https://doi.org/10.1016/j.foreco.2018.02.037. https://www.sciencedirect.com/science/article/pii/S0378112717316547.

Halofsky JE, Hibbs DE. 2009. Controls on early post-fire woody plant colonization in riparian areas. For Ecol Manage. 258(7):1350–1358. doi:10.1016/j.foreco.2009.06.038.

Hanus ML, Marshall DD, Hann DW. 1999. Height-Diameter Equations for Six Species in the Coastal Regions of the Pacific Northwest. Res Contrib For Res Lab Oregon State Univ.(August):12.

Holmes TP, McNulty S, Vose JM, Prestemon JP, Li H. 2009. A Conceptual Framework for Adaptive Forest Management under Climate Change. Clim Chang Adapt Mitig Manag options A Guid Nat Resour Manag South For Ecosyst.:45–60.

Interdisciplinary Planning Team. 2005. McDonald-Dunn Forest Plan.

Kuehne C, Weiskittel AR, Fraver S, Puettmann KJ. 2015. Effects of thinning-induced changes in structural heterogeneity on growth, ingrowth, and mortality in secondary coastal Douglas-fir forests. Can J For Res. 45(11):1448–1461. doi:10.1139/cjfr-2015-0113. https://doi.org/10.1139/cjfr-2015-0113.

Lee EH, Beedlow PA, Brooks JR, Tingey DT, Wickham C, Rugh W. 2022. Physiological responses of Douglas-fir to climate and forest disturbances as detected by cellulosic carbon and oxygen isotope ratios. Tree Physiol. 42(1):5–25. doi:10.1093/treephys/tpab122. https://doi.org/10.1093/treephys/tpab122.

Littell JS, Oneil EE, McKenzie D, Hicke JA, Lutz JA, Norheim RA, Elsner MM. 2010. Forest ecosystems, disturbance, and climatic change in Washington State, USA. Clim Change. 102(1–2):129–158. doi:10.1007/s10584-010-9858-x.

Littell JS, Peterson DL, Tjoelker M. 2008. Douglas-Fir Growth in Mountain Ecosystems: Water Limits Tree Growth from Stand to Region. Ecolological Monogr. 78(3):1–20. papers3://publication/uuid/24364A69-9981-4F58-9D67-6A860071FD45.

Littell JS, Peterson DL, Tjoelker M, Monographs E, Littell S. 2014. Douglas-Fir Growth in Mountain Ecosystems : Water Limits Tree Growth from Stand to Region Published by : Ecological Society of America content in a trusted digital archive . We use information technology and tools to increase productivity and facilitate n. 78(3):349–368.

Littke KM, Zabowski D, Turnblom E, Harrison RB. 2018. Estimating shallow soil available water supply for Douglas-fir forests of the coastal Pacific Northwest: climate change impacts. Can J For Res. 48(4):421–430. doi:10.1139/cjfr-2017-0385. https://doi.org/10.1139/cjfr-2017-0385.

Little J, Peterson D, Riley K, Liu Y. 2016. A review of the relationships between drought and forest fire in the United States. Glob Chang Biol. 22(7):2353–2369. doi:10.1111/gcb.13275. https://www.deepdyve.com/lp/wiley/a-review-of-the-relationships-between-drought-and-forest-fire-in-the-VfYrRw776E.

McDowell N, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams DG, et al. 2008. Mechanisms of plant survival and mortality during drought: Why do some plants survive while others succumb to drought? New Phytol. 178(4):719–739. doi:10.1111/j.1469-8137.2008.02436.x.

McDowell NG, Adams HD, Bailey JD, Hess M, Kolb TE. 2006. Homeostatic Maintenance Of Ponderosa Pine Gas Exchange In Response To Stand Density Changes. Ecol Appl. 16(3):1164–1182. doi:https://doi.org/10.1890/1051-0761(2006)016[1164:HMOPPG]2.0.CO;2. https://doi.org/10.1890/1051-0761(2006)016[1164:HMOPPG]2.0.CO.

Messier C, Bauhus J, Doyon F, Maure F, Sousa-Silva R, Nolet P, Mina M, Aquilué N, Fortin MJ, Puettmann K. 2019. The functional complex network approach to foster forest resilience to global changes. For Ecosyst. 6(1). doi:10.1186/s40663-019-0166-2.

Millar CI, Stephenson NL, Stephens SL. 2007. CLIMATE CHANGE AND FORESTS OF THE FUTURE : mm. Ecol Appl. 17(8):2145–2151.

Montwé D, Spiecker H, Hamann A. 2015. Five decades of growth in a genetic field trial of

Douglas-fir reveal trade-offs between productivity and drought tolerance. Tree Genet Genomes. 11(2):1–11. doi:10.1007/s11295-015-0854-1.

Mote PW, Salathé EP. 2010. Future climate in the Pacific Northwest. Clim Change. 102(1):29–50. doi:10.1007/s10584-010-9848-z. https://doi.org/10.1007/s10584-010-9848-z.

Nabel MR, Newton M, Cole EC. 2013. Abundance of natural regeneration and growth comparisons with planted seedlings 10-13years after commercial thinning in 50-year-old Douglas-fir, Douglas-fir/western hemlock, Oregon Coast Range. For Ecol Manage. 292:96–110. doi:10.1016/j.foreco.2012.12.009. http://dx.doi.org/10.1016/j.foreco.2012.12.009.

Nagel LM, Palik BJ, Battaglia MA, D'Amato AW, Guldin JM, Swanston CW, Janowiak MK, Powers MP, Joyce LA, Millar CI, et al. 2017. Adaptive silviculture for climate change: A national experiment in manager-scientist partnerships to apply an adaptation framework. J For. 115(3):167–178. doi:10.5849/jof.16-039.

Newton M, Cole EC. 2006. Harvesting impacts on understory regeneration in two-storied Douglas-fir stands. West J Appl For. 21(1):14–18. doi:10.1093/wjaf/21.1.14.

Newton M, Cole L. 2015. Overstory development in douglas-fir-dominant forests thinned to enhance late-seral features. For Sci. 61(4):809–816. doi:10.5849/forsci.14-194.

Palik BJ, D'Amato AW. 2019. Variable retention harvesting in Great Lakes mixed-pine forests: emulating a natural model in managed ecosystems. Ecol Process. 8(1). doi:10.1186/s13717-019-0171-y.

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team. 2021. nlme: Linear and Nonlinear Mixed Effects Models. https://cran.r-project.org/package=nlme.

Powers MD, Webster CR, Pregitzer KS, Palik BJ. 2009. Spatial dynamics of radial growth and growth efficiency in residual Pinus resinosa following aggregated retention harvesting. Can J For Res. 39(1):109–117. doi:10.1139/X08-162. https://doi.org/10.1139/X08-162.

Priebe JE, Powers MD, Cole EC. 2018. Species, tree size, and overstory environment affect likelihood of ice storm damage to understory trees in a mature Douglas-fir forest. For Ecol Manage. 409(April 2017):777–788. doi:10.1016/j.foreco.2017.11.041. https://doi.org/10.1016/j.foreco.2017.11.041.

Puettmann KJ, Ares A, Burton JI, Dodson EK. 2016a. Forest restoration using variable density thinning: Lessons from douglas-fir stands in western Oregon. Forests. 7(12):1–15. doi:10.3390/f7120310.

Puettmann KJ, Ares A, Burton JI, Dodson EK. 2016b. Forest restoration using variable density thinning: Lessons from douglas-fir stands in western Oregon. Forests. 7(12):1–14. doi:10.3390/f7120310.

Rehfeldt GE, Crookston NL, Warwell M V., Evans JS. 2006. Empirical analyses of plant-climate relationships for the Western United States. Int J Plant Sci. 167(6):1123–1150. doi:10.1086/507711.

Restaino CM, Peterson DL, Littell J. 2016. Increased water deficit decreases Douglas fir growth throughout western US forests. Proc Natl Acad Sci U S A. 113(34):9557–9562. doi:10.1073/pnas.1602384113.

Del Río M, Bravo-Oviedo A, Pretzsch H, Löf M, Ruiz-Peinado R. 2017. A review of thinning effects on Scots pine stands: From growth and yield to new challenges under global change. For Syst. 26(2):eR03S. doi:10.5424/fs/2017262-11325.

Ritchie MW, Hann DW. 1984. Nonlinear Equations for Predicting Diameter and Squared Diameter Inside Bark at Breast Height for Douglas-Fir.

Roberts SD, Harrington CA. 2008. Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests. For Ecol Manage. 255(7):2771–2781. doi:https://doi.org/10.1016/j.foreco.2008.01.043. https://www.sciencedirect.com/science/article/pii/S0378112708001114.

Skov K, Kolb T, Wallin K. 2004. Tree Size and Drought Affect Ponderosa Pine Physiological Response to Thinning and Burning Treatments. For Sci. 50:81–91.

Sohn JA, Saha S, Bauhus J. 2016. Potential of forest thinning to mitigate drought stress: A meta-analysis. For Ecol Manage. 380:261–273. doi:10.1016/j.foreco.2016.07.046.

Spittlehouse DL, Stewart RB. 2003. Adaptation to climate change in forest management. BC J Ecosyst Manag. 4(1):1–11.

Tappeiner JC, Huffman DW, Marshall D, Spies TA, Bailey JD. 1997. Density, ages, and growth rates in old-growth and young-growth forests in coastal Oregon. Can J For Res. 27(5):638–648. doi:10.1139/x97-015.

Thomas JW, Franklin JF, Gordon J, Johnson NK. 2006. The Northwest Forest Plan: Origins, Components, Implementation Experience, and Suggestions for Change. Conserv Biol. 20(2):277–287. doi:https://doi.org/10.1111/j.1523-1739.2006.00385.x. https://doi.org/10.1111/j.1523-1739.2006.00385.x.

Thompson NP, Lewis KJ, Poirier LM. 2018. Adjacency to a harvest trail increases drought resistance of interior douglas-fir (Pseudotsuga menziesii var. glauca) in partially harvested stands in central British Columbia. Can J For Res. 48(7):809–820. doi:10.1139/cjfr-2018-0007.

Trouvé R, Bontemps J-D, Collet C, Seynave I, Lebourgeois F. 2014. Growth partitioning in forest stands is affected by stand density and summer drought in sessile oak and Douglas-fir. For Ecol Manage. 334:358–368. doi:https://doi.org/10.1016/j.foreco.2014.09.020. https://www.sciencedirect.com/science/article/pii/S0378112714005611.

Vernon MJ, Sherriff RL, van Mantgem P, Kane JM. 2018. Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. For Ecol Manage. 422:190–198. doi:https://doi.org/10.1016/j.foreco.2018.03.043. https://www.sciencedirect.com/science/article/pii/S0378112717321321.

Walters DK, Hann DW, Clyde MA. 1985. Equations and Tables Predicting Gross Total Stem Volumes in Cubic Feet for Six Major Conifers of Southwest Oregon. (Research Bulletin 50):37.

Weiskittel AR, Crookston NL, Rehfeldt GE. 2012. Projected future suitable habitat and productivity of Douglas-fir in western North America. Schweizerische Zeitschrift fur Forstwes. 163(3):70–78. doi:10.3188/szf.2012.0070.

Willis JL, Roberts SD, Harrington CA. 2018. Variable density thinning promotes variable structural responses 14?years after treatment in the Pacific Northwest. For Ecol Manag 410 114-125. 410:114–125. doi:10.1016/j.foreco.2018.01.006. https://www.fs.fed.us/pnw/pubs/journals/pnw_2018_willis001.pdf.

Wilson DS, Puettmann KJ. 2007. Density management and biodiversity in young Douglas-fir forests: Challenges of managing across scales. For Ecol Manage. 246(1 SPEC. ISS.):123–134. doi:10.1016/j.foreco.2007.03.052.

Zhang J, Finley KA, Johnson NG, Ritchie MW. 2019. Lowering stand density enhances resiliency of ponderosa pine forests to disturbances and climate change. For Sci. doi:10.1093/forsci/fxz006.

2. Manuscript: Effects of Thinning on Tradeoffs Between Drought Resistance, Drought Resilience, and Wood Production in mature Douglas-fir in Western Oregon

2.1 Introduction

Climate change is a significant threat to forest health across the globe as shifting precipitation and temperature patterns are projected to affect a variety of forest ecosystem processes. At global and regional scales, there is growing evidence that increased drought severity and length could suppress growth, increase mortality, and ultimately make forests more susceptible to disturbance agents. Under this new paradigm, wildfire, insects and diseases could alter our forests beyond the stand level (Chmura et al. 2011). Already, we have begun to see more frequent and severe droughts and higher temperatures in Western Oregon. This poses a serious threat to the health and productivity of our forests but with careful forest management, we can offset these concerns to a certain extent.

Under projected shifts towards warmer and drier summers, we can expect to see decreased growth in the Douglas-fir forests of western Oregon and Washington that will reduce productivity and affect structure (Littell et al. 2008; Restaino et al. 2016; Littke et al. 2018). In a region that produces 29% of national softwood lumber harvest in Douglas-fir alone, the negative impacts of reduced productivity have far-reaching economic impacts. This reduced vigor may make trees more susceptible to insects, wildfire and wind throw mortality further decreasing productivity (Bentz et al. 2010; Littell et al. 2010; Agne et al. 2018). Adaptive management, including density management, has the potential to increase resistance and resilience to the effects of climate change, especially if it is based on predicted future climates and has the flexibility to be adapted as more information becomes available (Spittlehouse and Stewart 2003).

Drought response is frequently assessed using two metrics: resistance and resilience. Resistance represents a tree's ability to keep growing at its pre-drought rate during a drought event, while resilience represents a tree's ability to return to its pre-drought growth rate after a drought (Millar et al. 2007; D'Amato et al. 2013; Nagel et al. 2017). These two definitions are key to understanding how to assess an individual's response and can be expanded to the stand or landscape scale (Messier et al. 2019).

Density management is an important silvicultural tool for a variety of outcomes and now is being looked at in a plethora of ecosystems for increasing drought resistance and resilience. A rise in temperatures in the spring begins the growing season but soil moisture availability is critical in determining the amount and duration of growth (Zhang et al. 2019). Water availability is the main growth limiter in Douglas-fir (Littell et al. 2014), so projected increases in drought activity are likely to limit Douglas-fir growth across the Pacific Northwest. Thinning reallocates water to the remaining trees and can support healthier forests (Sohn et al. 2016). As a result, thinning has frequently been suggested as a tool for reducing drought stress (D'Amato et al. 2013; Bottero et al. 2017; Halofsky et al. 2018), and may be an effective silvicultural approach for promoting resistance and resilience to projected increases of drought in the Pacific Northwest.

There has been significant evidence that trees in lower density stands have a greater ability to adapt to drought (Chmura et al. 2011; D'Amato et al. 2013; Bottero et al. 2017). However, thinning impacts on a tree's responses to drought can vary with thinning intensity, and may decline over time as overstory densities and leaf area recover following the harvest. Studies in a variety of forest types have found a negative correlation between forest density and drought resistance and resilience (McDowell et al. 2006; D’Amato et al. 2013; Fernández-de-Uña et al. 2016; Bottero et al. 2017; Zhang et al. 2019). For Douglas-fir (*Pseudotsuga menziesii*) systems, Littell et al. (2014) demonstrated similar findings in several different states across the Western US and additionally found that water availability was the most common limiting factor for growth and that increased summer temperatures would exacerbate the need for water.

Although stand density reductions have been linked to improvements in drought resistance in resilience, there is some evidence that these benefits can decrease with time after initial thinning treatments, and may even reverse in low density stands as individual trees rapidly attain large sizes and require more water (D’Amato et al. 2013). In Pacific Northwest coastal sites, thinning has been found to increase diameter growth in Douglas-fir especially towards the base of a tree but this effect is parabolic, with growth increasing over several years following thinning, reaching a peak, and then declining as residual tree growth and new ingrowth return competition to pre-thinning levels (Briggs and Kantavichai 2018). In mortality studies in California, stands with lower basal area densities were able to tolerate more extreme droughts than stands with higher densities (Young et al. 2017). Additionally, trees on historically drier sites were more susceptible to mortality than those on wetter sites despite having evolved under drier conditions. It is important to understand these dynamics between competition and thinning as they are further restricted during droughts.

Although conventional thinning practices have been shown to promote drought resistance and resilience in a variety of forest types, variable density thinning (VDT) treatments that generate a wide range of competitive environments within the residual stand may result in a wider range of tree responses to drought. VDT uses skips (i.e., unharvested leave patches), gaps and matrix thinning to create structurally complex stands, and is frequently suggested as a treatment to balance wood production and biodiversity conservation needs (Bauhus et al. 2009; Franklin and Johnson 2012). By creating a variety of competitive environments within individual stands, VDT produces a range of tree growth responses that are generally negatively related to residual density (Roberts and Harrington 2008; Comfort et al. 2010; Dodson et al. 2014; Kuehne et al. 2015; Willis et al. 2018). As a result, we might expect a greater variety of drought responses in stands treated with VDT approaches than in uniformly thinned stands.

This work focuses on exploring relationships between thinning intensity, spatial pattern, and drought resistance and resilience in Douglas-fir forests. I assessed tree growth, drought resistance, and drought resilience in the Mature Forest Study (MFS), a long-term thinning study located on Oregon State University's McDonald-Dunn Research Forest, north of Corvallis, Oregon. MFS thinning treatments were completed in 1993 with four density levels nested within two different of spatial arrangements: uniform thinning and thinning with gaps (henceforth referred to as the gap treatment). This study has been used to investigate growth patterns, snag creation, wildlife habitat and the effects of ice glaze events (Brandeis et al. 2002; Newton and Cole 2006; Cole and Newton 2009; Newton and Cole 2015; Cole et al. 2017; Priebe et al. 2018). My research expands upon this body of work to address the impacts of drought in the transition zone between the Oregon Coast Range and the Willamette Valley.

Increased temperatures and summer moisture deficits are projected to reduce the suitability of habitat for Douglas-fir in low elevation sites along valley margins and the rain shadows of coastal ranges in the Pacific Northwest (Rehfeldt et al. 2006; Littell et al. 2010). Given the location of the McDonald Forest installations of the MFS at low elevation sites in the rain shadow of the Oregon Coast Range, increasing drought activity is likely to cause more significant and earlier impacts on these sites than elsewhere in the Coast Range or western Cascades. As the Coast Range is critical to supporting both the region's biodiversity and timber economy, drought effects on these forests could have a significant impact on biodiversity conservation and the local economies.

Most management decisions also include assessments of potential tradeoffs in treatment outcomes across multiple resource management goals (Bradford and D'Amato 2012). Given the tendency for lower stand densities to promote increasing drought resistance and resilience (Boterro et al. 2017), heavy thinning might be expected to maximize drought resistance and resilience. However, maintaining stands at low densities can also reduce total timber yields, suggesting the potential for tradeoffs between drought resistance, resilience and commercial wood production goals (Curtis 2006; D'Amato et al. 2010; Newton and Cole 2015). With this in mind, I wanted to explore potential tradeoffs between drought resistance, drought resilience, periodic annual increment and standing volume. I used tree core samples from overstory Douglas-fir in the MFS to assess tree growth, drought resistance, and drought resilience to drought events in 2001 and 2015-2016. My work focused on the following research questions designed to explore the impacts of thinning on drought resistance and resilience in Douglas-fir:

1. How does stand density affect drought resistance and resilience?
2. How does spatial arrangement (i.e., uniform thinning vs thinning with gaps) affect drought resistance and resilience?
3. How does the timing and intensity of drought affect drought resistance and resilience?

4. How do stand density and spatial arrangement impact the tradeoffs between drought resistance, drought resilience, and wood production?

The goal of this research was to provide information that land managers can use to plan and manage their forests for an uncertain future while still meeting multiple objectives given the predictions of increasing drought stress in the Pacific Northwest. My hypothesis is that due to a reduction in competition for water, the heavier thinning treatments will increase drought resistance and resilience as compared to the lighter thins. I predict that the treatment with the heaviest thin will show superior drought response as seen in higher drought resistance and resilience than the other treatments. Additionally, I predict that as time since thinning increases there will be a decrease in drought resistance and resilience due to the corresponding increases in stand density and competition for resources associated with the growth of residual trees and understory vegetation after thinning (Briggs and Kantavichai 2018).

2.2 Methods

2.2.1 Study Sites

All data was collected at the Mature Forest Study (MFS) experiment and nearby stands on the McDonald-Dunn Experimental Forest owned by Oregon State University. Located approximately eight kilometers north of Corvallis, the McDonald-Dunn Forest is on the eastern edge of Oregon’s Coast Range. This area is characterized by warm dry summers and cool wet winters and generally receives less precipitation than the rest of the Coast Range.

At the initial implementation of the MFS in 1993, stands with an overstory dominated by approximately 50 year-old Douglas-fir (*Pseudotsuga menziesii*) were chosen for the experiment.

Other species present in the overstory included, grand fir (*Abies grandis*), bigleaf maple (*Acer macrophyllum*) and in smaller quantities, Port-Orford-cedar (*Chamaecyparis lawsoniana*), Oregon white oak (*Quercus garryana*) and Pacific Madrone (*Arbutus menziesii).* The shrub layer included hazel (*Corylus cornuta var. californica*), blue elderberry (*Sambucu nigra var. cerulea*), ocean spray (*Holodiscus discolor*) and in many areas was dominated by Himalayan blackberry (*Rubus armeniacus***)**. The forest floor was covered in a combination of poison oak (*Toxicodendron diversilobum)*, sword fern (*Polystichum munitum**)*** and false-brome (*Brachypodium sylcaticum*). At the time of MFS establishment in 1993, the stands had been previously thinned twice, in 1964 and 1980. Additionally, a winter glaze event took place in 2014 that broke the tops out of many of the trees. The effect of this storm has been explored in prior research (Priebe et al. 2018). In some of the plots, extensive laminated root rot (*Phellinus weirii*) pockets were present.

2.2.2 Experimental Design

The Mature Forest Study was designed as a split-split plot study. Stands on the McDonald Forest were selected for uniformity of stand composition and structure, using elevation as a proxy for site quality. Three, 20-hectare blocks were created. Each block was then subdivided into two, 10-hectare plots that were randomly assigned either a uniform or gappy clumpy patchy (from here on out referred to as gap) pattern for their thinning. Gap plots had 12, 0.10-hectare and 12, 0.06-hectare gaps cut into a matrix of evenly spaced trees. Each plot was further divided into 4, 2.5-ha subplots which were randomly assigned a thinning treatment of low (16.7-18.8 m^2/ha), medium (19.3-25.1 m^2/ha), medium high (26.9-29.6 m^2/ha) and high residual density (27.7-32.9 m^2/ha) (Nabel et al. 2013) (Table 2.1). Gap subplots only received matrix thinning if necessary to bring the whole subplot down to the prescribed basal area leading to the matrix of gap subplots being 25% more dense than the uniform density subplots of the corresponding residual density level. The MFS sites were thinned from below in 1993. Both the medium and medium-high density subplots were re-thinned in 2001 back to their initial prescribed density.

Every subplot was planted with an equal mixture of grand fir, Douglas-fir, western redcedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) in 1994. Trees were planted in a 3 m by 3 m grid with two rows of the same species next to each other in a random order. Additionally, each subplot was divided into three sub-sub-plots of 0.5-hectares for understory vegetation management treatments. These treatments included plant only (no herbicide application), a broadcast spray treatment and a release spray of glyphosate and imazapyr. Previous studies have indicated that the understory vegetation management treatments did not have an effect on overstory growth (Nabel et al. 2013), so we have not included them in our analyses.

2.2.3 Field Measurements

Sampling took place in the summer of 2020. Five sample points were randomly selected within each subplot and constrained to be 25 m from the subplot edges. All Douglas-fir and grand fir > 10 cm DBH that occurred within a 0.04-ha (low and medium density subplots), or 0.02-ha (medium-high and high density subplots) circle centered on each sample point were selected for tree coring. The two different tree core plot sizes were based on previous TPH estimates in order to obtain approximately the same number of cores per sample point, regardless of the treatment that the sample point fell into. Tree cores were extracted at breast height (1.3m) and perpendicular to the slope. Additionally, species, permanent monitoring tree tag number, dbh, total height, height to base of live crown, crown class and notes of damage were recorded for each cored tree. I also recorded the dbh, species, and crown class for all trees over 10 cm dbh in a 0.1-ha circle centered around each tree core sample point to characterize the neighborhood environment around cored trees.

2.2.4 Data Collection

Tree Core Processing and Measurement

Tree cores were air dried, mounted in core mounts and sanded with increasingly fine sandpaper up to 320 grit. After visually dating, annual growth rings widths were measured using a Velmex TA Measurement System, a Unislide sliding stage (Velmex Inc., Bloomfield NY), and a QC 1100 encoder readout Measure (Heidenhain Corporation, Schaumberg IL). J2X software (Voortech Consulting, Holderness NH) and the Cofecha software program (Holmes, 1983) were used to crossdate the cores according to standard procedures. Grand-fir cores were excluded from measurements as the sample size of grand fir cores was too low for effective cross-dating. I was unable to crossdate a few cores and they were excluded leaving 400 cores.

2.2.5 Drought Selection

Prior to tree sampling, Matthew Powers conducted a preliminary analysis using the Palmer Drought Severity Index (PDSI) that found two significant drought events have occurred since the implementation of the MFS. Monthly PDSI values were averaged to create a water year average, and water years with mean, monthly PSDI of -2.0 or lower were classified as drought events. If there was no evidence that the drought abated between years, then successive drought years were treated as a single drought event. From this preliminary work, 2001 and 2015-2016 were identified as years with moderate or higher severity drought at the MFS study sites.

2.2.6 Data Analysis

Response Calculations

Diameter inside bark (DIB) was calculated using locally-derived allometric equations (Ritchie and Hann 1984) (Table 2.2). I calculated DIB estimates for each year by subtracting the raw annual ring widths for each subsequent year from the tree's total DIB and used the DIB estimates for individual years to calculate basal area for each year back to 1996. By subtracting the previous year's basal area, I calculated basal area increment (BAI) for each year of interest. BAI was used rather than ring width because it is less influenced by tree size (Bottero et al. 2017). Then drought resistance and drought resilience were calculated on an individual tree basis for the 2001 and 2015-2016 drought events using the following equations (D'Amato et al. 2013).

$$\text{Resistance} = GI_{D/}GI_{Pre}$$

$$\text{Resilience} = GI_{Post}/GI_{Pre}$$

where:

GI=basal area increment

D=during-drought

Pre=5-year pre-drought mean

Post=3-year post drought mean

I limited the mean GI_{post} to three years to keep it consistent between the two drought events because I only had three complete years of tree growth after the second drought before the tree cores were collected. I inserted a 0.01 mm measurement for rings of suppressed trees with zero to minimal measurable growth to avoid the mathematical issue of having zeros in the response equations. Suppressed trees will often show what looks like flatlined growth without much differentiation in growth between years regardless of environmental impacts. Therefore, using means from multiple years of predrought and post drought BAIs encompasses more data and minimizes the effects of suppression. This avoids the situation where equations look like this: Resistance $=GI_{D}/GI_{Pre}=0.01/0.01=1$ and Resilience $=GI_{Post}/GI_{Pre}=0.01/0.01=1$ which artificially inflates the resistance and resilience of the suppressed trees.

2.2.7 Individual Tree Models

All analyses were completed using RStudio (version 4.0.3). I used linear mixed models to assess the effect of density treatment (low, medium, medium-high, or high), spatial arrangement (gap or uniform) and the interaction between the two variables on individual tree drought response. To assess the effects of individual tree social status and size on the response variables, subject tree crown class, DBH, tree height and live crown ratio were used in the linear mixed model with drought resistance and resilience as the response variables, and with random effects of blocks, plots, sub-plots, and sample points for the 2001 drought. The same models with the addition of 0.1-ha neighborhood plot basal area estimates derived from 2020 measurements were used for the second, 2015-2016 drought. BA was not used in the model for the first drought since there had been re-thinning in the medium and medium-high density subplots between the two drought events and we did not have pre-re-thinning basal area estimates at the sample point level. Initial significance of predicter variables was evaluated through Anova X^2 tests.

When Anova X^2 tests indicated significant treatment effects, contrasts of estimated marginal means were used to compare the effects of density and spatial arrangement without a multiple comparisons adjustment since the research was exploratory. Assumptions of normality and constant variance of the errors were checked graphically using plots of model residuals and appeared to be met. Collinearity of the covariates was also assessed through a scatterplot matrix and while some was found none was deemed high enough to warrant adjusting the model.

To compare the effects of drought event on individual tree drought response, I used a linear mixed model to assess the response variables of drought resistance and drought resilience with a three way interaction of drought, density level, and spatial arrangement as independent variables. The random effects of these multi-drought models were blocks, plots, sub-plots, sample points and tree. Following the results of X^2 Anova tests, the main effects and interactions of density, spatial arrangement and drought were assessed with estimated marginal mean comparisons. Assumptions of normality and constant variance of the errors were checked graphically using plots of model residuals and appeared to be met. Estimated marginal means were once again used without a multiple comparisons adjustment since the research is exploratory.

2.2.8 Stand Level Tradeoff Models

Since silvicultural treatments are most often applied at the stand level, I ran a series of linear mixed models to assess tradeoffs of resistance, resilience, standing volume in 2020 and volume increment from 2010-2019 at the subplot level. Given the 2014 glaze event broke the tops out of many of the trees in the study, I used commercial volumes to a 15 cm top rather than total volumes. Data collected after the 2014 glaze event suggested that few breaks occurred at stem diameters greater than 10 cm (Liz Cole, unpublished data), so volume estimates to a 15 cm top were not heavily impacted by broken tops. Tree volumes at the time of measurement in 2020 were estimated from diameter and predicted heights (Hanus et al. 1999). Total volume for all cored trees in each sample point was calculated then expanded to m^3 per hectare to estimate mean subplot volume per ha in 2020 (Walters et al. 1985).

Using the same height and volume equations, standing volume for 2010 and 2019 were calculated based on diameter estimates derived from the tree core measurements (Brackett 1973; Brackett 1977; Walters et al. 1985; Hanus et al. 1999). I subtracted the 2010 volume from 2019 volume and divided by 10 to calculate a mean, 10-year periodic annual growth increment for 2010-2019. 2020 was not used as the final year in the increment calculation as the trees that were sampled earlier in the summer of 2020 would not have had as much latewood ring growth as those sampled later in the summer.

To assess the tradeoffs among mean resistance (for both the first and second drought), mean resilience (for both the first and second drought), periodic annual increment growth (second drought only) and standing volume (second drought only), benefit scores were calculated at the subplot level for each of these attributes. Each stand level response was ranked from lowest to highest, then I used Bradford and D'Amato's (2012) methods to normalize a subplot level benefit score for each variable on a scale of 0 to 1 where a benefit score of zero represents the subplot with the lowest observed value for a given variable and 1 represents the subplot with the highest observed value for that variable. Thus, each subplot's benefit score is relativized to fall between 0 and 1. For a subplot's response A, the score is calculated as follows:

$$B_{Ai} = \frac{(A_{OBSi} - A_{min})}{(A_{max} - A_{min})}$$

Where A_{OBSi} is the observed response value for variable A in stand *i,* A_{min} is the value of the lowest response value for variable A and A_{max} is the value of the highest response score for variable A.

Once benefit scores were assigned for each subplot and response variable, the values were put into the following root mean squared error (RMSE) calculation to assess the tradeoff between each paired combination of response variables (Bradford and D'Amato, 2012). For the case of two response variables, *A* and *B*, the trade-off for stand *I* (T_{aBi}) is calculated as:

$$T_{\mathrm{aBi}} = \sqrt{\frac{(\mathrm{B_{Ai}} - \bar{x}_{\mathrm{aBi}})^2(\mathrm{B_{Bi}} - \bar{x}_{\mathrm{aBi}})^2}{2}}$$

where $\bar{x}_{aBi}$ is the mean of the previously calculated benefit score for response variables *A* and *B*, for stand *i*. B_{Ai} and B_{Bi} is the benefit score of the variable for stand *i*. In this way, I calculated tradeoffs between 1) resistance and resilience for both droughts, 2) resistance and standing volume for the 2015-2016 drought, 3) resilience and standing volume for the 2015-2016 drought,

4) resistance and periodic annual increment for the 2015-2016 drought, and 5) resilience and periodic annual increment for the 2015-2016 drought.

2.2.9 Analysis of Stand Level Responses

I ran linear mixed models (LMMs) with each of the five two-way tradeoffs listed above, as well as with periodic annual increment, and standing volume as response variables. Each model included subplot density level and spatial arrangement, and their interaction as indepdent variables and random effects of block and plot. I looked at plots of residuals vs fitted values and qq plots and saw the assumption of equal variance was not met so I relaxed the assumption of constant variance by allowing the power variance function structure along the fitted values (Pinheiro et al. 2021). These models were assessed with Anova t-tests and further explored with estimated marginal mean contrasts to compare main effects.

2.3 Results

2.3.1 Individual Tree, Single Drought Interaction Models

Density level was significant in the 2001 resistance ($X^2_{9.02}$, p = 0.029), 2001 resilience ($X^2_{11.9,}$ p = 0.008) and 2015-2016 resistance ($X^2_{12.28,}$ p = 0.06) models, but the density level did not have a significant effect on drought resilience in the 2015-2016 drought model ($X^2_{0.96,}$ p = 0.81) (Tables 2.3 and 2.4). The marginal means for 2001 drought resistance were significantly higher in the low density treatment than in the high density treatment (Figure 2.1). 2001 drought resilience was higher in both the low and medium density treatments than in the high density treatment (Figure 2.2). In the 2015-2016 main effects comparisons, resistance scores for the medium density treatment were significantly higher from all other densities (Figure2.3). Spatial arrangement was marginally significant in the 2001 resilience model ($X^2_{4.18}$, p = 0.041), but did not have a significant effect in the 2001 resistance, 2015-2016 resistance, or 2015-2016 resilience models ($X^2_{0.02}$, p = 0.897, $X^2_{0.35}$, p = 0.554, $X^2_{2.81}$, p = 0.094 respectively) (Figures 2.1, 2.2, 2.3 and 2.4). The interaction between spatial arrangement and density was never significant in the individual tree and individual drought models (Tables 2.3 and 2.4).

Most of the covariates in our models were not significant in any of the single drought models. However, DBH and LCR were significant in one model each. In the 2001 individual tree resilience model, DBH had a parameter value of -0.003 (SD = 0.001, p = 0.043) (Table 2.3). In the 2015-2016 individual tree resilience model, LCR had a parameter value of 0.004 (SD = 0.002, p = 0.033) (Table 2.4).

2.3.2 Individual Tree, Two-Drought Interaction Models

To understand the differences in drought response across the two different droughts, I ran the interaction models with the added variable of drought event. For resistance, spatial arrangement was not significant ($X^2_{0.19}$, p = 0.666), but density ($X^2_{15.74}$, p = 0.001) and drought event were ($X^2_{606.5}$, p = <0.001) (Table 2.5). Additionally, the interaction between all three variables was significant ($X^2_{11.65}$, p=0.009) (Table 2.5). Across all spatial and density variables, drought resistance was significantly lower for the 2015-2016 drought than for the 2001 drought (Figure 2.5). The estimated marginal mean for resistance in the low density treatments in the first drought was 1.0 (95% CI, 0.89 to 1.11) which was significantly lower than the second drought which was 0.56 (95% CI, 0.45 to 0.66) (Figure 2.5). The estimated marginal mean for resistance in the high density treatments in the 2001 drought was 0.89 (95% CI, 0.78 to 1.01) which was significantly lower than the 2015-2016 drought which was 0.52 (95% CI, 0.41 to 0.64) (Table 2.5). For the 2001 drought, resistance was significantly higher in the low and medium density treatments than in the high density treatment (Figure 2.5). In the 2015-2016 drought, however, drought resistance was higher in the medium density treatment than in the medium-high and high density treatment, but there were no significant differences between the low density treatment and any other treatment (Figure 2.5).

In the individual tree, two-drought resilience model, spatial arrangement neared statistical significance ($X^2_{3.47,}$ p=0.063) while density ($X^2_{10.63,}$ p=0.014) and drought ($X^2_{239.17,}$ p=<0.001) were highly significant (Table 2.5). No interactions between spatial arrangement, density, or drought event were significant for the two-drought resilience model. Across all spatial and density variables, drought resilience was significantly lower for the 2015-2016 drought than for the 2001 drought (Figure 2.5). The estimated marginal mean for resilience in the low density treatments in the first drought was 0.95 (95% CI, 0.81 to 1.08) which is significantly lower than the second drought which was 0.61 (95% CI, 0.49 to 0.75) (Figure 2.5). The estimated marginal mean for resilience in the high density treatments in the first drought was 0.82 (95% CI, 0.68 to 0.96) which is significantly lower than the second drought which was 0.58 (95% CI, 0.44 to 0.72) (Figure 2.5). For the 2001 drought, resilience in the low and medium density treatments was higher than in the high density treatment. For the 2015-2016 drought, there were no significant differences in resilience among density treatments (Figure 2.5).

2.3.3 Stand Level Models

The 2010-2019 periodic annual increment did not significantly differ between density levels or spatial arrangement treatments (Table 2.6). Total, standing volume per hectare in 2020 did significantly differ among density treatments ($F_{1,12} = 4.89$, $p = 0.019$) but not with spatial arrangement or with the interaction of density and spatial arrangement (Table 2.6). Overall, the low and medium density treatments had lower mean standing volumes than the medium-high and high density treatments, regardless of spatial arrangement.

No significant differences were associated with density level or spatial arrangement in the 2001 resistance-resilience tradeoff model, the 2015-2016 resistance-resilience tradeoff model, any tradeoff models involving standing volume, or the periodic annual increment - 2015-2016 resilience tradeoff (Table 2.7). The only tradeoff that had significance was the tradeoff between 2010-2019 period annual increment and 2015-2016 drought resistance, where the density effect was significant ($F_{1,12}=5.66$, $p=0.012$), but spatial arrangement was not significant (Table 2.7). Benefit score rankings indicate that that the significant density effect in the periodic annual increment – 2015-2016 drought resistance model was due to the low and medium densities having higher resistance scores while the medium-high and high densities had somewhat (though not significantly) higher periodic annual increments.

2.3 Discussion

2.3.1 How does density affect drought resistance and resilience?

Thinning to different density levels had a significant effect on drought resistance and resilience, but the effect was not consistent across drought events. During the 2001 drought, which occurred eight years after initial treatments in the MFS, trees in treatments with higher residual densities had lower resistance and resilience than trees in the low density treatment. This result supports our hypothesis that thinning can improve drought resistance and resilience and is consistent with findings from previous studies in other conifer forests. In a study looking at ponderosa pine (*Pinus ponderosa*) and red pine *(Pinus resinosa*) across a latitude and aridity gradient, lower density forests were found to have better drought resistance and resilience than those with higher density (Bottero et al. 2017). Heavier thinning was consistently found to be more effective in improving resistance and resilience. (Bottero et al. 2017; Finley and Zhang 2019).

In contrast to the 2001 drought, the effects of stand density on resistance and resilience in the 2015-2015 drought, which occurred 21 years after initial treatment, were more muted, and not always consistent with previous findings that thinning to lower residual densities promotes greater drought resistance and resilience. There were no significant differences between trees in the low and high density treatments for either resistance or resilience to the 2015-2016 drought, although our results suggest a non-significant trend of low and medium densities having higher resistance and resilience scores than the medium-high and high densities. Resistance during the 2015-2016 was significantly higher for trees in the medium density treatment than in all other densities. After the re-thinning of the medium and medium-high treatments, the basal area of medium uniform thinning plots was lower than that of the low treatments and in the gap thinning, the basal area of the mediums was only slightly higher than that of the lows (Table 2.1). Since the medium and medium-high density subplots were re-thinned between the two droughts, they potentially had a second release from competition that was not experienced in the low density and high density treatments. This could explain the higher response of drought resistance for the medium treatment and indicates that follow-up thinnings maybe necessary to maintain drought resistance.

In a long-term study of *Pinus resinosa* stands, thinning was found to initially improve drought resistance and resilience, but this trend reversed in low density stands as the stands aged (D'Amato et al. 2013). D'Amato et al. (2013) attributed this reversal to development of greater individual tree sizes and leaf areas in the older low density treatments, which caused greater water demand than could not be met during droughts. While we did not see a full reversal in treatment rankings of drought resistance and resilience by the second drought in our study, the current developmental trajectories in the MFS treatment units suggest increasing proportions of large-diameter trees in the lower density treatments (Newton and Cole 2015) and the absence of significant differences in the 2015-2016 drought response between trees in the low density and high density treatments could suggest that the MFS treatments are moving towards a reversal of the initially high drought resistance and resilience demonstrated by trees in the low density treatment in comparison to trees in the high density treatment.

Most covariates describing individual tree characteristics were not significant in any of our models, however, DBH had a slight negative relationship with resilience for the 2001 drought and LCR had a slightly positive relationship with resilience for the 2015-2016 drought. DBH is one of our main indicators of tree size and larger trees have higher water demand, which may increase stress during drought events (D'Amato et al. 2013). The positive relationship between LCR and resilience initially seems to contrast with the DBH findings, although it may simply suggest that trees with larger crowns, regardless of absolute tree size, are better positioned to recover after a drought event. Although this study was focused on evaluating the effects of thinning intensity and spatial pattern on the response to repeated droughts, future attention should be paid to more detailed assessment of neighborhood-scale stand structure and individual tree characteristics as the drought response may not be even across all trees of the same species (D'Amato et al. 2013).

2.4.2 How does spatial arrangement affect drought resistance and resilience?

Spatial arrangement was never associated with significant differences in drought resistance, but trees in gap treatments had significantly higher resilience than trees in the uniform thinning treatments for the 2001 drought and a nearly significantly higher resilience for trees in the gap treatment for the 2015-2016 drought. The harvested gaps were not very large and may not have had a large effect on drought response. The lack of apparent spatial pattern effects on drought resistance stands somewhat in contrast to a study looking at trees Douglas-fir in the open, along the edges of logging trails and in an un-thinned interior stands that found the trees growing in the open or on the edges had higher drought resistance or resilience (Thompson et al. 2018). However, the range of BA densities in my study was narrower between low and highs than the range of BA densities between the open and interior stands in the Thompson et al. study.

2.4.3 How does the timing and intensity of drought affect drought resistance and resilience?

Our results suggest that the effects of thinning differed between a single-year drought occurring 8 years after initial treatment in the MFS and a two-year drought that occurred 22 years after initial treatment. Both drought resistance and resilience were significantly lower for the 2015-2016 drought than for the 2001 drought across all density and spatial arrangement combinations. With the addition of the drought interaction, the difference in the first drought resistance observed between medium and high densities, and the second drought low and medium densities was no longer significant. Since a resistance or resilience score of 1.0 means that the drought had no effect on radial growth, it is important to note that all of the confidence intervals for resistance and resilience of the second drought were below one, indicating a fairly strong drought effect on tree growth. Meanwhile the resistance and resilience confidence intervals from the first drought were above 1.0 for all of the density levels and for most of the spatial arrangements' means. This suggests that the resistance and resilience responses to the two droughts were very different and potentially can be attributed to two general mechanisms, time since thinning and drought characteristics.

The timing of each drought is important to note; the first drought occurred 8 years after initial thinning in the MFS while the second drought occurred 22 years after initial thinning. Douglas-fir growth responses to overstory density reductions can be delayed by 5-25 years, and growth increases may occur for two decades or more following treatment (Latham and Tappeiner 2005, Garber and Maguire 2011). As a result, some trees in our study may have still been experiencing the effects of a release from competition associated with thinning in 1993 that produced increases in growth throughout the early 2000's despite the drought in 2001.

Over the next 14 years, overstory growth (Newton and Cole 2015) and understory growth (Cole et al. 2017) have continued, likely causing increasing competition for water. Light thins can reclose their canopies in as little as 3 years in Douglas-fir (Davis et al. 2007), and increases in Douglas-fir diameter growth following thinning decline as increased stocking returns competition to its pre-treatment levels over time (Briggs and Kantavichai 2018). As a result, increased levels of competition by the time of the 2015-2016 drought may have limited the effects of the initial 1993 thinning treatments on drought resistance and resilience.

Thinning intensity may also affect the duration of the thinning response. Several studies across many different tree species indicate that moderate to heavy thins support greater and longer lasting resistance and resilience than lighter thins (Sohn et al. 2016; Zhang et al. 2019). Our results, and previous work on the MFS (Newton and Cole 2015) indicate that standing volumes were higher in the high and medium high treatments than in the low and medium density treatments throughout the duration of our drought response analyses. This suggests the potential for longer-lasting reductions in competition in the low and medium density treatments to promote increased drought resistance and resilience for the 2015-2016 drought, but we did not see strong evidence of this type of effect in our results.

Differences in drought characteristics may also help explain why the effects of density treatment were less obvious during the later drought in 2015-2016. In addition to increases in competition during the 14 years between our two droughts, the 2015-2016 drought lasted one year longer, and temperatures were on average higher than during the 2001 drought. Increases in vapor pressure deficit (VPD) caused by higher temperatures are being recognized as important components of tree water stress, and have been found to decrease growth in Douglas-fir (Restaino et al. 2016; Lee et al. 2022). Hotter droughts have also been found to produce more mortality than droughts of average temperature or below due to increased evaporative demand (Allen et al. 2015; Lee et al. 2022). Given the higher temperatures and longer duration of the 2015-2016 drought, it is not surprising that resistance and resilience were lower for this second drought than for the 2001 drought.

2.4.4 Are there tradeoffs between drought resistance, drought resilience, and tree growth?

When making management decisions about forests, land managers must frequently balance demands for multiple goods and services. Using tradeoff analysis can help make these decisions clearer. My results do not suggest any significant tradeoffs between drought resistance and resilience for either drought. Both resistance and resilience were lower in the higher density treatments, at least during the 2001 drought, resulting in decreasing benefit score rankings from the lowest to highest density treatments. Relatively similar declines in both drought resistance and resilience across low to high stand density gradients is broadly consistent with other studies in North American conifer forests (D'Amato et al. 2013, Bottero et al. 2017), and suggests that stand density management is a relatively robust tool to reduce drought effects on tree growth.

In contrast, when looking at the increment tradeoffs, we did see a significant tradeoff between period annual increment and resistance, at least during the 2015-2016 drought. While there was no significant difference in periodic annual increment between density treatments, there was a general trend of the higher densities having greater periodic annual increment. In contrast, resistance was generally highest among the lower density treatments, leading to a tradeoff between maximum resistance and periodic annual increment. This tradeoff suggests that managers interested in maximizing drought resistance may need to weigh this desire against the potential for reduced wood production at low stand densities. However, volume and basal area growth in Douglas-fir can be maintained at relatively constant levels across a fairly wide range of residual densities and generally decline only following heavy thinning (Curtis 2006; Newton and Cole 2015; Del Río et al. 2017), and we found no significant differences in periodic annual increment among the MFS thinning treatments. The absence of significant periodic annual increment – drought resistance tradeoffs for the 2001 drought, coupled with the lack of significant periodic annual increment – drought resilience tradeoffs for either drought or the capacity for Douglas-fir to maintain high levels of wood production across a range of stand densities suggests that managers may have some flexibility to use stand density reductions to address drought resistance and resilience concerns with limited impacts on wood production.

The lack of significant tradeoffs between periodic annual increment and drought resilience was probably because there was little difference in benefit scores for resilience across thinning treatments, resulting in limited potential for tradeoffs with any other management goal. Research in this area has mainly focused on growth – drought response tradeoffs among genotypes for planting and not in managed, naturally regenerated stands such as the MFS. However, the lack of significant tradeoffs between periodic annual increment and drought resilience in this work is consistent with a previous study in Douglas-fir forests that found there was no trade-off in growth and drought hardiness (Darychuk et al. 2012). In contrast, provenance-based research on Canadian coastal Douglas-fir found the trees from moist areas had greater annual increment but lower drought resilience(Montwé et al. 2015). Trees from drier origins had lower annual increment and higher resilience. Resistance however was not different in provenances from different moisture regimes.

The lack of significant tradeoffs between standing volume and drought resistance and resilience was surprising since stand density gradients were linked to differences in drought response in this and other studies (D’Amato et al. 2013, Bottero et al. 2017). However, even if the tradeoffs are high, if they are uniformly high a linear mixed model will show no differences between treatments. So, if a land manager wants to make a decision, they will have to look at the analysis of the individual responses to treatments.

2.4.5 Scope and Limitations of Research

There are some statistical limitations of this research. Especially in the stand level analysis there are not many degrees of freedom given the limited number of experimental units in the study. Overall, sample size likely limited the power of the statistics. More importantly, without a true, un-thinned control, we do not have an ideal baseline to compare our responses to, and likely failed to capture the full range of potential stand density conditions and associated drought responses. Expanding the density range would allow us to further explore how to encourage drought resistance and resilience especially on the lower density end of the spectrum to have longer lasting effects.

The McDonald-Dunn Forest is located in unique part of the Coast Range that is drier than the rest of the range. While there are sizeable Douglas-fir forests in the same rain shadow, one should be cautious to assume that my findings apply to other parts of the Coast Range or Willamette Valley since data was collected at one site along the ecotone between the wetter areas of the Coast Range to the west and the somewhat drier Willamette Valley ecoregion to the east. More research into this topic should be conducted at other sites in the region to better assess how local climate and moisture availability influence relationships between stand density management activities and drought response.

2.5 Conclusions

Climate change threatens the health and productivity of forests, not just in Oregon but worldwide. The predicted increase in droughts and higher temperatures have the potential to slow tree growth, cause mortality, and make forests more susceptible to disturbances such as insects and wildfire (Chmura et al. 2011). Preparing for these changes will require careful forest management planning that is fine-tuned to the local landscape and based on predicted future climate models, while still flexible enough to shift management approaches as we learn more about climate change (Palik and D'Amato 2019).

As an intermediate treatment, variable density thinning (VDT) provides one solution that is customizable to stand and landscape level features (Brodie and Harrington 2020). VDT can accelerate the development of structure similar to old growth forests that has become the focus of many land managers since the 1990s. While, thinning has been broadly proven to increase drought resistance and resilience (Chmura et al. 2011; Bottero et al. 2017; D'Amato et al. 2017), few studies have compared the drought resistance and resilience potential of traditional, uniform thinning treatments to VDT treatments that incorporate gaps within the thinned matrix . My results suggest that VDT treatments incorporating gaps generally had similar drought responses to uniform thinning treatments with similar average residual stand densities and provide some evidence that VDT treatments with gaps may result in somewhat improved drought resilience compared to uniform thinning treatments .

Similar to previous research, I found that lower residual stand densities were associated with improved drought resistance and resilience during a drought event occurring 8 years after treatment, although this effect was muted during a drought event occurring 22 years after treatment . My research broadens the scope of this phenomena to Douglas-fir in the rain shadow of the Oregon Coast Range. It is important to note that as trees grow, and competition resumes these advantages fade (D'Amato et al. 2013; Briggs and Kantavichai 2018). Therefore, repeated stand density reductions may be necessary to maintain drought resistance and resilience benefits over multiple decades. This research found that spatial arrangement did not improve or decrease drought resistance and resilience, but other studies have found that across greater density gradients logging trails had a positive impact on drought resistance and resilience so further research is needed in this area (Thompson et al. 2018).

Recent work has begun to focus on creating resistant and resilient forests under a changing climate for the sake of maintaining the economic viability of these resources. Some of this work focuses on the idea that restoration to previous conditions will not necessarily provide the desired benefits under future conditions (Holmes et al. 2009). Periodic annual increment growth during the 2010 to 2019 period that bookends the 2015-2016 drought did not significantly vary among thinning treatments, which generally aligns with findings from other thinning studies (Newton and Cole 2015). Overall, the gap spatial arrangement did not have a negative effect on total volume which suggests that the benefits of structural heterogeneity can coexist with volume production.

Managers will have to increasingly prioritize climate change mitigation in their silvicultural planning, and this work combined with previous research strongly suggests that forests with lower densities are better adapted to predicted increases in drought frequency. Further, my results suggest that the density reductions sufficient to foster increased drought resistance and drought resilience in Douglas-fir forests may have limited tradeoffs with wood production, although additional research is needed to evaluate drought responses across a wider range of stand density and local climate conditions before broad conclusions can be drawn for the coastal Douglas-fir region of the Pacific Northwest.

2.6 Tables

Table 2.1. Mean treatment conditions of the Mature Forest Study sites at McDonald Forest immediately after thinning in 1993, 7 years after thinning, and 10 years after thinning (from (Cole and Newton 2009).

	Year 0				Year 7		Year 10			
Stand density	BA (m^2/ha)	TPH	QMD (cm)	Relative density*	BA (m^2/ha)	Relative density	BA (m^2/ha)	TPH	QMD (cm)	Relative density
Gap thinning										
LOW	17.5	104	47.6	2.5	21.9	3.0	23.6	108	53.9	3.2
MED	23.5	137	47.5	3.4	28.2	3.9	23.9	103	55.2	3.2
MHI	27.7	160	47.4	4.0	33.1	4.6	28.8	121	55.3	3.9
HIGH	29.7	198	44.1	4.5	35.3	5.1	37.6	194	50.2	5.3
Uniform thinning										
LOW	18.6	98	49.4	2.6	23.3	3.1	25.4	101	57.1	3.4
MED	22.8	110	52.0	3.2	28.1	3.7	24.1	84	61.9	3.1
MHI	27.8	140	50.8	3.9	33.7	4.5	28.7	101	60.7	3.7
HIGH	30.9	211	43.3	4.7	37.4	5.4	40.2	202	50.4	5.7

Note: MED and MHI units were rethinned in year 8. BA, basal area; TPH, trees/ha; QMD, quadratic mean diameter.
*From Curtis (1982).

Table 2.2 Volume equations for Douglas fir. All volumes calculated in cubic feet and were converted to cubic meters: $\frac{V\ in\ ft^3}{0.0283168}$= V in m^3

Metric	Equation	Source
Cubic Vol (ft$^{3)}$	$=V_{abh+}V_{bbh}$	Walters et al, 1985
V_{abh}	$=0.001168*\left(\frac{H}{DBH}\right)^{0.265430}*(DBH^2*H)$	Walters et al, 1985
H	$=4.5+e^{(7.262195456+(-5.899759104*DBH\text{^}-0.28207389)}$	Hanus et al, 1999
V_{bbh}	$=\frac{\pi DIB_S^2}{175616}[729+81\left(\frac{DIB}{DIBs}\right)^{\frac{2}{3}}+297\left(\frac{DIB}{DIB_s}\right)^{\frac{4}{3}}+265\left(\frac{DIB}{DIB_s}\right)^2$	Walters et al, 1985
DIB	$=.97133(DBH)^{.966365}$	Ritchie, 1984
DIB_s	=.989819(DBH)	Walters et al, 1985
CVTSL	$=-3.21809+.04948*\log(H)*\log(DBH)-.15664*\log(DBH)^2$	Brackett, 1973, 1977
CVTS	$=10^{CVTSl}$	Brackett, 1973, 1977
Tarif	$=\frac{CVTS(.912733)}{(1.033\left(1.0+1.32937*\exp\left(-4.015393\left(\frac{DBH}{10.0}\right)\right)\right)(BA+0.087266)-0.174533)}$	Brackett, 1973, 1977
CV4	$\frac{Tarif(BA-.087266)}{.912733}$	Brackett, 1973, 1977

Table 2.3 Results from a linear mixed model (LMM) of the 2001 drought examining the relationships between drought response (resistance or resilience) and thinning treatments resulting in different stand densities and spatial arrangements (uniform versus thinning with gaps), the interaction between density and spatial arrangement, and individual tree characteristics. P-values reported from t-tests for continuous variables and X^2 tests for discrete variables.

2001 Resistance

Variable	Parameter Value	SE	DF	X2	T-statistic	P-Value
Spatial Arrangement	-	-	1	0.02	-	0.897
Density	-	-	3	9.02	-	0.029
DBH	<0.001	0.001	225	-	0.38	0.705
Height	0.005	0.004	225	-	1.09	0.277
LCR	-0.003	0.002	225	-	-1.43	0.154
Crown Class Dom.	-0.026	0.044	4	3.41	-	0.492
Crown Class Int.	0.001	0.049	4	3.41	-	0.492
Crown Class Mid.	0.26	0.161	4	3.41	-	0.492
Crown Class Sup.	0.06	0.172	4	3.41	-	0.492
Spatial Arrangement:Density	-	-	3	6.11	-	0.106

2001 Resilience

Variable	Parameter Value	SE	DF	X2	T-statistic	P-Value
Spatial Arrangement	-	-	1	4.18	-	0.041
Density	-	-	3	11.9	-	0.008
DBH	-0.003	0.001	225	-	-2.04	0.043
Height	0.004	0.005	225	-	0.91	0.363
LCR	-0.001	0.002	225	-	-0.32	0.749
Crown Class Dom.	-0.034	0.05	4	0.87	-	0.928
Crown Class Int.	-0.001	0.055	4	0.87	-	0.928
Crown Class Mid.	-0.039	0.181	4	0.87	-	0.928
Crown Class Sup.	-0.096	0.193	4	0.87	-	0.928
Spatial Arrangement:Density	-	-	3	1.89	-	0.595

Table 2.4 Results from a linear mixed model (LMM) of the 2015-2016 drought examining the relationships between drought response (resistance or resilience) and thinning treatments resulting in different stand densities and spatial arrangements (uniform versus thinning with gaps), the interaction between density and spatial arrangement, and individual tree characteristics. P-values reported from t-tests for continuous variables and X^2 tests for discrete variables.

2015-2016 Resistance

Variable	Parameter Value	SE	DF	X2	T-statistic	P-Value
Spatial Arrangement	-	-	1	0.35	-	0.554
Density	-	-	3	12.78	-	0.006
DBH	0.001	0.001	224	-	0.93	0.351
Height	0.003	0.003	224	-	1.08	0.281
LCR	0.002	0.001	224	-	1.65	0.101
Crown Class Dom.	0.014	0.033	4	3.61	-	0.461
Crown Class Int.	-0.018	0.036	4	3.61	-	0.461
Crown Class Mid.	0.142	0.119	4	3.61	-	0.461
Crown Class Sup.	0.105	0.127	4	3.61	-	0.461
BA	<0.001	<0.001	224	-	0.72	0.47
Spatial Arrangement:Density	-	-	3	5.69	-	0.128

2015-2016 Resilience

Variable	Parameter Value	SE	DF	X2	T-statistic	P-Value
Spatial Arrangement	-	-	1	2.81	-	0.094
Density	-	-	3	0.96	-	0.81
DBH	<0.001	0.001	224	-	-0.07	0.947
Height	0.003	0.004	224	-	0.71	0.48
LCR	0.004	0.002	224	-	2.14	0.033
Crown Class Dom.	0.056	0.044	4	5.72	-	0.221
Crown Class Int.	-0.066	0.049	4	5.72	-	0.221
Crown Class Mid.	0.094	0.16	4	5.72	-	0.221
Crown Class Sup.	0.073	0.171	4	5.72	-	0.221
BA	<0.001	<0.001	224	-	0.66	0.51
Spatial Arrangement:Density	-	-	3	2.37	-	0.5

Table 2.5 Results from a linear mixed model (LMM) of both the 2001 and 2015-2016 drought examining the relationships between drought response (resistance or resilience) and thinning treatments resulting in different stand densities and spatial arrangements (uniform versus thinning with gaps), and the interactions between density, spatial arrangement, and drought. P-values reported from t-tests for continuous variables and X^2 tests for discrete variables.

Repeated Drought Resistance

Variable	X^2	DF	P-Value
Spatial Arrangement	0.19	1	0.666
Density	15.74	3	0.001
Drought	606.5	1	<0.001
Spatial Arrangement:Density	2.86	3	0.414
Spatial Arrangement:Drought	0	1	0.982
Density:Drought	5.54	3	0.136
Spatial Arrangement:Density:Drought	11.65	3	0.009

Repeated Drought Resilience

Variable	X^2	DF	P-Value
Spatial Arrangement	3.47	1	0.063
Density	10.63	3	0.014
Drought	239.17	1	<0.001
Spatial Arrangement:Density	0.92	3	0.82
Spatial Arrangement:Drought	3.15	1	0.076
Density:Drought	2.52	3	0.471
Spatial Arrangement:Density:Drought	6.19	3	0.103

Table 2.6 Results from a linear mixed model (LMM) examining the relationships between volume metrics (PAI and total volume) and thinning treatments resulting in different stand densities and spatial arrangements (uniform versus thinning with gaps) and the interaction between density and spatial arrangement. P-values reported from t-tests.

Periodic Annual Increment

Variable	DF	F-Statistic	P-Value
Spatial Arrangement	1, 2	0.08	0.807
Density	1, 12	2.09	0.155
Spatial Arrangement:Density	3, 12	0.08	0.967

Total Volume (M^3 per hectare)

Variable	DF	F-Statistic	P-Value
Spatial Arrangement	1, 2	0.35	0.615
Density	1, 12	4.89	0.019
Spatial Arrangement:Density	3, 12	0.54	0.662

Table 2.7 Results from a linear mixed model (LMM) examining the relationships between tradeoffs calculations and thinning treatments resulting in different stand densities and spatial arrangements (uniform versus thinning with gaps) and the interaction between density and spatial arrangement. P-values reported from t-tests.

2001 Resistance Resilience Tradeoff

Variable	DF	F-Statistic	P-Value
Spatial Arrangement	1, 2	9.77	0.089
Density	1, 12	0.23	0.87
Spatial Arrangement:Density	3, 12	0.87	0.483

2015-2016 Resistance Resilience Tradeoff

Variable	DF	F-Statistic	P-Value
Spatial Arrangement	1, 2	4.02	0.183
Density	1, 12	0.56	0.654
Spatial Arrangement:Density	3, 12	0.28	0.836

Volume 2015-2016 Resistance Tradeoff

Variable	DF	F-Statistic	P-Value
Spatial Arrangement	1, 2	3.16	0.217
Density	1, 12	1.38	0.296
Spatial Arrangement:Density	3, 12	0.6	0.629

Volume 2015-2016 Resilience Tradoff

Variable	DF	F-Statistic	P-Value
Spatial Arrangement	1, 2	0.06	0.825
Density	1, 12	0.84	0.497
Spatial Arrangement:Density	3, 12	0.45	0.721

Increment 2015-2016 Resistance

Variable	DF	F-Statistic	P-Value
Spatial Arrangement	1, 2	0.56	0.532
Density	1, 12	5.66	0.012
Spatial Arrangement:Density	3, 12	1.79	0.204

Increment 2015-2016 Resilience

Variable	DF	F-Statistic	P-Value
Spatial Arrangement	1, 2	0.02	0.908
Density	1, 12	1.2	0.353
Spatial Arrangement:Density	3, 12	1	0.427

2.7 Figures

Figure 2.1 Estimated marginal means of resistance in the 2001 drought for thinning treatments resulting in different residual densities and spatial arrangements (uniform versus thinning with gaps). Different letters within each treatment category indicate statistically significant differences (α = 0.05). Error bars indicate a 95% CI.

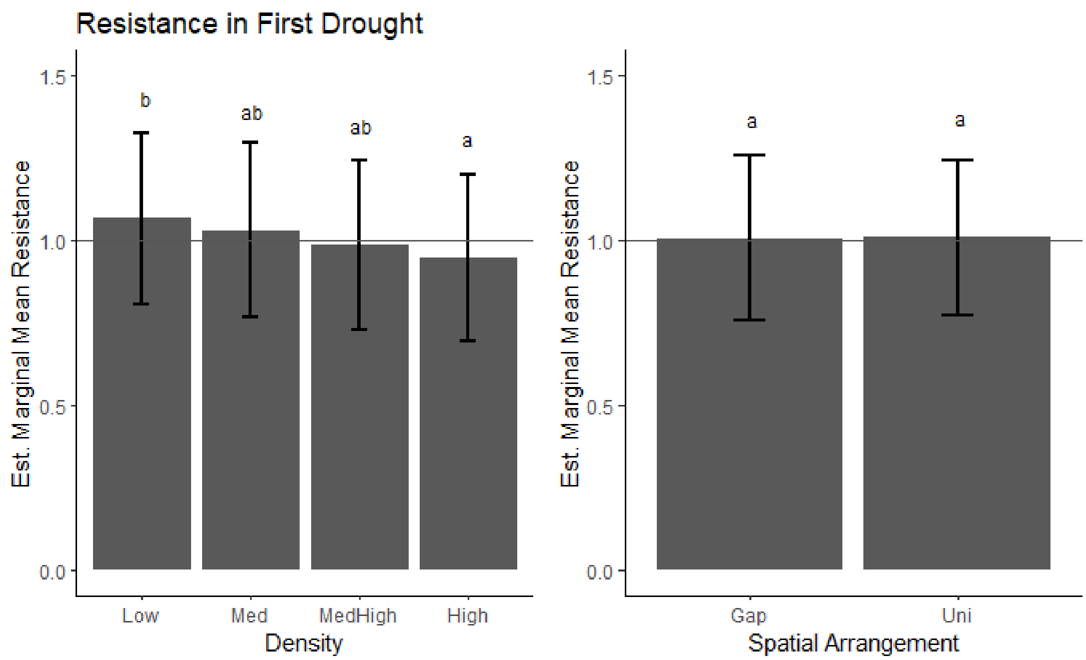


Figure 2.2 Estimated marginal means of resilience in the 2001 drought for thinning treatments resulting in different residual densities and spatial arrangements (uniform versus thinning with gaps). Different letters within each treatment category indicate statistically significant differences (α = 0.05). Error bars indicate a 95% CI.

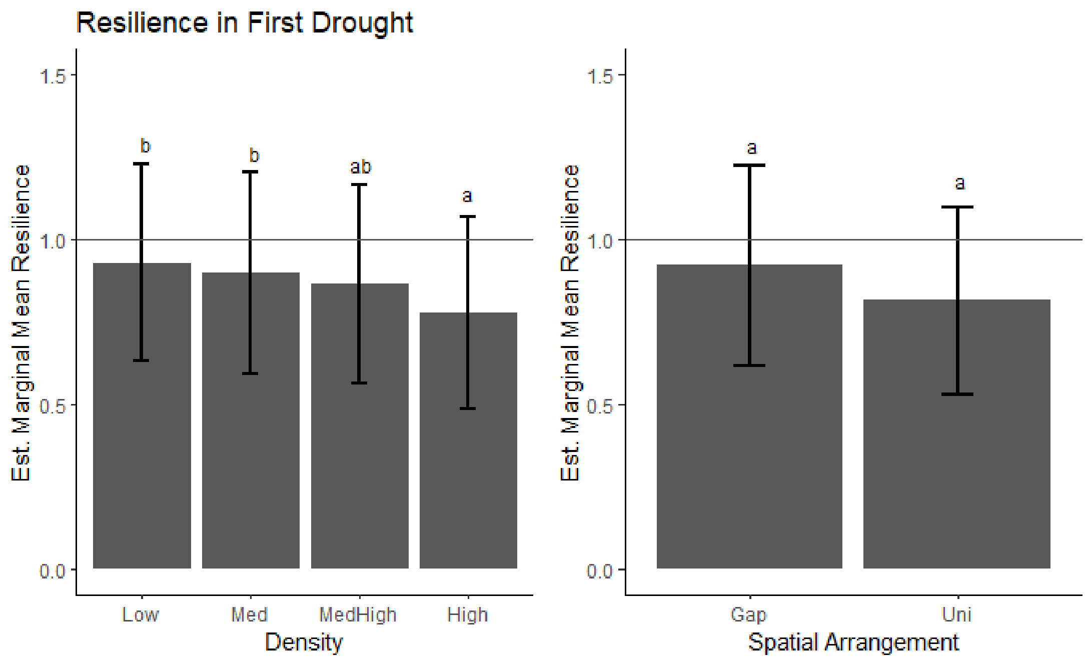


Figure 2.3 Estimated marginal means of resistance in the 2015-2016 drought for thinning treatments resulting in different residual densities and spatial arrangements (uniform versus thinning with gaps). Different letters within each treatment category indicate statistically significant differences (α = 0.05). Error bars indicate a 95% CI.

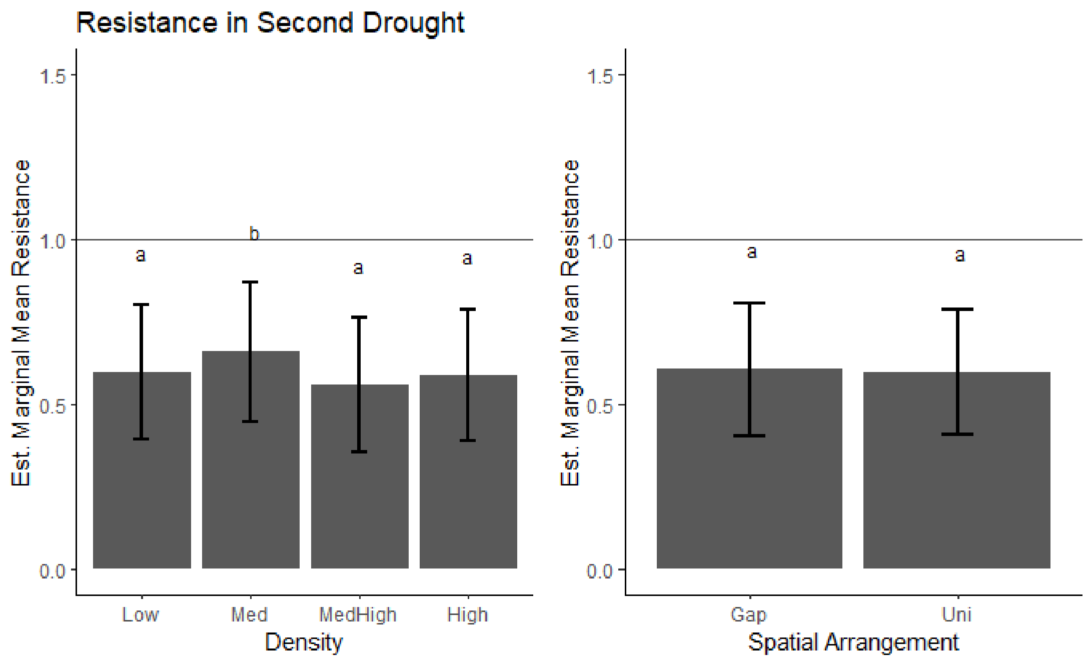


Figure 2.4 Estimated marginal means of resilience in the 2015-2016 drought for thinning treatments resulting in different residual densities and spatial arrangements (uniform versus thinning with gaps). Different letters within each treatment category indicate statistically significant differences (α = 0.05). Error bars indicate a 95% CI

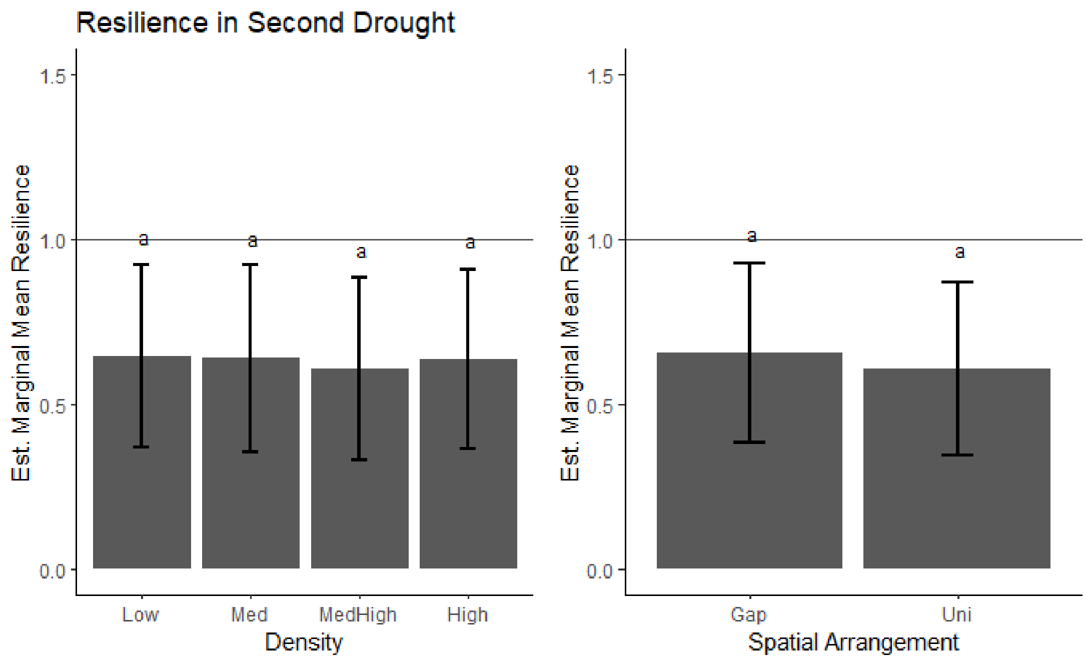
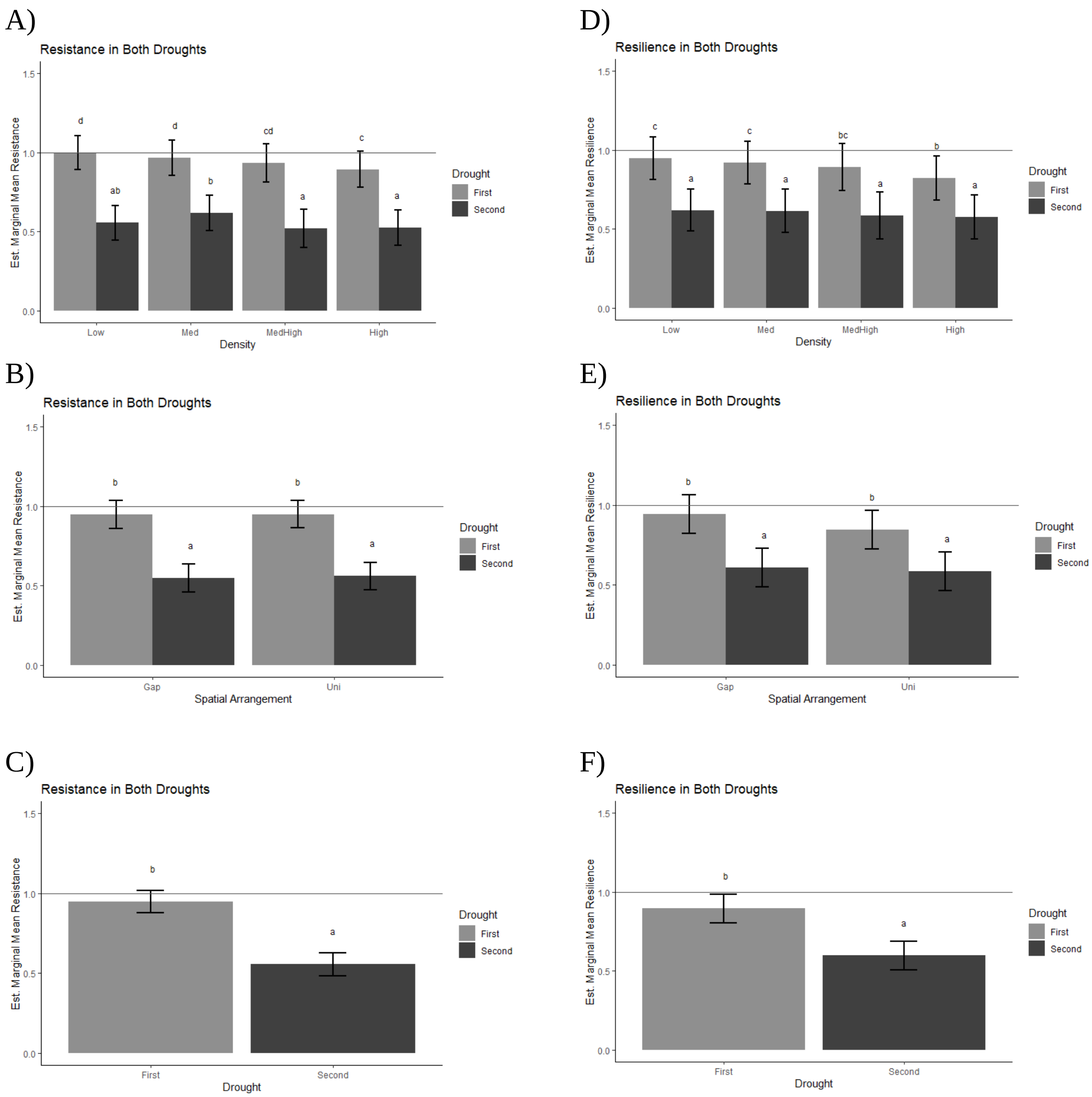


Figure 2.5 Estimated marginal means of resistance and resilience in both the 2001 and 2015-2016 droughts for thinning treatments resulting in different residual densities and spatial arrangements (uniform versus thinning with gaps) and the effect of drought. Different letters within each figure indicate statistically significant differences ($\alpha = 0.05$). Error bars indicate a 95% CI.



2.8 Works Cited

Agne MC, Beedlow PA, Shaw DC, Woodruff DR, Lee EH, Cline SP, Comeleo RL. 2018. Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. For Ecol Manage. 409:317–332. doi:https://doi.org/10.1016/j.foreco.2017.11.004. https://www.sciencedirect.com/science/article/pii/S0378112717306928.

Allen CD, Breshears DD, McDowell NG. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere. 6(8):1–55. doi:10.1890/ES15-00203.1.

Bailey JD, Tappeiner JC. 1998. Effects of thinning on structural development in 40- to 100-year, old Douglas-fir stands in western Oregon. For Ecol Manage. 108(1–2):99–113. doi:10.1016/S0378-1127(98)00216-3.

Bauhus J, Puettmann K, Messier C. 2009. Silviculture for old-growth attributes. For Ecol Manage. 258(4):525–537. doi:10.1016/j.foreco.2009.01.053.

Bentz BJ, Rgnire J, Fettig CJ, Hansen EM, Hayes JL, Hicke JA, Kelsey RG, Negron JF, Seybold SJ. 2010. Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. Bioscience. 60(8):602–613. doi:10.1525/bio.2010.60.8.6.

Bottero A, D’Amato AW, Palik BJ, Bradford JB, Fraver S, Battaglia MA, Asherin LA. 2017. Density-dependent vulnerability of forest ecosystems to drought. J Appl Ecol. 54(6):1605–1614. doi:10.1111/1365-2664.12847.

Brackett M. 1973. Notes on TARIF tree volume computation. Olympia.

Brackett M. 1977. Notes on TARIF tree volume computation. Olympia.

Bradford JB, D’Amato AW. 2012. Recognizing trade-offs in multi-objective land management. Front Ecol Environ. 10(4):210–216. doi:10.1890/110031.

Brandeis TJ, Newton M, Cole EC. 2002. Biotic injuries on conifer seedlings planted in forest understory environments. New For. 24(1):1–14. doi:10.1023/A:1020553021748.

Briggs DG, Kantavichai R. 2018. Effects of thinning on ring mass growth along stem of douglas fir in four coastal pacific northwest sites. For Sci. 64(2):139–148. doi:10.1093/forsci/fxx003.

Brodie LC, Harrington CA. 2020. Guide to variable-density thinning using skips and gaps. USDA For Serv - Gen Tech Rep PNW-GTR. 2020(GTR-989):1–37.

Carnwath G, Nelson C. 2017. Effects of biotic and abiotic factors on resistance versus resilience of Douglas fir to drought. PLoS One. 12(10):1–19. doi:10.1371/journal.pone.0185604.

Chesson P, Gebauer RLE, Schwinning S, Huntly N, Ernest MSK, Sher A, Novoplansky A, Weltzin JF, Schwinning S, Huntly N, et al. 2016. International Association for Ecology Resource Pulses , Species Interactions , and Diversity Maintenance in Arid and Semi-Arid Environments Published by : Springer in cooperation with International Association for Ecology Stable URL :

http://www.jstor.org. (May). doi:10.1007/s00442-004-1551-l.

Chmura DJ, Anderson PD, Howe GT, Harrington CA, Halofsky JE, Peterson DL, Shaw DC, Brad St.Clair J. 2011. Forest responses to climate change in the northwestern United States: Ecophysiological foundations for adaptive management. For Ecol Manage. 261(7):1121–1142. doi:10.1016/j.foreco.2010.12.040. http://dx.doi.org/10.1016/j.foreco.2010.12.040.

Cole E, Newton M. 2009. Tenth-year survival and size of underplanted seedlings in the Oregon coast range. Can J For Res. 39(3):580–595. doi:10.1139/X08-198.

Cole E, Newton M, Bailey JD. 2017. Understory vegetation dynamics 15 years post-thinning in 50-year-old Douglas-fir and Douglas-fir/western hemlock stands in western Oregon, USA. For Ecol Manage. 384:358–370. doi:10.1016/j.foreco.2016.11.003. http://dx.doi.org/10.1016/j.foreco.2016.11.003.

Comfort EJ, Roberts SD, Harrington CA. 2010. Midcanopy growth following thinning in young-growth conifer forests on the Olympic Peninsula, western Washington. For Ecol Manag 259 1606-1614. 259:1606–1614. https://www.fs.fed.us/pnw/pubs/journals//pnw_2010_comfort001.pdf.

Curtis RO. 2006. Volume Growth Trends in a Douglas-Fir Levels-of-Growing-Stock Study. West J Appl For. 21(2):79–86. doi:10.1093/wjaf/21.2.79.

D’Amato AW, Bradford JB, Fraver S, Palik BJ. 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. Ecol Appl. 23(8):1735–1742. doi:10.1890/13-0677.1.

D’Amato AW, Jokela EJ, O’Hara KL, Long JN. 2017. Silviculture in the United States: An Amazing Period of Change over the Past 30 Years. J For. 116(January):55–67. doi:10.5849/jof-2016-035.

D’Amato AW, Palik BJ, Kern CC. 2010. Growth, yield, and structure of extended rotation Pinus resinosa stands in Minnesota, USA. Can J For Res. 40(5):1000–1010. doi:10.1139/X10-041. https://doi.org/10.1139/X10-041.

Dale V, Joyce LA, Mcnulty S, Neilson R, Ayres M, Flannigan M, Hanson P, Irland L, Lugo A, Peterson CJ, et al. 2001. Climate Change and Forest Disturbances. Bioscience. 51:723.

DARYCHUK N, HAWKINS BJ, STOEHR M. 2012. Trade-offs between growth and cold and drought hardiness in submaritime Douglas-fir. Can J For Res. 42(8):1530–1541. doi:10.1139/x2012-092.

Davis LR, Puettmann KJ, Tucker GF. 2007. Overstory response to alternative thinning treatments in young Douglas-fir forests of Western Oregon. Northwest Sci. 81(1):1–14. doi:10.3955/0029-344X-81.1.1.

Dodson EK, Ares A, Puettmann KJ. 2012. Early responses to thinning treatments designed to accelerate late successional forest structure in young coniferous stands of Western Oregon, USA. Can J For Res. 42(2):345–355. doi:10.1139/X11-188.

Dodson EK, Burton JI, Puettmann KJ. 2014. Multiscale controls on natural regeneration dynamics after partial overstory removal in douglas-fir forests in Western Oregon, USA. For Sci. 60(5):953–961. doi:10.5849/forsci.13-011.

Fernández-de-Uña L, McDowell NG, Cañellas I, Gea-Izquierdo G. 2016. Disentangling the effect of competition, CO2 and climate on intrinsic water-use efficiency and tree growth. J Ecol. 104(3):678–690. doi:https://doi.org/10.1111/1365-2745.12544. https://doi.org/10.1111/1365-2745.12544.

Finley K, Zhang J. 2019. Climate effect on ponderosa pine radial growth varies with tree density and shrub removal. Forests. 10(6). doi:10.3390/f10060477.

Ford KR, Breckheimer IK, Franklin JF, Freund JA, Kroiss SJ, Larson AJ, Theobald EJ, HilleRisLambers J. 2017. Competition alters tree growth responses to climate at individual and stand scales. Can J For Res. 47(1):53–62. doi:10.1139/cjfr-2016-0188.

Franklin JF, Johnson KN. 2012. A Restoration Framework for Federal Forests in the Pacific Northwest. J For. 110(8):429–439. doi:10.5849/jof.10-006. https://doi.org/10.5849/jof.10-006.

Fritts HC. 1976. Tree rings and climate. Caldwell, NJ: Blackburn.

Halofsky JE, Andrews-Key SA, Edwards JE, Johnston MH, Nelson HW, Peterson DL, Schmitt KM, Swanston CW, Williamson TB. 2018. Adapting forest management to climate change: The state of science and applications in Canada and the United States. For Ecol Manage. 421:84–97. doi:https://doi.org/10.1016/j.foreco.2018.02.037. https://www.sciencedirect.com/science/article/pii/S0378112717316547.

Halofsky JE, Hibbs DE. 2009. Controls on early post-fire woody plant colonization in riparian areas. For Ecol Manage. 258(7):1350–1358. doi:10.1016/j.foreco.2009.06.038.

Hanus ML, Marshall DD, Hann DW. 1999. Height-Diameter Equations for Six Species in the Coastal Regions of the Pacific Northwest. Res Contrib For Res Lab Oregon State Univ.(August):12.

Holmes TP, McNulty S, Vose JM, Prestemon JP, Li H. 2009. A Conceptual Framework for Adaptive Forest Management under Climate Change. Clim Chang Adapt Mitig Manag options A Guid Nat Resour Manag South For Ecosyst.:45–60.

Interdisciplinary Planning Team. 2005. McDonald-Dunn Forest Plan.

Kuehne C, Weiskittel AR, Fraver S, Puettmann KJ. 2015. Effects of thinning-induced changes in structural heterogeneity on growth, ingrowth, and mortality in secondary coastal Douglas-fir forests. Can J For Res. 45(11):1448–1461. doi:10.1139/cjfr-2015-0113. https://doi.org/10.1139/cjfr-2015-0113.

Lee EH, Beedlow PA, Brooks JR, Tingey DT, Wickham C, Rugh W. 2022. Physiological responses of Douglas-fir to climate and forest disturbances as detected by cellulosic carbon and oxygen isotope ratios. Tree Physiol. 42(1):5–25. doi:10.1093/treephys/tpab122. https://doi.org/10.1093/treephys/tpab122.

Littell JS, Oneil EE, McKenzie D, Hicke JA, Lutz JA, Norheim RA, Elsner MM. 2010. Forest ecosystems, disturbance, and climatic change in Washington State, USA. Clim Change. 102(1–2):129–158. doi:10.1007/s10584-010-9858-x.

Littell JS, Peterson DL, Tjoelker M. 2008. Douglas-Fir Growth in Mountain Ecosystems: Water Limits Tree Growth from Stand to Region. Ecolological Monogr. 78(3):1–20. papers3://publication/uuid/24364A69-9981-4F58-9D67-6A860071FD45.

Littell JS, Peterson DL, Tjoelker M, Monographs E, Littell S. 2014. Douglas-Fir Growth in Mountain Ecosystems : Water Limits Tree Growth from Stand to Region Published by : Ecological Society of America content in a trusted digital archive . We use information technology and tools to increase productivity and facilitate n. 78(3):349–368.

Littke KM, Zabowski D, Turnblom E, Harrison RB. 2018. Estimating shallow soil available water supply for Douglas-fir forests of the coastal Pacific Northwest: climate change impacts. Can J For Res. 48(4):421–430. doi:10.1139/cjfr-2017-0385. https://doi.org/10.1139/cjfr-2017-0385.

Little J, Peterson D, Riley K, Liu Y. 2016. A review of the relationships between drought and forest fire in the United States. Glob Chang Biol. 22(7):2353–2369. doi:10.1111/gcb.13275. https://www.deepdyve.com/lp/wiley/a-review-of-the-relationships-between-drought-and-forest-fire-in-the-VfYrRw776E.

McDowell N, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams DG, et al. 2008. Mechanisms of plant survival and mortality during drought: Why do some plants survive while others succumb to drought? New Phytol. 178(4):719–739. doi:10.1111/j.1469-8137.2008.02436.x.

McDowell NG, Adams HD, Bailey JD, Hess M, Kolb TE. 2006. Homeostatic Maintenance Of Ponderosa Pine Gas Exchange In Response To Stand Density Changes. Ecol Appl. 16(3):1164–1182. doi:https://doi.org/10.1890/1051-0761(2006)016[1164:HMOPPG]2.0.CO;2. https://doi.org/10.1890/1051-0761(2006)016[1164:HMOPPG]2.0.CO.

Messier C, Bauhus J, Doyon F, Maure F, Sousa-Silva R, Nolet P, Mina M, Aquilué N, Fortin MJ, Puettmann K. 2019. The functional complex network approach to foster forest resilience to global changes. For Ecosyst. 6(1). doi:10.1186/s40663-019-0166-2.

Millar CI, Stephenson NL, Stephens SL. 2007. CLIMATE CHANGE AND FORESTS OF THE FUTURE : mm. Ecol Appl. 17(8):2145–2151.

Montwé D, Spiecker H, Hamann A. 2015. Five decades of growth in a genetic field trial of Douglas-fir reveal trade-offs between productivity and drought tolerance. Tree Genet Genomes. 11(2):1–11. doi:10.1007/s11295-015-0854-1.

Mote PW, Salathé EP. 2010. Future climate in the Pacific Northwest. Clim Change. 102(1):29–50. doi:10.1007/s10584-010-9848-z. https://doi.org/10.1007/s10584-010-9848-z.

Nabel MR, Newton M, Cole EC. 2013. Abundance of natural regeneration and growth comparisons with planted seedlings 10-13years after commercial thinning in 50-year-old

Douglas-fir, Douglas-fir/western hemlock, Oregon Coast Range. For Ecol Manage. 292:96–110. doi:10.1016/j.foreco.2012.12.009. http://dx.doi.org/10.1016/j.foreco.2012.12.009.

Nagel LM, Palik BJ, Battaglia MA, D'Amato AW, Guldin JM, Swanston CW, Janowiak MK, Powers MP, Joyce LA, Millar CI, et al. 2017. Adaptive silviculture for climate change: A national experiment in manager-scientist partnerships to apply an adaptation framework. J For. 115(3):167–178. doi:10.5849/jof.16-039.

Newton M, Cole EC. 2006. Harvesting impacts on understory regeneration in two-storied Douglas-fir stands. West J Appl For. 21(1):14–18. doi:10.1093/wjaf/21.1.14.

Newton M, Cole L. 2015. Overstory development in douglas-fir-dominant forests thinned to enhance late-seral features. For Sci. 61(4):809–816. doi:10.5849/forsci.14-194.

Palik BJ, D'Amato AW. 2019. Variable retention harvesting in Great Lakes mixed-pine forests: emulating a natural model in managed ecosystems. Ecol Process. 8(1). doi:10.1186/s13717-019-0171-y.

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team. 2021. nlme: Linear and Nonlinear Mixed Effects Models. https://cran.r-project.org/package=nlme.

Powers MD, Webster CR, Pregitzer KS, Palik BJ. 2009. Spatial dynamics of radial growth and growth efficiency in residual Pinus resinosa following aggregated retention harvesting. Can J For Res. 39(1):109–117. doi:10.1139/X08-162. https://doi.org/10.1139/X08-162.

Priebe JE, Powers MD, Cole EC. 2018. Species, tree size, and overstory environment affect likelihood of ice storm damage to understory trees in a mature Douglas-fir forest. For Ecol Manage. 409(April 2017):777–788. doi:10.1016/j.foreco.2017.11.041. https://doi.org/10.1016/j.foreco.2017.11.041.

Puettmann KJ, Ares A, Burton JI, Dodson EK. 2016a. Forest restoration using variable density thinning: Lessons from douglas-fir stands in western Oregon. Forests. 7(12):1–15. doi:10.3390/f7120310.

Puettmann KJ, Ares A, Burton JI, Dodson EK. 2016b. Forest restoration using variable density thinning: Lessons from douglas-fir stands in western Oregon. Forests. 7(12):1–14. doi:10.3390/f7120310.

Rehfeldt GE, Crookston NL, Warwell M V., Evans JS. 2006. Empirical analyses of plant-climate relationships for the Western United States. Int J Plant Sci. 167(6):1123–1150. doi:10.1086/507711.

Restaino CM, Peterson DL, Littell J. 2016. Increased water deficit decreases Douglas fir growth throughout western US forests. Proc Natl Acad Sci U S A. 113(34):9557–9562. doi:10.1073/pnas.1602384113.

Del Río M, Bravo-Oviedo A, Pretzsch H, Löf M, Ruiz-Peinado R. 2017. A review of thinning effects on Scots pine stands: From growth and yield to new challenges under global change. For Syst. 26(2):eR03S. doi:10.5424/fs/2017262-11325.

Ritchie MW, Hann DW. 1984. Nonlinear Equations for Predicting Diameter and Squared Diameter Inside Bark at Breast Height for Douglas-Fir.

Roberts SD, Harrington CA. 2008. Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests. For Ecol Manage. 255(7):2771–2781. doi:https://doi.org/10.1016/j.foreco.2008.01.043. https://www.sciencedirect.com/science/article/pii/S0378112708001114.

Skov K, Kolb T, Wallin K. 2004. Tree Size and Drought Affect Ponderosa Pine Physiological Response to Thinning and Burning Treatments. For Sci. 50:81–91.

Sohn JA, Saha S, Bauhus J. 2016. Potential of forest thinning to mitigate drought stress: A meta-analysis. For Ecol Manage. 380:261–273. doi:10.1016/j.foreco.2016.07.046.

Spittlehouse DL, Stewart RB. 2003. Adaptation to climate change in forest management. BC J Ecosyst Manag. 4(1):1–11.

Tappeiner JC, Huffman DW, Marshall D, Spies TA, Bailey JD. 1997. Density, ages, and growth rates in old-growth and young-growth forests in coastal Oregon. Can J For Res. 27(5):638–648. doi:10.1139/x97-015.

Thomas JW, Franklin JF, Gordon J, Johnson NK. 2006. The Northwest Forest Plan: Origins, Components, Implementation Experience, and Suggestions for Change. Conserv Biol. 20(2):277–287. doi:https://doi.org/10.1111/j.1523-1739.2006.00385.x. https://doi.org/10.1111/j.1523-1739.2006.00385.x.

Thompson NP, Lewis KJ, Poirier LM. 2018. Adjacency to a harvest trail increases drought resistance of interior douglas-fir (Pseudotsuga menziesii var. glauca) in partially harvested stands in central British Columbia. Can J For Res. 48(7):809–820. doi:10.1139/cjfr-2018-0007.

Trouvé R, Bontemps J-D, Collet C, Seynave I, Lebourgeois F. 2014. Growth partitioning in forest stands is affected by stand density and summer drought in sessile oak and Douglas-fir. For Ecol Manage. 334:358–368. doi:https://doi.org/10.1016/j.foreco.2014.09.020. https://www.sciencedirect.com/science/article/pii/S0378112714005611.

Vernon MJ, Sherriff RL, van Mantgem P, Kane JM. 2018. Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. For Ecol Manage. 422:190–198. doi:https://doi.org/10.1016/j.foreco.2018.03.043. https://www.sciencedirect.com/science/article/pii/S0378112717321321.

Walters DK, Hann DW, Clyde MA. 1985. Equations and Tables Predicting Gross Total Stem Volumes in Cubic Feet for Six Major Conifers of Southwest Oregon. (Research Bulletin 50):37.

Weiskittel AR, Crookston NL, Rehfeldt GE. 2012. Projected future suitable habitat and productivity of Douglas-fir in western North America. Schweizerische Zeitschrift fur Forstwes. 163(3):70–78. doi:10.3188/szf.2012.0070.

Willis JL, Roberts SD, Harrington CA. 2018. Variable density thinning promotes variable structural responses 14?years after treatment in the Pacific Northwest. For Ecol Manag 410 114-125. 410:114–125. doi:10.1016/j.foreco.2018.01.006.

https://www.fs.fed.us/pnw/pubs/journals/pnw_2018_willis001.pdf.

Wilson DS, Puettmann KJ. 2007. Density management and biodiversity in young Douglas-fir forests: Challenges of managing across scales. For Ecol Manage. 246(1 SPEC. ISS.):123–134. doi:10.1016/j.foreco.2007.03.052.

Zhang J, Finley KA, Johnson NG, Ritchie MW. 2019. Lowering stand density enhances resiliency of ponderosa pine forests to disturbances and climate change. For Sci. doi:10.1093/forsci/fxz006.

3. General Conclusions

In the Pacific Northwest, climate change is predicted to cause warmer and drier summers which will have an impact on tree growth and vigor. It is broadly accepted that forests at the drier margins of their growing spectrum are at higher risk of adverse effects of climate change, which includes Douglas-fir forests in the foothills surrounding Oregon's Willamette Valley, than those at the wetter margins (Fritts 1976; Montwé et al. 2015; Carnwath and Nelson 2017). These forests are also critical to timber production and biodiversity in the region, so any management actions must be based on predicted future conditions and adaptable given the uncertainties of climate models (Bauhus et al. 2009; Littke et al. 2018).

My research shows that thinning stands to lower residual densities increased drought resistance and resilience in at least the first 8 years after harvesting which aligns with other research on the topic (Bottero et al. 2017; Finley and Zhang 2019). Thinning has great potential for drought resistance and resilience, but managers must consider longer-term stand dynamics when assessing thinning as a tool for promoting drought resistance and resilience as these benefits appear to fade as time passes since treatments and forests regrow, returning densities to the original competition levels (Davis et al. 2007; D'Amato et al. 2013; Sohn et al. 2016; Briggs and Kantavichai 2018; Finley and Zhang 2019). In addition to the eventual return a competitive environment, VDT accelerates the development of larger trees which may have increased exposure to drought due to their greater water needs, so we need to consider additional treatments (D'Amato et al. 2013).

Although heavier thinning appeared to increase drought resistance and resilience to a drought event occurring 8 years after treatment, there were no consistent improvements in drought resistance or resilience during a warmer, drier, and longer-duration drought event that occurred 22-23 years after thinning. Given the severity of the second drought and the evidence that the MFS treatments did not have a beneficial effect on tree resistance and resilience response during them, we need to ask what characteristics of droughts we will see in the future and if our treatments will continue to have an effect against them (Restaino et al. 2016; Lee et al. 2022). A single thinning treatment is less likely to be effective against future droughts if projected increases in drought intensity and duration play out, and drought events occur multiple decades after thinning. The medium and medium-high residual density treatments in the MFS were re-thinned 14 years before the 2015-2016 drought, and I found some evidence that this may have helped sustain increases in drought resilience in the medium density treatment relative to higher density treatments through the second drought, although re-thinning in the medium and medium-high density treatments did not appear to improve drought resistance and during the second drought. Further research is needed on follow-up treatment intensities, timings, and methods to develop strategies that provide longer-lived drought mitigate beyond. The loss of differences in drought resistance or resilience between the low and high density treatments during the second drought in 2015-2016 suggests that without follow-up treatments, the initial benefits of thinning may reverse. The June 2021 heat-dome that encompassed most of the Pacific Northwest would be a useful follow-up drought to study to see if the MFS thinning treatments have any residual benefits nearly 30 years after they were implemented.

Land managers are constantly trying to balance a plethora of outcomes, but I focused on tradeoffs between drought resistance, resilience and timber production. From the stand level models, I did not find evidence of a significant difference in PAI between density levels or spatial arrangements, but there was significantly more standing volume in the higher density sub-plots. This did not however lead to significant tradeoffs between standing volume, drought resistance and resilience between the low and high density treatments. The only significant tradeoff between drought response and timber production metrics was between PAI measured from 2010-2019 and 2015-2016 drought resistance as a result of low benefit scores for drought resistance contrasting with relatively high benefit scores for periodic annual increment in higher density treatment units. This could suggest a potential concern for managers interested in maximizing wood production in a droughtier future but given the lack of significant tradeoffs between drought resistance, resilience and PAI during the 2015-2016 drought, and the absence of significant differences in period volume production among thinning treatments, further work may be necessary to fully evaluate any drought resistance and resilience – wood production tradeoffs associated with thinning.

Since thinning with gaps was correlated with slightly higher resilience than uniform thinning during the first drought and helps with creating heterogenous structure, VDT approaches that incorporate gaps may support both goals of drought resistance, resilience and late-successional/old-growth habitat development. There is significant evidence that variable density thinning (VDT) can accelerate the transformation of even-aged stands into more structurally diverse stands (Roberts and Harrington 2008; Comfort et al. 2010; Dodson et al. 2014; Kuehne et al. 2015; Willis et al. 2018). VDT also can support economic goals especially when considering forests that already have logging infrastructure that can be used for future management activities (Puettmann et al. 2016b). In the context of trying to balance multiple competing objectives, VDT has the potential to balance old-growth like structure and timber production in addition to the looming concerns of climate change induced droughts. VDT is a useful tool when managing for multiple objectives but, my results suggest that we may need to plan for multiple treatments that can be adjusted farther into the future to promote resistance and resilience to projected increases in drought activity.

3.1 Works Cited

Agne MC, Beedlow PA, Shaw DC, Woodruff DR, Lee EH, Cline SP, Comeleo RL. 2018. Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. For Ecol Manage. 409:317–332. doi:https://doi.org/10.1016/j.foreco.2017.11.004. https://www.sciencedirect.com/science/article/pii/S0378112717306928.

Allen CD, Breshears DD, McDowell NG. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere. 6(8):1–55. doi:10.1890/ES15-00203.1.

Bailey JD, Tappeiner JC. 1998. Effects of thinning on structural development in 40- to 100-year, old Douglas-fir stands in western Oregon. For Ecol Manage. 108(1–2):99–113. doi:10.1016/S0378-1127(98)00216-3.

Bauhus J, Puettmann K, Messier C. 2009. Silviculture for old-growth attributes. For Ecol Manage. 258(4):525–537. doi:10.1016/j.foreco.2009.01.053.

Bentz BJ, Rgnire J, Fettig CJ, Hansen EM, Hayes JL, Hicke JA, Kelsey RG, Negron JF, Seybold SJ. 2010. Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. Bioscience. 60(8):602–613. doi:10.1525/bio.2010.60.8.6.

Bottero A, D’Amato AW, Palik BJ, Bradford JB, Fraver S, Battaglia MA, Asherin LA. 2017. Density-dependent vulnerability of forest ecosystems to drought. J Appl Ecol. 54(6):1605–1614. doi:10.1111/1365-2664.12847.

Brackett M. 1973. Notes on TARIF tree volume computation. Olympia.

Brackett M. 1977. Notes on TARIF tree volume computation. Olympia.

Bradford JB, D’Amato AW. 2012. Recognizing trade-offs in multi-objective land management. Front Ecol Environ. 10(4):210–216. doi:10.1890/110031.

Brandeis TJ, Newton M, Cole EC. 2002. Biotic injuries on conifer seedlings planted in forest understory environments. New For. 24(1):1–14. doi:10.1023/A:1020553021748.

Briggs DG, Kantavichai R. 2018. Effects of thinning on ring mass growth along stem of douglas fir in four coastal pacific northwest sites. For Sci. 64(2):139–148. doi:10.1093/forsci/fxx003.

Brodie LC, Harrington CA. 2020. Guide to variable-density thinning using skips and gaps. USDA For Serv - Gen Tech Rep PNW-GTR. 2020(GTR-989):1–37.

Carnwath G, Nelson C. 2017. Effects of biotic and abiotic factors on resistance versus resilience of Douglas fir to drought. PLoS One. 12(10):1–19. doi:10.1371/journal.pone.0185604.

Chesson P, Gebauer RLE, Schwinning S, Huntly N, Ernest MSK, Sher A, Novoplansky A, Weltzin JF, Schwinning S, Huntly N, et al. 2016. International Association for Ecology Resource Pulses , Species Interactions , and Diversity Maintenance in Arid and Semi-Arid Environments Published by : Springer in cooperation with International Association for Ecology Stable URL :

http://www.jstor.org. (May). doi:10.1007/s00442-004-1551-l.

Chmura DJ, Anderson PD, Howe GT, Harrington CA, Halofsky JE, Peterson DL, Shaw DC, Brad St.Clair J. 2011. Forest responses to climate change in the northwestern United States: Ecophysiological foundations for adaptive management. For Ecol Manage. 261(7):1121–1142. doi:10.1016/j.foreco.2010.12.040. http://dx.doi.org/10.1016/j.foreco.2010.12.040.

Cole E, Newton M. 2009. Tenth-year survival and size of underplanted seedlings in the Oregon coast range. Can J For Res. 39(3):580–595. doi:10.1139/X08-198.

Cole E, Newton M, Bailey JD. 2017. Understory vegetation dynamics 15 years post-thinning in 50-year-old Douglas-fir and Douglas-fir/western hemlock stands in western Oregon, USA. For Ecol Manage. 384:358–370. doi:10.1016/j.foreco.2016.11.003. http://dx.doi.org/10.1016/j.foreco.2016.11.003.

Comfort EJ, Roberts SD, Harrington CA. 2010. Midcanopy growth following thinning in young-growth conifer forests on the Olympic Peninsula, western Washington. For Ecol Manag 259 1606-1614. 259:1606–1614. https://www.fs.fed.us/pnw/pubs/journals//pnw_2010_comfort001.pdf.

Curtis RO. 2006. Volume Growth Trends in a Douglas-Fir Levels-of-Growing-Stock Study. West J Appl For. 21(2):79–86. doi:10.1093/wjaf/21.2.79.

D’Amato AW, Bradford JB, Fraver S, Palik BJ. 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. Ecol Appl. 23(8):1735–1742. doi:10.1890/13-0677.1.

D’Amato AW, Jokela EJ, O’Hara KL, Long JN. 2017. Silviculture in the United States: An Amazing Period of Change over the Past 30 Years. J For. 116(January):55–67. doi:10.5849/jof-2016-035.

D’Amato AW, Palik BJ, Kern CC. 2010. Growth, yield, and structure of extended rotation Pinus resinosa stands in Minnesota, USA. Can J For Res. 40(5):1000–1010. doi:10.1139/X10-041. https://doi.org/10.1139/X10-041.

Dale V, Joyce LA, Mcnulty S, Neilson R, Ayres M, Flannigan M, Hanson P, Irland L, Lugo A, Peterson CJ, et al. 2001. Climate Change and Forest Disturbances. Bioscience. 51:723.

DARYCHUK N, HAWKINS BJ, STOEHR M. 2012. Trade-offs between growth and cold and drought hardiness in submaritime Douglas-fir. Can J For Res. 42(8):1530–1541. doi:10.1139/x2012-092.

Davis LR, Puettmann KJ, Tucker GF. 2007. Overstory response to alternative thinning treatments in young Douglas-fir forests of Western Oregon. Northwest Sci. 81(1):1–14. doi:10.3955/0029-344X-81.1.1.

Dodson EK, Ares A, Puettmann KJ. 2012. Early responses to thinning treatments designed to accelerate late successional forest structure in young coniferous stands of Western Oregon, USA. Can J For Res. 42(2):345–355. doi:10.1139/X11-188.

Dodson EK, Burton JI, Puettmann KJ. 2014. Multiscale controls on natural regeneration dynamics after partial overstory removal in douglas-fir forests in Western Oregon, USA. For Sci. 60(5):953–961. doi:10.5849/forsci.13-011.

Fernández-de-Uña L, McDowell NG, Cañellas I, Gea-Izquierdo G. 2016. Disentangling the effect of competition, CO2 and climate on intrinsic water-use efficiency and tree growth. J Ecol. 104(3):678–690. doi:https://doi.org/10.1111/1365-2745.12544. https://doi.org/10.1111/1365-2745.12544.

Finley K, Zhang J. 2019. Climate effect on ponderosa pine radial growth varies with tree density and shrub removal. Forests. 10(6). doi:10.3390/f10060477.

Ford KR, Breckheimer IK, Franklin JF, Freund JA, Kroiss SJ, Larson AJ, Theobald EJ, HilleRisLambers J. 2017. Competition alters tree growth responses to climate at individual and stand scales. Can J For Res. 47(1):53–62. doi:10.1139/cjfr-2016-0188.

Franklin JF, Johnson KN. 2012. A Restoration Framework for Federal Forests in the Pacific Northwest. J For. 110(8):429–439. doi:10.5849/jof.10-006. https://doi.org/10.5849/jof.10-006.

Fritts HC. 1976. Tree rings and climate. Caldwell, NJ: Blackburn.

Halofsky JE, Andrews-Key SA, Edwards JE, Johnston MH, Nelson HW, Peterson DL, Schmitt KM, Swanston CW, Williamson TB. 2018. Adapting forest management to climate change: The state of science and applications in Canada and the United States. For Ecol Manage. 421:84–97. doi:https://doi.org/10.1016/j.foreco.2018.02.037. https://www.sciencedirect.com/science/article/pii/S0378112717316547.

Halofsky JE, Hibbs DE. 2009. Controls on early post-fire woody plant colonization in riparian areas. For Ecol Manage. 258(7):1350–1358. doi:10.1016/j.foreco.2009.06.038.

Hanus ML, Marshall DD, Hann DW. 1999. Height-Diameter Equations for Six Species in the Coastal Regions of the Pacific Northwest. Res Contrib For Res Lab Oregon State Univ.(August):12.

Holmes TP, McNulty S, Vose JM, Prestemon JP, Li H. 2009. A Conceptual Framework for Adaptive Forest Management under Climate Change. Clim Chang Adapt Mitig Manag options A Guid Nat Resour Manag South For Ecosyst.:45–60.

Interdisciplinary Planning Team. 2005. McDonald-Dunn Forest Plan.

Kuehne C, Weiskittel AR, Fraver S, Puettmann KJ. 2015. Effects of thinning-induced changes in structural heterogeneity on growth, ingrowth, and mortality in secondary coastal Douglas-fir forests. Can J For Res. 45(11):1448–1461. doi:10.1139/cjfr-2015-0113. https://doi.org/10.1139/cjfr-2015-0113.

Lee EH, Beedlow PA, Brooks JR, Tingey DT, Wickham C, Rugh W. 2022. Physiological responses of Douglas-fir to climate and forest disturbances as detected by cellulosic carbon and oxygen isotope ratios. Tree Physiol. 42(1):5–25. doi:10.1093/treephys/tpab122. https://doi.org/10.1093/treephys/tpab122.

Littell JS, Oneil EE, McKenzie D, Hicke JA, Lutz JA, Norheim RA, Elsner MM. 2010. Forest ecosystems, disturbance, and climatic change in Washington State, USA. Clim Change. 102(1–2):129–158. doi:10.1007/s10584-010-9858-x.

Littell JS, Peterson DL, Tjoelker M. 2008. Douglas-Fir Growth in Mountain Ecosystems: Water Limits Tree Growth from Stand to Region. Ecolological Monogr. 78(3):1–20. papers3://publication/uuid/24364A69-9981-4F58-9D67-6A860071FD45.

Littell JS, Peterson DL, Tjoelker M, Monographs E, Littell S. 2014. Douglas-Fir Growth in Mountain Ecosystems : Water Limits Tree Growth from Stand to Region Published by : Ecological Society of America content in a trusted digital archive . We use information technology and tools to increase productivity and facilitate n. 78(3):349–368.

Littke KM, Zabowski D, Turnblom E, Harrison RB. 2018. Estimating shallow soil available water supply for Douglas-fir forests of the coastal Pacific Northwest: climate change impacts. Can J For Res. 48(4):421–430. doi:10.1139/cjfr-2017-0385. https://doi.org/10.1139/cjfr-2017-0385.

Little J, Peterson D, Riley K, Liu Y. 2016. A review of the relationships between drought and forest fire in the United States. Glob Chang Biol. 22(7):2353–2369. doi:10.1111/gcb.13275. https://www.deepdyve.com/lp/wiley/a-review-of-the-relationships-between-drought-and-forest-fire-in-the-VfYrRw776E.

McDowell N, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams DG, et al. 2008. Mechanisms of plant survival and mortality during drought: Why do some plants survive while others succumb to drought? New Phytol. 178(4):719–739. doi:10.1111/j.1469-8137.2008.02436.x.

McDowell NG, Adams HD, Bailey JD, Hess M, Kolb TE. 2006. Homeostatic Maintenance Of Ponderosa Pine Gas Exchange In Response To Stand Density Changes. Ecol Appl. 16(3):1164–1182. doi:https://doi.org/10.1890/1051-0761(2006)016[1164:HMOPPG]2.0.CO;2. https://doi.org/10.1890/1051-0761(2006)016[1164:HMOPPG]2.0.CO.

Messier C, Bauhus J, Doyon F, Maure F, Sousa-Silva R, Nolet P, Mina M, Aquilué N, Fortin MJ, Puettmann K. 2019. The functional complex network approach to foster forest resilience to global changes. For Ecosyst. 6(1). doi:10.1186/s40663-019-0166-2.

Millar CI, Stephenson NL, Stephens SL. 2007. CLIMATE CHANGE AND FORESTS OF THE FUTURE : mm. Ecol Appl. 17(8):2145–2151.

Montwé D, Spiecker H, Hamann A. 2015. Five decades of growth in a genetic field trial of Douglas-fir reveal trade-offs between productivity and drought tolerance. Tree Genet Genomes. 11(2):1–11. doi:10.1007/s11295-015-0854-1.

Mote PW, Salathé EP. 2010. Future climate in the Pacific Northwest. Clim Change. 102(1):29–50. doi:10.1007/s10584-010-9848-z. https://doi.org/10.1007/s10584-010-9848-z.

Nabel MR, Newton M, Cole EC. 2013. Abundance of natural regeneration and growth comparisons with planted seedlings 10-13years after commercial thinning in 50-year-old

Douglas-fir, Douglas-fir/western hemlock, Oregon Coast Range. For Ecol Manage. 292:96–110. doi:10.1016/j.foreco.2012.12.009. http://dx.doi.org/10.1016/j.foreco.2012.12.009.

Nagel LM, Palik BJ, Battaglia MA, D'Amato AW, Guldin JM, Swanston CW, Janowiak MK, Powers MP, Joyce LA, Millar CI, et al. 2017. Adaptive silviculture for climate change: A national experiment in manager-scientist partnerships to apply an adaptation framework. J For. 115(3):167–178. doi:10.5849/jof.16-039.

Newton M, Cole EC. 2006. Harvesting impacts on understory regeneration in two-storied Douglas-fir stands. West J Appl For. 21(1):14–18. doi:10.1093/wjaf/21.1.14.

Newton M, Cole L. 2015. Overstory development in douglas-fir-dominant forests thinned to enhance late-seral features. For Sci. 61(4):809–816. doi:10.5849/forsci.14-194.

Palik BJ, D'Amato AW. 2019. Variable retention harvesting in Great Lakes mixed-pine forests: emulating a natural model in managed ecosystems. Ecol Process. 8(1). doi:10.1186/s13717-019-0171-y.

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team. 2021. nlme: Linear and Nonlinear Mixed Effects Models. https://cran.r-project.org/package=nlme.

Powers MD, Webster CR, Pregitzer KS, Palik BJ. 2009. Spatial dynamics of radial growth and growth efficiency in residual Pinus resinosa following aggregated retention harvesting. Can J For Res. 39(1):109–117. doi:10.1139/X08-162. https://doi.org/10.1139/X08-162.

Priebe JE, Powers MD, Cole EC. 2018. Species, tree size, and overstory environment affect likelihood of ice storm damage to understory trees in a mature Douglas-fir forest. For Ecol Manage. 409(April 2017):777–788. doi:10.1016/j.foreco.2017.11.041. https://doi.org/10.1016/j.foreco.2017.11.041.

Puettmann KJ, Ares A, Burton JI, Dodson EK. 2016a. Forest restoration using variable density thinning: Lessons from douglas-fir stands in western Oregon. Forests. 7(12):1–15. doi:10.3390/f7120310.

Puettmann KJ, Ares A, Burton JI, Dodson EK. 2016b. Forest restoration using variable density thinning: Lessons from douglas-fir stands in western Oregon. Forests. 7(12):1–14. doi:10.3390/f7120310.

Rehfeldt GE, Crookston NL, Warwell M V., Evans JS. 2006. Empirical analyses of plant-climate relationships for the Western United States. Int J Plant Sci. 167(6):1123–1150. doi:10.1086/507711.

Restaino CM, Peterson DL, Littell J. 2016. Increased water deficit decreases Douglas fir growth throughout western US forests. Proc Natl Acad Sci U S A. 113(34):9557–9562. doi:10.1073/pnas.1602384113.

Del Río M, Bravo-Oviedo A, Pretzsch H, Löf M, Ruiz-Peinado R. 2017. A review of thinning effects on Scots pine stands: From growth and yield to new challenges under global change. For Syst. 26(2):eR03S. doi:10.5424/fs/2017262-11325.

Ritchie MW, Hann DW. 1984. Nonlinear Equations for Predicting Diameter and Squared Diameter Inside Bark at Breast Height for Douglas-Fir.

Roberts SD, Harrington CA. 2008. Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests. For Ecol Manage. 255(7):2771–2781. doi:https://doi.org/10.1016/j.foreco.2008.01.043. https://www.sciencedirect.com/science/article/pii/S0378112708001114.

Skov K, Kolb T, Wallin K. 2004. Tree Size and Drought Affect Ponderosa Pine Physiological Response to Thinning and Burning Treatments. For Sci. 50:81–91.

Sohn JA, Saha S, Bauhus J. 2016. Potential of forest thinning to mitigate drought stress: A meta-analysis. For Ecol Manage. 380:261–273. doi:10.1016/j.foreco.2016.07.046.

Spittlehouse DL, Stewart RB. 2003. Adaptation to climate change in forest management. BC J Ecosyst Manag. 4(1):1–11.

Tappeiner JC, Huffman DW, Marshall D, Spies TA, Bailey JD. 1997. Density, ages, and growth rates in old-growth and young-growth forests in coastal Oregon. Can J For Res. 27(5):638–648. doi:10.1139/x97-015.

Thomas JW, Franklin JF, Gordon J, Johnson NK. 2006. The Northwest Forest Plan: Origins, Components, Implementation Experience, and Suggestions for Change. Conserv Biol. 20(2):277–287. doi:https://doi.org/10.1111/j.1523-1739.2006.00385.x. https://doi.org/10.1111/j.1523-1739.2006.00385.x.

Thompson NP, Lewis KJ, Poirier LM. 2018. Adjacency to a harvest trail increases drought resistance of interior douglas-fir (Pseudotsuga menziesii var. glauca) in partially harvested stands in central British Columbia. Can J For Res. 48(7):809–820. doi:10.1139/cjfr-2018-0007.

Trouvé R, Bontemps J-D, Collet C, Seynave I, Lebourgeois F. 2014. Growth partitioning in forest stands is affected by stand density and summer drought in sessile oak and Douglas-fir. For Ecol Manage. 334:358–368. doi:https://doi.org/10.1016/j.foreco.2014.09.020. https://www.sciencedirect.com/science/article/pii/S0378112714005611.

Vernon MJ, Sherriff RL, van Mantgem P, Kane JM. 2018. Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. For Ecol Manage. 422:190–198. doi:https://doi.org/10.1016/j.foreco.2018.03.043. https://www.sciencedirect.com/science/article/pii/S0378112717321321.

Walters DK, Hann DW, Clyde MA. 1985. Equations and Tables Predicting Gross Total Stem Volumes in Cubic Feet for Six Major Conifers of Southwest Oregon. (Research Bulletin 50):37.

Weiskittel AR, Crookston NL, Rehfeldt GE. 2012. Projected future suitable habitat and productivity of Douglas-fir in western North America. Schweizerische Zeitschrift fur Forstwes. 163(3):70–78. doi:10.3188/szf.2012.0070.

Willis JL, Roberts SD, Harrington CA. 2018. Variable density thinning promotes variable structural responses 14?years after treatment in the Pacific Northwest. For Ecol Manag 410 114-125. 410:114–125. doi:10.1016/j.foreco.2018.01.006.

https://www.fs.fed.us/pnw/pubs/journals/pnw_2018_willis001.pdf.

Wilson DS, Puettmann KJ. 2007. Density management and biodiversity in young Douglas-fir forests: Challenges of managing across scales. For Ecol Manage. 246(1 SPEC. ISS.):123–134. doi:10.1016/j.foreco.2007.03.052.

Zhang J, Finley KA, Johnson NG, Ritchie MW. 2019. Lowering stand density enhances resiliency of ponderosa pine forests to disturbances and climate change. For Sci. doi:10.1093/forsci/fxz006.