Long-term trajectories of fuel and stand structure in experimentally-treated dry forests of central Washington

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Questions/comments are in red. To this point I’ve worked much more on implementation and visualization of the statistical methods than I have on writing down and deeply thinking through interpretations of the results.

**Abstract**

Abstract text here.

**Introduction**

Severe wildfire is increasing in dry forests of western North America, often threatening forest persistence (Coop et al. 2020) and human community stability (Radeloff et al. 2018). Climate change, expanding human development, and fire suppression are contributing to the increasing trend in severe wildfire (Hessburg et al. 2021). Fire suppression and exclusion of Indigenous fire in dry forests has led to uncharacteristic stand conditions, including increased fuel load and continuity, relative to pre-colonization levels (Hagmann et al. 2021). Therefore, fuel treatments are considered an integral tool for of dry forest restoration planning (Franklin and Johnson 2012). Fuel treatments can also be effective at reducing wildfire severity in a wide range of weather conditions, particularly treatments that include prescribed burning, when wildfire occurs less than ten years following treatment (Prichard et al. 2021).

Although the short-term effects of fuel treatments on fuel loads are well studied, the longer-term (> 5 years) dynamics of fuel treatments are not well understood. Most studies that have empirically addressed long-term fuel and stand structure dynamics on the stand scale have found that most variables are statistically indistinguishable from controls and/or pretreatment values, with high variability within and among treatment units (Battaglia et al. 2008, Chiono et al. 2012, Stephens et al. 2012, van Mantgem et al. 2016, Crotteau et al. 2018, Hood et al. 2020, Morici and Bailey 2021). Tree density and canopy fuel loads, however, likely remain below pretreatment levels into longer term study periods in thin and thin plus burn treatments. In stands receiving a thin or thin plus burn treatment, recruitment of ladder fuels, those fuels that connect surface and canopy fuels, appears to be a key process driving modelled wildfire severity (Stephens et al. 2012, Hood et al. 2020). In experiments, control units have sometimes shown similar temporal dynamics to treated units for some variables, decreasing estimates of the effect of treatment (Stephens et al. 2012, Hood et al. 2020, Morici and Bailey 2021).

High within- and among-stand variability in treatment units (Stephens et al. 2012, Hood et al. 2020, Morici and Bailey 2021) suggests that factors other than treatment category influence fine-scale fuel dynamics and fuel treatment longevity. These factors might include pretreatment condition, treatment intensity, and site productivity (Jain et al. 2012). Variance within treatment categories is important for managers to consider (Jain et al. 2012), and it may confound or weaken the power of categorical statistical tests used in many fuel treatment studies. Multivariate techniques such as ordination and cluster analysis afford succinct exploration of variance patterns within- and among- treatment units with complex datasets (Legendre and Legendre 2012). Therefore, multivariate techniques may be useful in studies focused fuel and fire behavior, which are characterized by high variance and large number of response variables (Reinhardt et al. 2008, Keane et al. 2012).

In this study, I will explore plot-scale long-term (~15-year posttreatment) fuel, stand structure, and modelled fire behavior responses to control, burn, thin, and thinburn treatments. I will use field data I collected at the Northeastern Cascades site of the nationwide Fire and Fire Surrogates study. Earlier publications focused on fuel, stand structure, and modelled fire behavior responses have found high within- and among- stand variance (Agee and Lolley 2006). Specifically, I will ask the questions, and have the following hypotheses:

**Question 1:*****Do plots within different treatment categories show similar patterns within multivariate space during the pretreatment sampling period, and do they appear to respond consistently to treatment in the longterm?***

**Question 2: *Do plots within a replicate unit and within spatially proximate replicate units will group together in multivariate space in the pretreatment sampling period, and do different replicate units within a treatment category group together after treatment?***

***Question 3: Could the number of variables needed in analysis potentially be reduced by data reduction methods?***

***Hypothesis 1: Plots within treatment categories will show some overlap in multivariate space but will have differences as well. They will respond in a consistent direction to treatment.***

***Hypothesis 2: Plots within a replicate unit and spatially proximate plots will largely group together in the pretreatment period, and treatment will cause more intermixing of spatially distant units within the same treatment category, although this relationship won’t be perfect.***

***Hypothesis 3: There is likely to be correlation in variables that will allow for data reduction, particularly because the modelled fire behavior variables depend directly on the field measured data.***

**Methods**

*Study Area*

The Northeastern Cascades site of the Fire and Fire Surrogates study is in central Washington State, south of Cashmere. The area was selected to characterize dry forests of the interior Columbia River basin (Agee and Lehmkuhl 2009). These forests occupy relatively low elevations, and the tree layer is dominated by ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*), with smaller components of western larch (*Larix occidentalis*) and grand fir (*Abies grandis*) (Rossman et al. 2020). The precolonial fire return interval was 6 to 21 years (Agee and Lehmkuhl 2009). Since the 1930s, however, fire-suppression and removal of Native Americans from the landscape has resulted in a buildup of fuels and increase of shade-tolerant, fire-intolerant tree species (Hessburg and Agee 2003). Today, structure and composition is highly affected by site moisture, which is largely driven by topography (Agee and Lehmkuhl 2009).

*Treatment selection and implementation*

The study was designed to experimentally test the effects of four treatments: control, burn, thin, and thin plus burn. In the late 1990s, researchers randomly chose 12 experimental units of ten hectares or larger, from a field of 30 potential units. Within the 12 chosen units, researchers randomly assigned three replicates for each of four treatments. Four units were changed from their initial assignment due to operator concerns about logistics and safety of prescribed burning, given proximity to structures for two of the units. Units were chosen to be roughly rectangular in shape, 90% forested, with slopes averaging less than 50%, and primarily consisting of the *Pseudotsuga menziesii* series of Lillybridge et al. (1995). Thinning projects were implemented in 2002 or 2003, and burning projects were delayed to 2004 or 2006 due to weather. 2004 burns were of lower intensity and severity than prescribed, while 2006 burns met management goals. In 2012, a wildfire (the Poison Fire) burned four replicates: two controls, one thin, and one burn unit. The long-term experimental balance therefore consists of three thinburn units, two thin units, two burn units, and one control unit (figure 4) (Agee and Lehmkuhl 2009).

*Data collection*

In 2019 and 2020, I led field crews resampling fuel plots. We sampled 204 plots: 66 thin plus burn plots from three units, 58 burn plots from two units, 55 thin plots from 2 units, and 25 control plots from one unit. The protocols below match those followed in pretreatment and short-term surveys (Agee and Lolley 2006, Agee and Lehmkuhl 2009), except where noted.

We measured vegetation structure and fuel profiles following standard approaches. At each plot we measured trees, shrub and herb fuels, fuel model (Anderson 1982), and canopy cover in a circular plot, and surface fuels in two Brown’s transects (figure 5) (Brown 1971). In each transect, we counted one-hour fuels for two meters, ten-hour fuels for three meters, hundred-hour fuels for five meters, and thousand-hour fuels for twenty meters. For thousand-hour fuels, diameter, decay class, and species were also recorded. Additionally, we measured litter depth, duff depth, and woody fuel height at three points per transect. Shrub and herb fuel coverage, density, and height were estimated ocularly over a 25-meter plot according to BEHAVE protocols (Burgan and Rothermel 1984). We estimated coverage of fuel models over the same plot, using Northern Forest Fire Lab (NFFL) models (Anderson 1982). Canopy cover A picture containing diagram

Description automatically generatedGraphical user interface, website

Description automatically generatedwas measured with densiometer readings facing each of the four cardinal directions from plot center.

Due to variable tree density, we used an adjustable radius design to determine tree plot size. We used two radii per tree plot: one for ‘small trees’ (≤0.1 cm diameter at breast height [dbh] to ˃30 cm dbh), and one for ‘large trees’ (≤30 cm dbh), to avoid clumps sapling clumps causing undersampling of larger, fire resistant trees. We customized at each plot to sample at least ten trees per plot, at least five of which had to be large trees. The maximum allowable plot radius was 18 meters. Radii were adjustable in meter increments. The small tree radius could be smaller than or equal to the large tree radius, but not larger. For each tree, we recorded species, dbh, total height, height to base of live crown, height to base of dead crown, char height, char circumference, likely cause of death if applicable, and mistletoe presence. The protocol for determining tree plot size was different than pretreatment surveys, which used variable rectangular plots with coarser size increments, and short-term surveys, which used crusing prisms. The individual tree measurements were the same (Agee and Lolley 2006, Agee and Lehmkuhl 2009).

*Statistical methods*

Question 1: NMDS

Question 2: Cluster Analyses

Question 3: PCA

Questions

* I relativized by maximum since this avoided negative numbers which cause issues with Euclidean distance. I wanted absolute differences between sample periods to mean something, so I relativized all the data together, and then divided out by treatment period. I ran each analysis separately for each sample period, so the together-relativization shouldn’t affect the relationships within a response variable, but it may affect the relationship among variables. Do you see any problems with this approach, or conversely with relativizing each sample period separately? The papers I reviewed for the analytical methods assignment aren’t detailed enough to know what they did.
* In the analytical methods assignment, you said that in order to look at changes in plots in ordination space over time, I would have to run both sample periods in one ordination and then draw arrows denoting change in the plot. I wasn’t really sure how to carry this out and thought a Procrustes analysis between separate ordinations seemed appropriate given that the ordinations I ran showed similar patterns between time periods. So for both NMDS and PCA, I ran two separate ordinations and then a Procrustes analysis between them. Should I change this approach?
* The visualization of the cluster analysis needs additional work; the dendrogram I made isn’t extraordinarily useful with 204 plots, although I can zoom in on the names in the jpg version of the dendrogram and I’ve been able to get some information from them. I’m envisioning instead something more like a table, with units or treatments as the rownames and cluster analysis groups as the column names, with a counts in each box of how many of each unit/treatment are within each cluster analysis group. Do you have any other creative ideas for cluster analysis with a high number of plots?
* For the PCA, my transformation attempts thus far have caused more than solved issues with data distributions, at least by my subjective visual interpretation. Therefore I’ve run the PCA without transformation thus far, although I want to explore transformation a bit more (different variables have different skews/issues). Some variables have some 0 or 1 inflation, which seems impossible to transform out of (and also probably causes issues with nonmetric evaluation since values are identical?). Results do seem logical, and consistent with the NMDS.

**Results**

You have a separate tables/figures section listed for below the references section, but I’ve put my figures here for now:

NMDS (three axes).

Stress: pretreatment 0.10, longterm 0.11

Stressplot nonmetric fits both 0.99.

Chart, radar chart

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Cluster analysis: hclust, complete linkage, 8 predefined groups. Visualization needs refining then I’m planning on trying other clustering/linkage methods. What I have so far suggest similarities within units and among spatially proximate units (eg. Crow1, Crow3, Crow6, Pendelton, or Camas, Ruby, Spromberg).

Chart

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More text on results needed.

**Discussion**

Discussion text needed.

**References**

Agee, J. K., and J. F. Lehmkuhl. 2009. Dry forests of the Northeastern Cascades Fire and Fire Surrogate project site, Mission Creek, Okanogan-Wenatchee National Forest. Page Res. Pap. PNW-RP-577. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 158 p. Portland, OR.

Agee, J. K., and M. R. Lolley. 2006. Thinning and Prescribed Fire Effects on Fuels and Potential Fire Behavior in an Eastern Cascades Forest, Washington, USA. Fire Ecology 2:3–19.

Anderson, H. E. 1982. Aids to determining fuel models for estimating fire behavior. Page Gen. Tech. Rep. INT-122. Ogden, Utah: U.S.Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22p. Ogden, UT.

Battaglia, M. A., F. W. Smith, and W. D. Shepperd. 2008. Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? Forest Ecology and Management 256:2029–2038.

Brown, J. K. 1971. A Planar Intersect Method for Sampling Fuel Volume and Surface Area. Forest Science 17:96–102.

Burgan, R. E., and R. C. Rothermel. 1984. BEHAVE: fire behavior prediction and fuel modeling system--FUEL subsystem. Page General Technical Report INT-167. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 126 p. Ogden, UT.

Chiono, L. A., K. L. O’Hara, M. J. De Lasaux, G. A. Nader, and S. L. Stephens. 2012. Development of Vegetation and Surface Fuels Following Fire Hazard Reduction Treatment. Forests 3:700–722.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, M. D. Hurteau, A. Tepley, E. Whitman, T. Assal, B. M. Collins, K. T. Davis, S. Dobrowski, D. A. Falk, P. J. Fornwalt, P. Z. Fulé, B. J. Harvey, V. R. Kane, C. E. Littlefield, E. Q. Margolis, M. North, M. A. Parisien, S. Prichard, and K. C. Rodman. 2020, August 1. Wildfire-Driven Forest Conversion in Western North American Landscapes. Oxford University Press.

Crotteau, J. S., C. R. Keyes, S. M. Hood, D. L. R. Affleck, and A. Sala. 2018. Fuel dynamics after a bark beetle outbreak impacts experimental fuel treatments. Fire Ecology 14.

Franklin, J. F., and K. N. Johnson. 2012. A Restoration Framework for Federal Forests in the Pacific Northwest. Journal of Forestry 110:429–439.

Hagmann, R. K., P. F. Hessburg, S. J. Prichard, N. A. Povak, P. M. Brown, P. Z. Fulé, R. E. Keane, E. E. Knapp, J. M. Lydersen, K. L. Metlen, M. J. Reilly, A. J. S. Meador, S. L. Stephens, J. T. Stevens, A. H. Taylor, L. L. Yocom, M. A. Battaglia, D. J. Churchill, L. D. Daniels, D. A. Falk, P. Henson, J. D. Johnston, M. A. Krawchuk, C. R. Levine, G. W. Meigs, A. G. Merschel, M. P. North, H. D. Safford, T. W. Swetnam, and A. E. M. Waltz. 2021. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. Ecological Applications 0:e02431.

Hessburg, P. F., and J. K. Agee. 2003. An environmental narrative of Inland Northwest United States forests, 1800-2000. Pages 23–59 Forest Ecology and Management. Elsevier.

Hessburg, P. F., S. J. Prichard, R. K. Hagmann, N. A. Povak, and F. K. Lake. 2021. Wildfire and climate change adaptation of western North American forests: a case for intentional management. Ecological Applications:e02432.

Hood, S. M., C. R. Keyes, K. J. Bowen, D. C. Lutes, and C. Seielstad. 2020. Fuel Treatment Longevity in Ponderosa Pine-Dominated Forest 24 Years After Cutting and Prescribed Burning. Frontiers in Forests and Global Change 3:78.

Jain, T., M. Battaglia, H.-S. Han, R. Graham, C. Keyes, J. Fried, and J. Sandquist. 2012. A Comprehensive Guide to Fuel Management Practices for Dry Mixed ConiferForests in the Northwestern United States. Page JFSP Synthesis Reports.

Keane, R. E., K. Gray, V. Bacciu, and S. Leirfallom. 2012. Spatial scaling of wildland fuels for six forest and rangeland ecosystems of the northern Rocky Mountains, USA. Landscape Ecology 27:1213–1234.

Legendre, P., and L. Legendre. 2012. Numerical Ecology. Third edition. Elsevier.

Lillybridge, T. R., B. L. Kovalchik, C. K. Williams, and B. G. Smith. 1995. Field guide for forested plant associations of the Wenatchee National Forest. Page Gen. Tech. Rep. PNW-GTR-359. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 335 p. In cooperation with: Pacific Northwest Region, Wenatchee National Forest. Portland, OR.

van Mantgem, P. J., L. B. Lalemand, M. B. Keifer, and J. M. Kane. 2016. Duration of fuels reduction following prescribed fire in coniferous forests of U.S. national parks in California and the Colorado Plateau. Forest Ecology and Management 379:265–272.

Morici, K. E., and J. D. Bailey. 2021. Long-Term Effects of Fuel Reduction Treatments on Surface Fuel Loading in the Blue Mountains of Oregon. Forests 2021, Vol. 12, Page 1306 12:1306.

Prichard, S. J., P. F. Hessburg, R. K. Hagmann, N. A. Povak, S. Z. Dobrowski, M. D. Hurteau, V. R. Kane, R. E. Keane, L. N. Kobziar, C. A. Kolden, M. North, S. A. Parks, H. D. Safford, J. T. Stevens, L. L. Yocom, D. J. Churchill, R. W. Gray, D. W. Huffman, F. K. Lake, and P. Khatri-Chhetri. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. Ecological Applications 0:e02433.

Radeloff, V. C., D. P. Helmers, H. Anu Kramer, M. H. Mockrin, P. M. Alexandre, A. Bar-Massada, V. Butsic, T. J. Hawbaker, S. Martinuzzi, A. D. Syphard, and S. I. Stewart. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. Proceedings of the National Academy of Sciences of the United States of America 115:3314–3319.

Reinhardt, E. D., R. E. Keane, D. E. Calkin, and J. D. Cohen. 2008, December 10. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Elsevier.

Rossman, A. K., J. D. Bakker, D. W. Peterson, and C. B. Halpern. 2020. Long-term effects of fuels treatments, overstory structure, and wildfire on tree regeneration in dry forests of Central Washington. Forests 11:888.

Stephens, S. L., B. M. Collins, and G. Roller. 2012. Fuel treatment longevity in a Sierra Nevada mixed conifer forest. Forest Ecology and Management 285:204–212.

Tables, Figures, References