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Perspectives: Six opportunities to improve understanding of fuel treatment longevity in historically frequent-fire forests

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ABSTRACT

Fuel-reduction and restoration treatments ("treatments") are conducted extensively in dry and historically frequent-fire forests of interior western North America ("dry forests") to reduce potential for uncharacteristically severe wildfire. However, limited understanding of treatment longevity and long-term treatment effects creates potential for inefficient treatment maintenance and inaccurate forecasting of wildfire behavior. In this perspectives paper, we briefly summarize current understanding of long-term effects of three common treatment types (burn-only, thin-only, and thin-plus-burn) in dry forests. We then propose six opportunities for future research: evaluate treatment longevity in the context of management goals and long-term treatment effects, reference departure from un-treated conditions and progress toward desired conditions, account for natural variance of dry forests and associated statistical challenges, explore within-treatment drivers of long-term responses, increase the frequency of post-treatment sampling, and incorporate spatial heterogeneity into long-term analyses. Integrating these opportunities into long-term treatment studies and adaptive management plans can improve treatment maintenance efficiency and wildfire modelling. Ultimately, improved understanding about long-term effects of treatment and treatment longevity can support climate-adaptive management that increases dry-forest resilience to wildfire.

1. Introduction

More than a century of fire suppression and exclusion of Indigenous fire has led to uncharacteristically high fuel loads in dry and historically frequent-fire forests of interior western North America ("dry forests") (Hagmann et al., 2021). Dry forests are dominated by thick-barked conifers such as ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), which are adapted to survive low-intensity fires and therefore threatened by increasing fire intensity in modern fire regimes (Merschel et al., 2021, Stoddard et al., 2021). Fuel reduction and forest restoration treatments ("treatments") that include prescribed burning and/or thinning are often used to mitigate such threats (Agee and Skinner, 2005, Prichard et al., 2021, Stephens et al., 2021), and have been applied across millions of acres in recent decades (Barnett et al., 2016, USDA Forest Service, 2022).

The short-term effects of treatments on fuel profiles, forest structure, and potential wildfire behavior are well demonstrated (Schwilk et al., 2009, Fulé et al. 2012, Davis et al., 2024), and attention to long-term effects (>10 years after implementation) is increasing (Bernal et al., 2025). Long-term studies primarily focus on comparing treatment types and suggest general patterns (Fig. 1 and Fig. 2). Thinning followed by prescribed burning ("thin-plus-burn treatment") most strongly reduces fuel loads (Stephens et al., 2012a, Morici and Bailey, 2021, Hood et al., 2024) and subsequent wildfire severity (Brodie et al., 2024, Davis et al., 2024) into the long-term, and is especially effective at reducing potential for active crown fire (Hood et al., 2020, Radcliffe et al., 2024, Brodie et al., 2024). Broadcast burn-only treatments reduce surface and/or ladder fuels for ten or more years following treatment but often have minor effects on canopy fuel (Keifer et al., 2006, Battaglia et al., 2008, van Mantgem et al., 2016, Busse and Gerrard, 2020). Conversely, thin-only treatments may reduce canopy fuel into the long-term (Hood et al., 2020, Radcliffe et al., 2024, Bernal et al., 2025), but often increase short-term surface fuel loading from activity fuels (Schwilk et al., 2009) and long-term ladder fuel from saplings that respond quickly to reduced

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Fig. 1. Conceptual pre-treatment conditions for dry forests in western North America in the early 21st century. The represented stand had the largest trees removed by high-grade logging a century earlier, has not been disturbed or treated since, and is dominated by ponderosa pine and Douglas-fir. Such stands are at high risk of intense fire behavior and severe fire effects. Alternative post-treatment fuel succession pathways are displayed in Fig. 2. Painting by Robert Van Pelt.

Fig. 2. Conceptual long-term treatment effects in the stand displayed in Fig. 1, following application of three common treatment types. This representation is a heuristic starting point for understanding long-term treatment effects; outcomes of specific treatments will vary. The thin-only treatment represents a thin from below without follow-up slash management. The burn-only treatment represents a prescribed low intensity broadcast burn. The thin-plus-burn treatment represents a thin from below followed one year later by a prescribed broadcast burn of relatively low intensity. Note fine-scale variation in treatment intensity and long-term responses following treatment. See Appendix 1 for more detailed views and explanations of individual panels. Paintings by Robert Van Pelt.

overstory density (Vaillant et al., 2015, Fialko et al., 2020, Hood et al., 2024). In any treatment type, development of a shrub-dominated rather than herbaceous-dominated understory is possible and can reduce long-term treatment effectiveness (Goodwin et al., 2018, Dudney et al., 2021). Following treatments that include thinning, residual live trees grow faster and become more fire-resistant over time relative to trees in un-treated units (Fulé et al. 2022, Roccaforte et al., 2024, Rodman et al., 2024).

These general trends for long-term treatment effects are used to support "rules of thumb" for estimating treatment longevity, such as 10–15 years for treatments generally (Martinson and Omi, 2013, USDA Forest Service, 2022, Davis et al., 2024). While these rules of thumb are valuable, refinement is needed to account for the broad environmental gradients and range of management contexts where treatments occur. Furthermore, decision-makers need research that supports finding balance between intensive treatment strategies (frequent maintenance of fewer treatment units) and extensive treatment strategies (infrequent maintenance of more treatment units). These research gaps hinder treatment maintenance planning and increase uncertainty about wildfire behavior in treated landscapes. Efficient treatment maintenance is needed for stewardship of dry forests, given major restoration needs (Haugo et al., 2019, Laughlin et al., 2023) and logistical, political, and budgetary constraints to treatment implementation (North et al., 2015, Kolden, 2019, Woolsey et al., 2024, Clark et al., 2024). Small differences in treatment maintenance timing, such delaying average maintenance by a year, can result major differences in annual treatment implementation at broad spatial scales. In this perspectives paper, we build on existing research by identifying and exploring six opportunities to address knowledge gaps related to treatment longevity:

- Evaluate treatment longevity in the context of management goals and long-term treatment effects
- Reference departure from un-treated conditions and progress toward desired conditions
- Account for natural variance of dry forests and associated statistical challenges
- Explore within-treatment drivers of long-term responses
- Increase the frequency of post-treatment sampling
- Incorporate spatial heterogeneity into long-term analyses

Integrating these opportunities into future study designs and adaptive management plans will improve understanding and operationalization of long-term treatment effects and treatment longevity. Such insight is needed to support management activities that foster dry forest resilience to wildfire in a changing climate (Bernal et al., 2025). Furthermore, many of the opportunities we highlight may be applicable across a variety of ecological and management contexts.

2. Evaluate treatment longevity in the context of management goals and long-term treatment effects

2.1. Context

Treatment longevity is the useful lifespan of a treatment for context-specific management goals (Jain et al., 2012), and is therefore jointly dependent on long-term treatment effects and management objectives (Fig. 3). Treatments with the same long-term effects can have different longevities depending on the management objectives for stands. For example, the same treatment may have greater longevity when applied in remote areas where higher flame lengths and moderate severity effects are consistent with ecological objectives, than when applied closer to homes and infrastructure where wildfire hazard reduction and associated low flame lengths are crucial (North et al., 2021, Stephens et al., 2021). A single treatment can also have different long-term effects depending on the focal response variable. For example, thin-plus-burn treatments often have greater long-term effects on canopy fuel loads

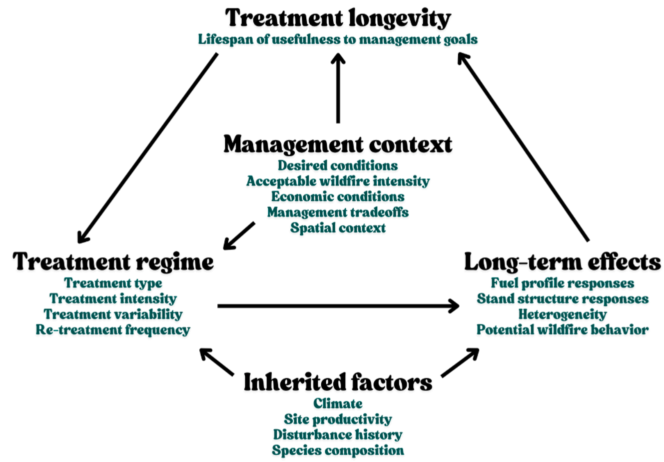

Fig. 3. Treatment longevity is determined by the interaction between management context and long-term treatment effects.

than surface fuel loads (Hood et al., 2020, Bernal et al., 2025). The specific long-term effects that influence treatment maintenance (e.g., potential surface fire vs. potential crown fire) will vary according to management context (Hood et al., 2022) and may also include ecological components not directly related to fuel profiles, such as biodiversity or cultural values (Kalies and Yocom Kent, 2016, Greenler et al., 2024).

2.2. Recommendations

We encourage distinguishing "treatment longevity" from "long-term treatment effects," and explicitly considering treatment longevity in the context of long-term treatment effects and management goals. This clarity can help contextualize the advisory role of science in informing treatment maintenance. That is, science is needed to characterize long-term treatment effects, but those effects exist in the context of desired conditions, resource availability, and risk tolerance that then dictate treatment longevity. Precise terminology about factors contributing to treatment longevity (Fig. 3) can foster deeper consideration of management needs among researchers, policymakers, and other stakeholders. This clarity may inspire methodological innovation for incorporating management goals in long-term treatment research.

3. Reference departure from un-treated conditions and progress toward desired conditions

3.1. Context

Treatment longevity is commonly assessed by testing for long-term departure from pre-treatment and un-treated controls (e.g., Morici and Bailey, 2021, Hood et al., 2024), drawing from standard statistical practice (Morrison et al., 2008). Testing for departure from control stands informs broad-scale planning, because it can help decision makers weigh tradeoffs between treating un-treated units vs. maintaining formerly treated units, or between intensive vs. extensive treatment strategies. However, un-treated and un-disturbed dry forests are often diverged from historical ranges of variation (Hagmann et al., 2021), making them poor benchmarks for determining treatment effectiveness. Comparisons with desired conditions may often be more appropriate when determining treatment longevity (Hood et al., 2022), especially in high-value areas managed for endangered species, timber revenue, or infrastructure protection. Additionally, desired conditions may be useful for assessing maintenance treatments, as pre-treatment controls may be absent or irrelevant to continued treatment maintenance.

3.2. Recommendations

We encourage testing for departure from un-treated conditions and progress toward clearly-articulated desired conditions using metrics of stand structure (Stephens et al., 2024) or potential wildfire behavior (Ager et al., 2014, Radcliffe et al., 2024). Contemporary dry forests with historically representative fire regimes can provide reference data (Falk, 2006, Jeronimo et al., 2019, Murphy et al., 2021, Chamberlain et al., 2023). However, historic and current ranges of variability may not align with future range of variability as climate change and non-native species alter ecosystems (Hessburg et al., 2019). Reference sites also represent wide productivity gradients (Stephens and Fulé 2005), adding difficulties to finding appropriate reference conditions for any given contemporary site. Alternately, the choice of desired conditions can be guided by management goals (Jain et al., 2012, Brown et al., 2003), wildfire simulation results (Johnson et al., 2011) or treatments that achieve desired outcomes in severe wildfire events (Chamberlain et al., 2024). Collaboration between researchers and managers can lead to developing specific thresholds for metrics such as potential wildfire behavior. However, it is also important to report enough information for different stakeholders to evaluate results across a range of management contexts and values (Urgenson et al., 2017, 2018). This can include reporting a variety of metrics of desired conditions, and reporting fire model outputs over a range of fire weather conditions (Radcliffe et al., 2024). At broad scales, metrics could include desired distributions of conditions to appropriately reflect dry forest variability (Hood et al., 2022, Laughlin et al., 2023).

4. Account for natural variance of dry forests and associated statistical challenges

4.1. Context

In dry forests, fuel profiles and forest structure are heterogeneous at multiple spatial scales (Keane et al., 2001, Larson and Churchill, 2012, Donato et al., 2013, Hessburg et al., 2015, Vakili et al., 2016). Such heterogeneity arises from disturbance history and topo-edaphic conditions (Larson and Churchill, 2012), treatment prescriptions that intentionally create or maintain heterogeneity (Churchill et al., 2013, Stephens et al., 2021), and/or heterogeneous responses to treatment over time (Radcliffe et al., 2024). High variance in responses (e.g., Agee and Lolley, 2006, Stephens et al., 2012b, Radcliffe et al., 2024) decreases the power of statistical tests that focus on measures of central tendency (Lieber, 1990, Morrison et al., 2008) and can lead to type II errors, or erroneous declarations of no difference between treatment and control (Baguley, 2004). In turn, this could lead researchers to underestimate long-term treatment effects and treatment longevity, when comparing means of treated conditions to means of pre-treatment or un-treated controls (Fig. 4).

4.2. Recommendations

We encourage using study designs that account for statistical uncertainty by increasing sample sizes, minimizing confounding factors, or focusing on distributions rather than means. Given a fixed budget for sampling, researchers can maximize statistical power by focusing on one treatment type of interest (Battaglia et al., 2008, van Mantgem et al., 2016, Johnston et al., 2021). Additionally, synthetic analyses and meta-analyses can reduce uncertainty by aggregating data or results from multiple studies (Lortie, 2014, Davis et al., 2024). We also

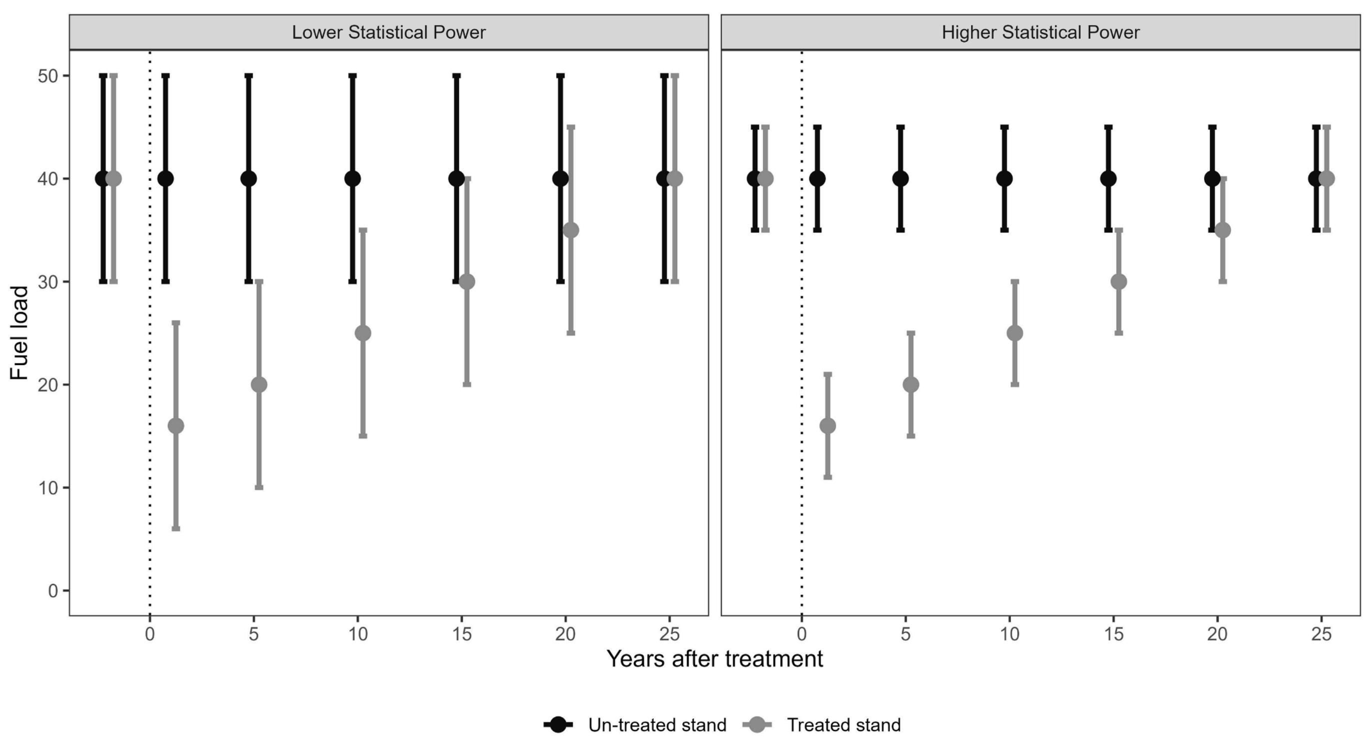

Fig. 4. Hypothetical demonstration of statistical power's influence on estimating treatment longevity. Left and right panels differ only in the level of statistical uncertainty in mean fuel loads over time. Dots represent mean fuel loads, lines bounded by ticks represent confidence intervals reflecting a researcher-chosen alpha level. If treatment longevity were determined by statistical significance, and the confidence interval overlap is used as determinant of statistical significance, a treatment would be effective for 5 years in the lower statistical power scenario and for 15 years in the higher statistical power scenario. Simplifying assumptions in this example include a static fuel load in the un-treated stands, linear increase of fuel loads with time since treatment in the treated stands, and identical statistical power for the un-treated and treated stands.

encourage a broader acceptance of uncertainty, interpreting results within the context of prior research, and being mindful of the many factors that affect statistical uncertainty including variance, sample size, effect size, and alpha value (Nakagawa and Cuthill, 2007, Shieh, 2019, Wasserstein et al., 2019). For example, low statistical power and wide confidence intervals could result from random sampling error, sample size limitations, or omission of important drivers of variation. Explicitly considering possible causes of low statistical power may improve interpretation of results and guide follow-up studies (Wasserstein et al., 2019). Furthermore, focusing on the distributions of key response variables rather than just central tendency measures can help align statistical analyses with the range of characteristics exhibited by dry forests (Churchill et al., 2013, Hood et al., 2022).

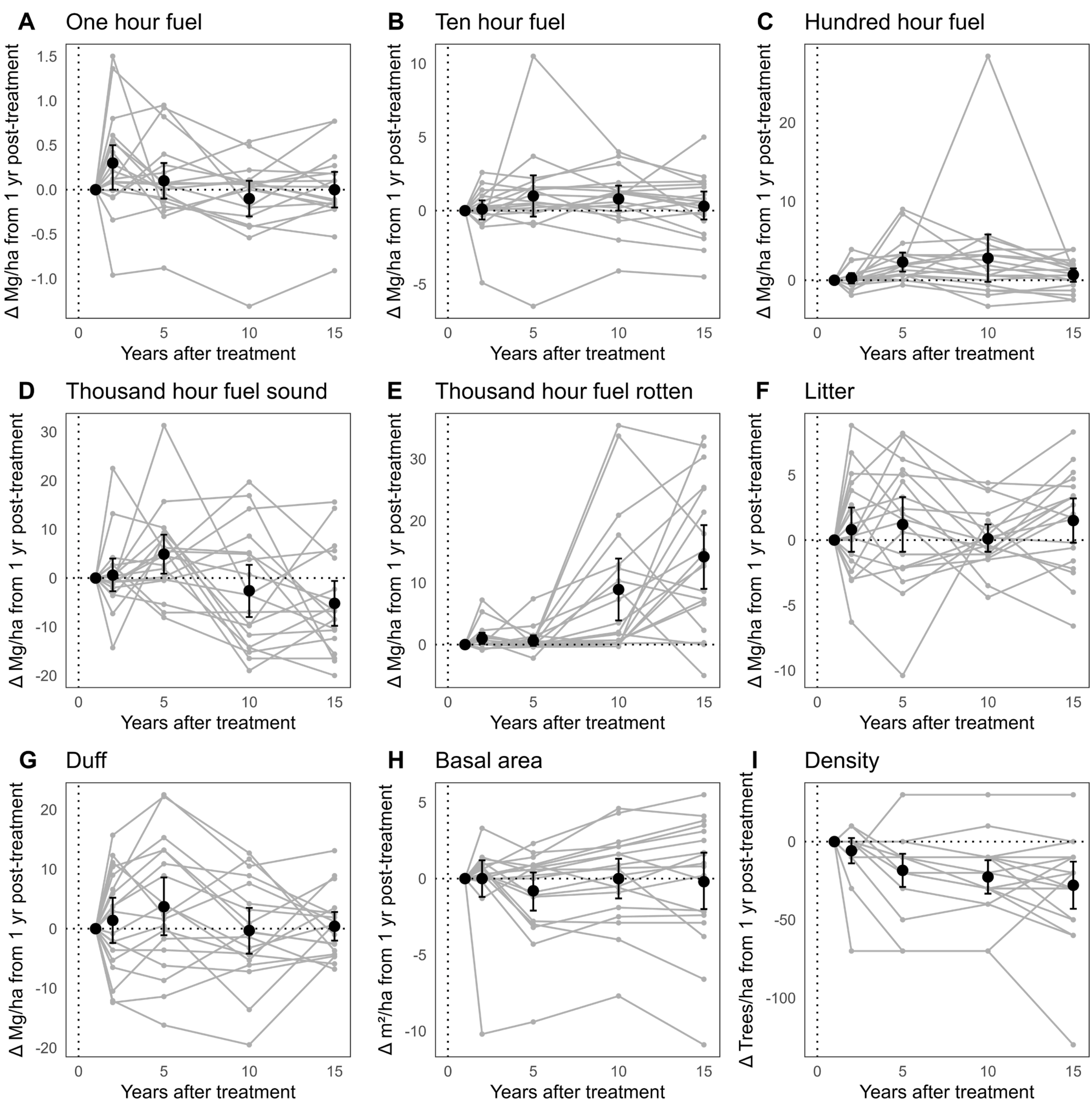

Fig. 5. Fuel profile and stand structure trajectories over time showing variable and nonlinear responses with time since treatment. Data are from 19 permanent plots sampled repeatedly at identical intervals after thin-plus-burn treatments (Radcliffe, 2024). The values at each sample period are expressed relative to short-term treatment values (1 year following treatment). Black dots represent means within time periods, black bars represent 95 % confidence intervals around those means. Gray lines show the trajectories of individual plots; lines connect measurements but are not intended to imply linear changes between sample periods. Vertical dotted lines represent the time of burn implementation in the "thin-plus-burn" sequence. Data are from the National Park Service Fire Effects Monitoring Program at the North Cascades and Lake Roosevelt National Recreation Areas of Washington state (USDI National Park Service, 2003).

5. Exploring within-treatment drivers of long-term responses

5.1. Context

High within- and among-stand variability in site conditions ("inherited factors") and treatment details ("regimes") can drive large variability in treatment effects and outcomes (Tinkham et al., 2016, Dudney et al., 2021, Zald et al., 2024, Radcliffe et al., 2024). Examples of inherited factors are pre-treatment stand structure and site productivity (Reinhardt et al., 2008). Pre-treatment stand structure reflects past management, disturbance, and abiotic conditions, and may affect fuel profile and stand structure responses to treatment over time (Radcliffe et al., 2024, Zald et al., 2024). Vegetation on more productive sites often regenerates, grows, and decomposes more rapidly, which may reduce long-term treatment effectiveness (Jain et al., 2012, Martinson and Omi, 2013, Francis et al., 2018, Ex et al., 2019). Treatment-regime drivers include treatment intensity and interactions of multiple treatments or disturbances over time. Treatment intensity can be quantified as the amount of fuel removed during treatment and measured as the change between pre-treatment and immediate post-treatment values for responses such as canopy cover (Dudney et al., 2021, Zald et al., 2024) or with vegetation change indices (Radcliffe et al., 2024). Information about compounding effects of multiple treatments or disturbances over time is vital to comprehensive treatment planning (Crotteau et al., 2018, Hood et al., 2022) and is becoming more feasible to study with sustained monitoring at long-term study sites (Bernal et al., 2025, Nagelson et al., 2025).

5.2. Recommendations

We encourage research focused on the long-term effects of within-treatment drivers, such as the hypothesized tradeoff between treatment intensity and treatment longevity (Jain et al., 2012, Zald et al., 2024) and the long-term interaction of treatment intensity and site productivity (Ex et al., 2019, Fialko et al., 2020). Studies designed to test within-treatment drivers may encompass broad environmental and management gradients, in contrast to prevailing experimental approaches seeking to minimize variation within treatment types (Puettmann et al., 2009, McIver and Weatherspoon, 2010). Researchers could analyze one treatment type at a time to focus sampling and conceptual efforts on within-treatment drivers (Battaglia et al., 2008, van Mantgem et al., 2016). Exploratory analyses evaluating different methods to quantify within-treatment drivers could support efficacy and consistency among studies.

6. Increase the frequency of post-treatment sampling

6.1. Context

Increased sampling frequency in long-term monitoring is necessary to understand shapes of fuel trajectories following treatment. Many published permanent-plot studies characterize long-term responses with a single long-term measurement period (Hood et al., 2020, Rossman et al., 2020, Dudney et al., 2021, Morici and Bailey, 2021, Roccaforte et al., 2024, Radcliffe et al., 2024). While this approach provides important insights at snapshots in time, it has limited ability to clarify how fuel trajectories change with time since treatment (Hanan et al., 2022). Different fuel components likely have different post-treatment trajectories (Fig. 5). Fine woody surface fuel, an important driver of surface fire behavior, is particularly dynamic and likely to show non-linear patterns following treatment (Fig. 5) as it is rapidly deposited from trees injured or killed during treatment (Keane, 2015) but decomposes rapidly due to its high surface area to volume ratio (Kennedy et al., 2021, Johnston et al., 2021). The shape of post-treatment trajectories (e.g., sustained, sigmoidal, or convex; Fig. 6) has direct implications for scheduling treatment maintenance. For example, a sigmoidal response may suggest that maintenance actions could be timed to follow rapid fuel accumulation as high fuel loading will be asymptotic (Fig. 6). Conversely, a convex response may suggest that maintenance actions could be delayed as high fuel loading is temporary (Fig. 6), in which case resources may be better spent on treating a formerly un-treated unit. Asymptotes and sustained treatment effects are unlikely over very long timescales as forest succession and climatic changes unfold, but may be useful heuristics at the decadal scales of treatment maintenance planning.

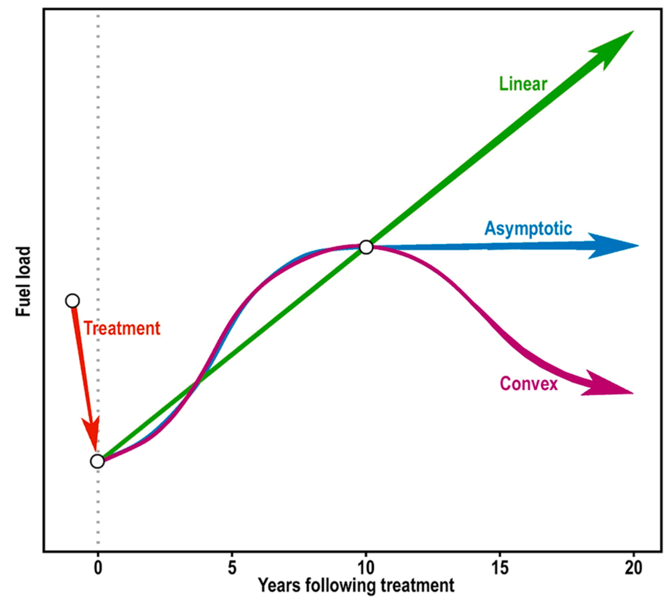

Fig. 6. Hypothetical demonstration of the limitations of infrequent remeasurement, with three possible trajectories of fuel profile and stand structure responses to treatment over time. The horizontal axis shows time since treatment, with the dotted vertical line representing the time of treatment implementation. The vertical axis represents the quantity of a fuel component of interest. The open circles identify three remeasurements as in a typical data collection schedule for treatment longevity studies. Note that it is impossible to distinguish trajectories from these limited data, and that the asymptotic and convex trajectories diverge after the last measurement. Pre-treatment sample period is presented to illustrate common study designs.

6.2. Recommendations

We encourage measuring post-treatment responses at more frequent intervals. One way to reduce the cost of frequent monitoring is to alter the temporal resolution at which different response variables are measured. For example, fine woody surface fuel may be more dynamic within ten years of treatment than coarse woody surface fuel (Fig. 5), so researchers may choose to measure fine woody surface fuel more frequently. This is analogous to the spatial scaling of fuel sizes, whereby smaller fuel components are expected to vary over finer spatial scales and therefore are sampled over finer spatial scales (Brown, 1974, Keane et al., 2012, 2016, Vakili et al., 2016). Chronosequence studies in which units are treated at different times are valuable for assessing the temporal dynamics of fuels (Battaglia et al., 2008, Chiono et al., 2012), though they have well-recognized limitations of confounding environmental variation among units (Foster and Tilman 2000).

7. Incorporate spatial heterogeneity into long-term analyses

7.1. Context

Spatial heterogeneity of fuel loads and forest structure affects resilience to contagious disturbances (Larson and Churchill, 2012, Koontz et al., 2020, Jeronimo et al., 2020, Hoffman et al., 2023), but changes in post-treatment spatial heterogeneity remain largely unstudied (Larson and Churchill, 2012, Hagmann et al., 2021). Treatment prescriptions can directly and often intentionally increase within-stand heterogeneity by creating canopy gaps and patches of low surface and ladder fuel (Churchill et al., 2013, Knapp et al., 2017, Stephens et al., 2021) or can reduce within-stand heterogeneity if they enforce consistent spacing between trees (Puettmann et al., 2009, Fahey et al., 2018). However, little work has examined the long-term effects of treatments on within-stand heterogeneity of fuel profiles and stand structure. For example, treated stands may become less heterogeneous over time if vegetation responses even out differences between more-intensely and less-intensely treated patches. Alternatively, it is also plausible that treated stands become more heterogeneous over time if differences in treatment intensity create fine-scale variation in successional pathways. Treatment regimes and inherited factors, discussed above, are likely to affect patterns of within-stand and among-stand heterogeneity in treated dry forests.

7.2. Recommendations

We encourage incorporating spatial heterogeneity as a response of interest in long-term treatment studies, and analyzing multiple spatial scales of heterogeneity (e.g., within-plot, within-stand, and among-stand) where feasible. Heterogeneity can be explored in existing field studies using approaches such as ordination or indices such as coefficient of variation (Radcliffe, 2024), and new studies can be explicitly designed to study heterogeneity by measuring the spatial distribution of fuel profiles and stand structure (Keane et al., 2012, 2016, Vakili et al., 2016). Studies that use repeat-measures data to quantify trends in heterogeneity over time would be especially useful. In addition to plot-based studies, researchers can apply technologically intensive methods of quantifying spatial heterogeneity. These could include aerial LiDAR (Jeronimo et al., 2019, Kane et al., 2019, Chamberlain et al., 2023), terrestrial LiDAR (Richardson et al., 2014, Chen et al., 2016), or physics-based fire modelling (Ritter et al., 2023, Bonner et al., 2024, Atchley et al., 2024).

8. Additional considerations for treatment maintenance planning

Our focus here is on changes of fuel profiles and stand structure following commonly studied treatments, but many other aspects of dry forest ecology, management, and research are relevant to treatment maintenance planning (Fig. 3). These include natural disturbances, additional treatment types, additional ecological values, and data archiving.

Natural disturbances, especially wildfire, are increasingly important in dry forest restoration planning (Laughlin et al., 2023). Natural disturbances can affect subsequent wildfire behavior (Parks et al., 2015, Prichard et al., 2017, Tortorelli et al., 2024), and create opportunities for follow-up fuel reduction and ecological restoration treatments (Churchill et al., 2022, Larson et al., 2022, Greenler et al., 2023). As for fuel treatments, long-term responses to natural disturbances (Schoennagel et al., 2004, Stevens-Rumann et al., 2012, Dunn and Bailey, 2015) and to post-disturbance management (Nemens et al., 2019, Leverkus et al., 2021, Cansler et al., 2022a) are studied less often than short-term responses (e.g., Johnson et al., 2020). Studies that evaluate how treatments greater than 10 years old affect wildfire behavior are particularly valuable (Cansler et al., 2022b, Davis et al., 2024), especially when there are opportunities to incorporate field data (Brodie et al., 2024).

Less-studied treatment types such as mastication (Kreye et al., 2014, Reed et al., 2020, Wozniak et al., 2020), livestock grazing (Kerby et al., 2007, Batcheler et al., 2024), and pile-burning (Rhoades and Fornwalt, 2015, Mott et al., 2021) also impact fuel profiles. We expect that our study design considerations and opportunities apply to the full range of treatment types used in dry forests.

Factors not directly affecting potential wildfire behavior are understudied in fuel treatment research (Kalies and Yocom Kent, 2016), and merit further research. Myriad ecological values and services other than fuel reduction are important for treatment planning, including biodiversity, carbon, soil, water, food, timber, aesthetics, and spirituality (Converse et al., 2006, Fontaine and Kennedy, 2012, Chiono et al., 2017, Franklin et al., 2018, Wynecoop et al., 2019). Furthermore, cost-benefit analyses are rarely incorporated into studies of long-term treatment effects but are critical because treatment longevity is a key variable affecting the overall cost to benefit ratio for a treatment (Finney et al., 2007, Jain et al., 2012, Barnett et al., 2016, Hunter and Taylor, 2022, Stephens et al., 2024).

Quality data archiving, metadata, and access are crucial to facilitating understanding of long-term treatment effects, as multiple generations of researchers are often required to complete long-term treatment studies (e.g., Youngblood et al., 2008, Morici and Bailey, 2021). Archiving data from short-term treatment studies will facilitate future long-term treatment study and comparison of future maintenance treatment outcomes with true pre-treatment conditions (Bernal et al., 2025). Archiving long-term data may facilitate greater understanding of trajectories over time and allow for future revisiting of wildfire models with changes in management goals or advances in wildfire modelling techniques. Uploading data and metadata to public repositories will facilitate synthetic analyses of long-term treatment effects across sites and may catalyze new insights (Reichman et al., 2011).

Finally, archived and accessible treatment histories are crucial for facilitating analyses of long-term treatment effects. For example, remote sensing studies of treatment effects require accurate and detailed mapping of treatment activity (Knight et al., 2022). Accurate treatment tracking may be especially crucial for understanding complex disturbance histories as multiple treatments and disturbances interact over time.

9. Conclusions

New approaches to conceptualizing and studying treatment longevity are needed and we highlight several opportunities for research innovations in this area. If incorporated into future studies and adaptive management plans, these opportunities would directly benefit dry forest stewardship by improving understanding of potential wildfire behavior in treated landscapes and informing treatment maintenance planning. Ultimately, more efficient treatment maintenance may increase dry forest resilience to wildfire in a changing climate.

CRediT authorship contribution statement

Radcliffe Don C.: Writing – review & editing, Writing – original draft, Visualization, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Bakker Jonathan D.:** Writing – review & editing, Visualization, Funding acquisition, Conceptualization. **Churchill Derek J.:** Writing – review & editing, Visualization, Funding acquisition, Conceptualization. **Van Pelt Robert:** Writing – review & editing, Visualization, Conceptualization. **Harvey Brian J.:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122761.

Data availability

Data will be made available on request.

References

Agee, J.K., Lolley, M.R., 2006. Thinning and prescribed fire effects on fuels and potential fire behavior in an Eastern Cascades forest, Washington, USA. Fire Ecol. 2, 3–19.

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manag. 211, 83–96.

Ager, A.A., Day, M.A., McHugh, C.W., Short, K., Gilbertson-Day, J., Finney, M.A., Calkin, D.E., 2014. Wildfire exposure and fuel management on western US national forests. J. Environ. Manag. 145, 54–70.

Atchley, A.L., Hoffman, C.M., Bonner, S.R., Ritter, S.M., O'Brien, J., Linn, R.R., 2024. Evaluating crown scorch predictions from a computational fluid dynamics wildland fire simulator. Fire Ecol. 20, 71.

Baguley, T., 2004. Understanding statistical power in the context of applied research. Appl. Ergon. 35, 73–80.

Barnett, K., Parks, S.A., Miller, C., Naughton, H.T., 2016. Beyond fuel treatment effectiveness: characterizing interactions between fire and treatments in the US. Forests 7, 237.

Batcheler, M., Smith, M.M., Swanson, M.E., Ostrom, M., Carpenter-Boggs, L., 2024. Assessing silvopasture management as a strategy to reduce fuel loads and mitigate wildfire risk. Sci. Rep. 2024 14, 5954.

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

Bernal, A.A., Stephens, S.L., Callaham, M.A., Collins, B.M., Crotteau, J.S., Dickinson, M.B., Hagan, D.L., Hedges, R., Hood, S.M., Hutchinson, T.F., Taylor, M.K., Coates, T.A., 2025. The national Fire and Fire Surrogate study: Effects of fuel treatments in the Western and Eastern United States after 20 years. Ecol. Appl. 35, e70003.

Bonner, S.R., Hoffman, C.M., Linn, R.R., Tinkham, W.T., Atchley, A.L., Sieg, C.H., Varner, J.M., O'Brien, J.J., Hiers, J.K., 2024. Forest structural complexity and ignition pattern influence simulated prescribed fire effects. Fire Ecol. 20, 82.

Brodie, E.G., Knapp, E.E., Brooks, W.R., Drury, S.A., Ritchie, M.W., 2024. Forest thinning and prescribed burning treatments reduce wildfire severity and buffer the impacts of severe fire weather. Fire Ecol. 20, 17.

Brown, J. 1974. Handbook for inventorying downed woody material. General Technical Report INT-16. USDA Forest Service, Ogden.

Brown, J.K., E.D. Reinhardt, K.A. Kramer. 2003. Coarse woody debris: managing benefits and fire hazard in the recovering forest. General Technical Report RMRS-GTR105. USDA Forest Service, Ogden.

Busse, M., Gerrard, R., 2020. Thinning and burning effects on long-term litter accumulation and function in young ponderosa pine forests. For. Sci. 66, 761–769.

Cansler, C.A., Kane, V.R., Bartl-Geller, B.N., Churchill, D.J., Hessburg, P.F., Povak, N.A., Lutz, J.A., Kane, J., Larson, A.J., 2022a. Postfire treatments alter forest canopy structure up to three decades after fire. For. Ecol. Manag. 505, 119872.

Cansler, C.A., Kane, V.R., Hessburg, P.F., Kane, J.T., Jeronimo, S.M.A., Lutz, J.A., Povak, N.A., Churchill, D.J., Larson, A.J., 2022b. Previous wildfires and management treatments moderate subsequent fire severity. For. Ecol. Manag. 504, 119764.

Chamberlain, C.P., Cova, G.R., Cansler, C.A., North, M.P., Meyer, M.D., Jeronimo, S.M.A., Kane, V.R., 2023. Consistently heterogeneous structures observed at multiple spatial scales across fire-intact reference sites. For. Ecol. Manag. 550, 121478.

Chamberlain, C.P., Meigs, G.W., Churchill, D.J., Kane, J.T., Sanna, A., Begley, J.S., Prichard, S.J., Kennedy, M.C., Bienz, C., Haugo, R.D., Smith, A.C., Kane, V.R., Cansler, C.A., 2024. Learning from wildfires: a scalable framework to evaluate treatment effects on burn severity. Ecosphere 15, e70073.

Chen, Y., Zhu, X., Yebra, M., Harris, S., Tapper, N., 2016. Strata-based forest fuel classification for wild fire hazard assessment using terrestrial LiDAR. J. Appl. Remote Sens. 10, 046025.

Chiono, L.A., Fry, D.L., Collins, B.M., Chatfield, A.H., Stephens, S.L., 2017. Landscape-scale fuel treatment and wildfire impacts on carbon stocks and fire hazard in California spotted owl habitat. Ecosphere 8, e01648.

Chiono, L.A., O'Hara, K.L., De Lasaux, M.J., Nader, G.A., Stephens, S.L., 2012. Development of vegetation and surface fuels following fire hazard reduction treatment. Forests 3, 700–722.

Churchill, D.J., Jeronimo, S.M.A., Hessburg, P.F., Cansler, C.A., Povak, N.A., Kane, V.R., Lutz, J.A., Larson, A.J., 2022. Post-fire landscape evaluations in Eastern Washington, USA: assessing the work of contemporary wildfires. For. Ecol. Manag. 504, 119796.

Churchill, D.J., Larson, A.J., Dahlgreen, M.C., Franklin, J.F., Hessburg, P.F., Lutz, J.A., 2013. Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. For. Ecol. Manag. 291, 442–457.

Clark, S.A., Archer, J.N., Stephens, S.L., Collins, B.M., Hankins, D.L., 2024. Realignment of federal environmental policies to recognize fire's role. Fire Ecol. 20, 1–16.

Converse, S.J., White, G.C., Farris, K.L., Zack, S., 2006. Small mammals and forest fuel reduction: national-scale responses to fire and fire surrogates. Ecol. Appl. 16, 1717–1729.

Crotteau, J.S., Keyes, C.R., Hood, S.M., Affleck, D.L.R., Sala, A., 2018. Fuel dynamics after a bark beetle outbreak impacts experimental fuel treatments. Fire Ecol. 14, 13.

Davis, K.T., Peeler, J., Fargione, J., Haugo, R.D., Metlen, K.L., Robles, M.D., Woolley, T., 2024. Tamm review: a meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the Western US. For. Ecol. Manag. 561, 121885.

Donato, D.C., Harvey, B.J., Romme, W.H., Simard, M., Turner, M.G., 2013. Bark beetle effects on fuel profiles across a range of stand structures in Douglas-fir forests of greater Yellowstone. Ecol. Appl. 23, 3–20.

Dudney, J., York, R.A., Tubbesing, C.L., Roughton, A.T., Foster, D., Stephens, S.L., Battles, J.J., 2021. Overstory removal and biological legacies influence long-term forest management outcomes on introduced species and native shrubs. For. Ecol. Manag. 491, 119149.

Dunn, C.J., Bailey, J.D., 2015. Temporal fuel dynamics following high-severity fire in dry mixed conifer forests of the eastern Cascades, Oregon, USA. Int. J. Wildland Fire 24, 470.

Ex, S.A., Ziegler, J.P., Tinkham, W.T., Hoffman, C.M., 2019. Long-term impacts of fuel treatment placement with respect to forest cover type on potential fire behavior across a mountainous landscape. Forests 10, 438.

Fahey, R.T., Alveshere, B.C., Burton, J.I., D'Amato, A.W., Dickinson, Y.L., Keeton, W.S., Kern, C.C., Larson, A.J., Palik, B.J., Puettmann, K.J., Saunders, M.R., Webster, C.R., Atkins, J.W., Gough, C.M., Hardiman, B.S., 2018. Shifting conceptions of complexity in forest management and silviculture. For. Ecol. Manag. 421, 59–71.

Falk, D.A., 2006. Process-centered restoration in a fire-adapted ponderosa pine forest. J. Nat. Conserv. 14, 140–151.

Fialko, K., Ex, S., Wolk, B.H., 2020. Ecological niches of tree species drive variability in conifer regeneration abundance following fuels treatments. For. Ecol. Manag. 476, 118475.

Finney, M.A., Seli, R.C., McHugh, C.W., Ager, A.A., Bahro, B., Agee, J.K., 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. Int. J. Wildland Fire 16, 712.

Fontaine, J.B., Kennedy, P.L., 2012. Meta-analysis of avian and small-mammal response to fire severity and fire surrogate treatments in U.S. fire-prone forests. Ecol. Appl. 22, 1547–1561.

Francis, D., Ex, S., Hoffman, C., 2018. Stand composition and aspect are related to conifer regeneration densities following hazardous fuels treatments in Colorado, USA. For. Ecol. Manag. 409, 417–424.

Franklin, J.F., Johnson, N.K., Johnson, D.L., 2018. Ecological forest management, First edition. Waveland Press, Long Grove.

Fulé, P.Z., Crouse, J.E., Roccaforte, J.P., Kalies, E.L., 2012. Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? For. Ecol. Manag. 269, 68–81.

Fulé, P.Z., Sánchez Meador, A.J., Moore, M.M., Covington, W.W., Kolb, T.E., Huffman, D.W., Normandin, D.P., Roccaforte, J.P., 2022. Forest restoration treatments increased growth and did not change survival of ponderosa pines in severe drought, Arizona. Ecol. Appl. 32, e2717.

Goodwin, M.J., North, M.P., Zald, H.S.J., Hurteau, M.D., 2018. The 15-year post-treatment response of a mixed-conifer understory plant community to thinning and burning treatments. For. Ecol. Manag. 429, 617–624.

Greenler, S.M., Dunn, C.J., Johnston, J.D., Reilly, M.J., Merschel, A.G., Hagmann, R.K., Bailey, J.D., 2023. Too hot, too cold, or just right: can wildfire restore dry forests of the interior Pacific Northwest? PLOS ONE 18, e0281927.

Greenler, S.M., Lake, F.K., Tripp, W., McCovey, K., Tripp, A., Hillman, L.G., Dunn, C.J., Prichard, S.J., Hessburg, P.F., Harling, W., Bailey, J.D., 2024. Blending indigenous and western science: quantifying cultural burning impacts in Karuk Aboriginal territory. Ecol. Appl. 34, e2973.

Hagmann, R.K., Hessburg, P.F., Prichard, S.J., Povak, N.A., Brown, P.M., Fulé, P.Z., Keane, R.E., Knapp, E.E., Lydersen, J.M., Metlen, K.L., Reilly, M.J., Meador, A.J.S., Stephens, S.L., Stevens, J.T., Taylor, A.H., Yocom, L.L., Battaglia, M.A., Churchill, D.

J., Daniels, L.D., Falk, D.A., Henson, P., Johnston, J.D., Krawchuk, M.A., Levine, C. R., Meigs, G.W., Merschel, A.G., North, M.P., Safford, H.D., Swetnam, T.W., Waltz, A. E.M., 2021. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. Ecol. Appl., e02431

Hanan, E.J., Kennedy, M.C., Ren, J., Johnson, M.C., Smith, A.M.S., 2022. Missing climate feedbacks in fire models: limitations and uncertainties in fuel loadings and the role of decomposition in fine fuel accumulation. J. Adv. Model. Earth Syst. 14, e2021MS002818.

Haugo, R.D., Kellogg, B.S., Cansler, C.A., Kolden, C.A., Kemp, K.B., Robertson, J.C., Metlen, K.L., Vaillant, N.M., Restaino, C.M., 2019. The missing fire: quantifying human exclusion of wildfire in Pacific Northwest forests, USA. Ecosphere 10, e02702.

Hessburg, P.F., Churchill, D.J., Larson, A.J., Haugo, R.D., Miller, C., Spies, T.A., North, M.P., Povak, N.A., Belote, R.T., Singleton, P.H., Gaines, W.L., Keane, R.E., Aplet, G.H., Stephens, S.L., Morgan, P., Bisson, P.A., Rieman, B.E., Salter, R.B., Reeves, G.H., 2015. Restoring fire-prone Inland Pacific landscapes: seven core principles. Landsc. Ecol. 30, 1805–1835.

Hessburg, P.F., Miller, C.L., Parks, S.A., Povak, N.A., Taylor, A.H., Higuera, P.E., Prichard, S.J., North, M.P., Collins, B.M., Hurteau, M.D., Larson, A.J., Allen, C.D., Stephens, S.L., Rivera-Huerta, H., Stevens-Rumann, C.S., Daniels, L.D., Gedalof, Z., Gray, R.W., Kane, V.R., Churchill, D.J., Hagmann, R.K., Spies, T.A., Cansler, C.A., Belote, R.T., Veblen, T.T., Battaglia, M.A., Hoffman, C., Skinner, C.N., Safford, H.D., Salter, R.B., 2019. Clim., Environ., Disturb. Hist. Gov. Resil. West. North Am. For. Front. Ecol. Evol. 7, 239.

Hoffman, C.M., Ziegler, J.P., Tinkham, W.T., Hiers, J.K., Hudak, A.T., 2023. A comparison of four spatial interpolation methods for modeling fine-scale surface fuel load in a mixed conifer forest with complex terrain. Fire 6, 216.

Hood, S.M., Crotteau, J.S., Cleveland, C.C., 2024. Long-term efficacy of fuel reduction and restoration treatments in Northern Rockies dry forests. Ecol. Appl., e2940

Hood, S.M., Keyes, C.R., Bowen, K.J., Lutes, D.C., Seielstad, C., 2020. Fuel treatment longevity in ponderosa pine-dominated forest 24 years after cutting and prescribed burning. Front. For. Glob. Change 3, 78.

Hood, S.M., Varner, J.M., Jain, T.B., Kane, J.M., 2022. A framework for quantifying forest wildfire hazard and fuel treatment effectiveness from stands to landscapes. Fire Ecol. 18, 1–12.

Hunter, M.E., Taylor, M.H., 2022. The economic value of fuel treatments: a review of the recent literature for fuel treatment planning. Forests 13, 2042.

Jain, T.B., M.A. Battaglia, H.S. Han, R.T. Graham, C.R. Keyes, J.S. Fried, and J.E. Sandquist. 2012. A comprehensive guide to fuel management practices for dry mixed conifer forests in the northwestern United States General Technical Report RMRS-GTR-292, 331. USDA Forest Service, Rocky Mountain Research Station, Fort Collins.

Jeronimo, S.M.A., Kane, V.R., Churchill, D.J., Lutz, J.A., North, M.P., Asner, G.P., Franklin, J.F., 2019. Forest structure and pattern vary by climate and landform across active-fire landscapes in the montane Sierra Nevada. For. Ecol. Manag. 437, 70–86.

Jeronimo, S.M.A., Lutz, J.A., R. Kane, V., Larson, A.J., Franklin, J.F., 2020. Burn weather and three-dimensional fuel structure determine post-fire tree mortality. Landsc. Ecol. 1–20.

Johnson, M.C., Kennedy, M.C., Peterson, D.L., 2011. Simulating fuel treatment effects in dry forests of the western United States: testing the principles of a fire-safe forest. Can. J. For. Res. 41, 1018–1030.

Johnson, M.C., Kennedy, M.C., Harrison, S.C., Churchill, D.J., Pass, J., Fischer, P.W., 2020. Effects of post-fire management on dead woody fuel dynamics and stand structure in a severely burned mixed-conifer forest, in northeastern Washington State, USA. For. Ecol. Manag. 470–471, 118190.

Johnston, J.D., Olszewski, J.H., Miller, B.A., Schmidt, M.R., Vernon, M.J., Ellsworth, L. M., 2021. Mechanical thinning without prescribed fire moderates wildfire behavior in an Eastern Oregon, USA ponderosa pine forest. For. Ecol. Manag. 501, 119674.

Kalies, E.L., Yocom Kent, L.L., 2016. Tamm review: are fuel treatments effective at achieving ecological and social objectives? A systematic review. For. Ecol. Manag. 375, 84–95.

Kane, V.R., Bartl-Geller, B.N., North, M.P., Kane, J.T., Lydersen, J.M., Jeronimo, S.M.A., Collins, B.M., Monika Moskal, L., 2019. First-entry wildfires can create opening and tree clump patterns characteristic of resilient forests. For. Ecol. Manag. 454, 117659.

Keane, R.E., 2015. Wildland fuel fundamentals and applications, First Edition. Springer International Publishing.

Keane, R.E., Bergeron, Y., Gauthier, S., 2016. Spatiotemporal variability of wildland fuels in US Northern Rocky Mountain forests. Forests 7, 129.

Keane, R.E., Burgan, R., Van Wagtendonk, J., 2001. Mapping wildland fuels for fire management across multiple scales: integrating remote sensing, GIS, and biophysical modeling. Int. J. Wildland Fire 10, 301–319.

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

Keifer, M., van Wagtendonk, J.W., Buhler, M., 2006. Long-term surface fuel accumulation in burned and unburned mixed-conifer forests of the central and Southern Sierra Nevada, CA (USA). Fire Ecol. 2, 53–72.

Kennedy, M.C., Johnson, M.C., Harrison, S.C., 2021. Model predictions of postwildfire woody fuel succession and fire behavior are sensitive to fuel dynamics parameters. For. Sci. 67, 30–42.

Kerby, J.D., Fuhlendorf, S.D., Engle, D.M., 2007. Landscape heterogeneity and fire behavior: scale-dependent feedback between fire and grazing processes. Landsc. Ecol. 22, 507–516.

Knapp, E.E., Lydersen, J.M., North, M.P., Collins, B.M., 2017. Efficacy of variable density thinning and prescribed fire for restoring forest heterogeneity to mixed-conifer forest in the central Sierra Nevada, CA. For. Ecol. Manag. 406, 228–241.

Knight, C.A., Tompkins, R.E., Wang, J.A., York, R., Goulden, M.L., Battles, J.J., 2022. Accurate tracking of forest activity key to multi-jurisdictional management goals: a case study in California. J. Environ. Manag. 302, 114083.

Kolden, C.A., 2019. We're not doing enough prescribed fire in the Western United States to mitigate wildfire risk. Fire 2, 30.

Koontz, M.J., North, M.P., Werner, C.M., Fick, S.E., Latimer, A.M., 2020. Local forest structure variability increases resilience to wildfire in dry western U.S. coniferous forests. Ecol. Lett. 23, 483–494.

Kreye, J.K., Brewer, N.W., Morgan, P., Varner, J.M., Smith, A.M.S., Hoffman, C.M., Ottmar, R.D., 2014. Fire behavior in masticated fuels: a review. For. Ecol. Manag. 314, 193–207.

Larson, A.J., Churchill, D., 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. For. Ecol. Manag. 267, 74–92.

Larson, A.J., Jeronimo, S.M.A., Hessburg, P.F., Lutz, J.A., Povak, N.A., Cansler, C.A., Kane, V.R., Churchill, D.J., 2022. Tamm Review: ecological principles to guide post-fire forest landscape management in the Inland Pacific and Northern Rocky Mountain regions. For. Ecol. Manag. 504, 119680.

Laughlin, M.M., Bakker, J.D., Churchill, D.J., Gregory, M.J., DeMeo, T., Alvarado, E.C., Harvey, B.J., 2023. Trends in forest structure restoration need over three decades with increasing wildfire activity in the interior Pacific Northwest US. For. Ecol. Manag. 527, 120607.

Leverkus, A.B., Buma, B., Wagenbrenner, J., Burton, P.J., Lingua, E., Marzano, R., Thorn, S., 2021. Tamm review: does salvage logging mitigate subsequent forest disturbances? For. Ecol. Manag. 481, 118721.

Lieber, R.L., 1990. Statistical significance and statistical power in hypothesis testing. J. Orthop. Res. 8, 304–309.

Lortie, C.J., 2014. Formalized synthesis opportunities for ecology: systematic reviews and meta-analyses. Oikos 123, 897–902.

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

Martinson, E.J., Omi, P.N., 2013. Fuel treatments and fire severity: A meta-analysis. Page Res. Pap. RMRS-RP-103WWW. USDA Forest Service. Rocky Mountain Research Station. Fort Collins.

McIver, J.D., Weatherspoon, C.P., 2010. On conducting a multisite, multidisciplinary forestry research project: lessons from the national fire and fire surrogate study. For. Sci. 56, 4–17.

Merschel, A.G., Beedlow, P.A., Shaw, D.C., Woodruff, D.R., Lee, E.H., Cline, S.P., Comeleo, R.L., Hagmann, R.K., Reilly, M.J., 2021. An ecological perspective on living with fire in ponderosa pine forests of Oregon and Washington: resistance, gone but not forgotten. Trees, For. People 4, 100074.

Morici, K.E., Bailey, J.D., 2021. Long-term effects of fuel reduction treatments on surface fuel loading in the Blue Mountains of Oregon. Forests 12, 1306.

Morrison, M.L., Block, W.M., Strickland, M.D., Collier, B.A., Peterson, M.J., 2008. Wildlife study design, Second edition. Springer, New York.

Mott, C.M., Hofstetter, R.W., Antoninka, A.J., 2021. Post-harvest slash burning in coniferous forests in North America: a review of ecological impacts. For. Ecol. Manag. 493, 119251.

Murphy, J.S., York, R., Rivera Huerta, H., Stephens, S.L., 2021. Characteristics and metrics of resilient forests in the Sierra de San Pedro Martír, Mexico. For. Ecol. Manag. 482, 118864.

Nagelson, P.B., York, R.A., Shoemaker, K.T., Foster, D.E., Stephens, S.L., Bisbing, S.M., 2025. Repeated fuel treatments fall short of fire-adapted regeneration objectives in a Sierra Nevada mixed conifer forest, USA. Ecol. Appl. 35, e3075.

Nakagawa, S., Cuthill, I.C., 2007. Effect size, confidence interval and statistical significance: a practical guide for biologists. Biol. Rev. 82, 591–605.

Nemens, D.G., J.M. Varner, and M.C. Johnson. 2019. Environmental effects of postfire logging: an updated literature review and annotated bibliography. General Technical Report PNW-GTR-975. USDA Forest Service, Pacific Northwest Research Station, Portland.

North, M., Brough, A., Long, J., Collins, B., Bowden, P., Yasuda, D., Miller, J., Sugihara, N., 2015. Constraints on mechanized treatment significantly limit mechanical fuels reduction extent in the Sierra Nevada. J. For. 113, 40–48.

North, M.P., York, R.A., Collins, B.M., Hurteau, M.D., Jones, G.M., Knapp, E.E., Kobziar, L., McCann, H., Meyer, M.D., Stephens, S.L., Tompkins, R.E., Tubbesing, C. L., 2021. Pyrosilviculture needed for landscape resilience of dry western United States forests. J. For. 119, 520–544.

Parks, S.A., Holsinger, L.M., Miller, C., Nelson, C.R., 2015. Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression. Ecol. Appl. 25, 1478–1492.

Prichard, S.J., Hessburg, P.F., Hagmann, R.K., Povak, N.A., Dobrowski, S.Z., Hurteau, M. D., Kane, V.R., Keane, R.E., Kobziar, L.N., Kolden, C.A., North, M., Parks, S.A., Safford, H.D., Stevens, J.T., Yocom, L.L., Churchill, D.J., Gray, R.W., Huffman, D.W., Lake, F.K., Khatri-Chhetri, P., 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. Ecol. Appl. 31, e02433.

Prichard, S.J., Stevens-Rumann, C.S., Hessburg, P.F., 2017. Tamm review: shifting global fire regimes: lessons from reburns and research needs, 396, 217–233.

Puettmann, K.J., Coates, D.K., Messier, C., 2009. A critique of silviculture: managing for complexity. Island Press, Washington D.C.

Radcliffe, D.C., 2024. Dry forest fuel and biodiversity management in the Pacific Northwest. Dissertation, University of Washington, Seattle, Washington.

Radcliffe, D.C., Bakker, J.D., Churchill, D.J., Alvarado, E.C., Peterson, D.W., Laughlin, M. M., Harvey, B.J., 2024. How are long-term stand structure, fuel profiles, and potential fire behavior affected by fuel treatment type and intensity in Interior Pacific Northwest forests? For. Ecol. Manag. 553, 121594.

Reed, W.P., Varner, J.M., Knapp, E.E., Kreye, J.K., 2020. Long-term changes in masticated woody fuelbeds in northern California and southern Oregon, USA. Int. J. Wildland Fire 29, 807–819.
Reichman, O.J., Jones, M.B., Schildhauer, M.P., 2011. Challenges and opportunities of open data in ecology. Science 331, 703–705.
Reinhardt, E.D., Keane, R.E., Calkin, D.E., Cohen, J.D., 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. For. Ecol. Manag. 256, 1997–2006.
Rhoades, C.C., Fornwalt, P.J., 2015. Pile burning creates a fifty-year legacy of openings in regenerating lodgepole pine forests in Colorado. For. Ecol. Manag. 336, 203–209.
Richardson, J.J., Moskal, L.M., Bakker, J.D., 2014. Terrestrial laser scanning for vegetation sampling. Sensors 14, 20304–20319.
Ritter, S.M., Hoffman, C.M., Battaglia, M.A., Linn, R., Mell, W.E., 2023. Vertical and horizontal crown fuel continuity influences group-scale ignition and fuel consumption. Fire 6, 321.
Roccaforte, J.P., Huffman, D.W., Rodman, K.C., Crouse, J.E., Pedersen, R.J., Normandin, D.P., Fulé, P.Z., 2024. Long-term ecological responses to landscape-scale restoration in a western United States dry forest. Restor. Ecol., e14181
Rodman, K.C., Bradford, J.B., Formanack, A.M., Fulé, P.Z., Huffman, D.W., Kolb, T.E., Kuile, A.T.M., Normandin, D.P., Ogle, K., Pedersen, R.J., Schlaepfer, D.R., Stoddard, M.T., Waltz, A.E.M., 2024. Restoration treatments enhance tree growth and alter climatic constraints during extreme drought. Ecol. Appl., e3072
Rossman, A.K., Bakker, J.D., Peterson, D.W., Halpern, C.B., 2020. Long-term effects of fuels treatments, overstory structure, and wildfire on tree regeneration in dry forests of Central Washington. Forests 11, 888.
Schoennagel, T., Veblen, T.T., Romme, W.H., 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. BioScience 54, 661–676.
Schwilk, D.W., Keeley, J.E., Knapp, E.E., McIver, J., Bailey, J.D., Fettig, C.J., Fiedler, C. E., Harrod, R.J., Moghaddas, J.J., Outcalt, K.W., Skinner, C.N., Stephens, S.L., Waldrop, T.A., Yaussy, D.A., Youngblood, A., 2009. The national fire and fire surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecol. Appl. 19, 285–304.
Shieh, G., 2019. Effect size, statistical power, and sample size for assessing interactions between categorical and continuous variables. Br. J. Math. Stat. Psychol. 72, 136–154.
Stephens, S.L., Battaglia, M.A., Churchill, D.J., Collins, B.M., Coppoletta, M., Hoffman, C. M., Lydersen, J.M., North, M.P., Parsons, R.A., Ritter, S.M., Stevens, J.T., 2021. Forest restoration and fuels reduction: convergent or divergent? BioScience 71, 85–101.
Stephens, S.L., Collins, B.M., Roller, G., 2012a. Fuel treatment longevity in a Sierra Nevada mixed conifer forest. For. Ecol. Manag. 285, 204–212.
Stephens, S.L., Foster, D.E., Battles, J.J., Bernal, A.A., Collins, B.M., Hedges, R., Moghaddas, J.J., Roughton, A.T., York, R.A., 2024. Forest restoration and fuels reduction work: different pathways for achieving success in the Sierra Nevada. Ecol. Appl., e2932
Stephens, S.L., Fulé, P.Z., 2005. Western pine forests with continuing frequent fire regimes: possible reference sites for management. J. For. 103, 357–362.
Stephens, S.L., McIver, J.D., Boerner, R.E.J., Fettig, C.J., Fontaine, J.B., Hartsough, B.R., Kennedy, P.L., Schwilk, D.W., 2012b. The effects of forest fuel-reduction treatments in the United States. BioScience 62, 549–560.
Stevens-Rumann, C.S., Sieg, C.H., Hunter, M.E., 2012. Ten years after wildfires: how does varying tree mortality impact fire hazard and forest resiliency? For. Ecol. Manag. 267, 199–208.
Stoddard, M.T., Roccaforte, J.P., Meador, A.J.Sánchez, Huffman, D.W., Fulé, P.Z., Waltz, A.E.M., Covington, W.W., 2021. Ecological restoration guided by historical reference conditions can increase resilience to climate change of southwestern U.S. ponderosa pine forests. For. Ecol. Manag. 493, 119256.
Tinkham, W.T., Hoffman, C.M., Ex, S.A., Battaglia, M.A., Saralecos, J.D., 2016. Ponderosa pine forest restoration treatment longevity: implications of regeneration on fire hazard. Forests 7, 137.
Tortorelli, C.M., Latimer, A.M., Young, D.J.N., 2024. Moderating effects of past wildfire on reburn severity depend on climate and initial severity in Western US forests. Ecol. Appl. 34, e3023.
Urgenson, L.S., Nelson, C.R., Haugo, R.D., Halpern, C.B., Bakker, J.D., Ryan, C.M., Waltz, A.E.M., Belote, R.T., Alvarado, E., 2018. Social perspectives on the use of reference conditions in restoration of fire-adapted forest landscapes. Restor. Ecol. 26, 987–996.
Urgenson, L.S., Ryan, C.M., Halpern, C.B., Bakker, J.D., Belote, R.T., Franklin, J.F., Haugo, R.D., Nelson, C.R., Waltz, A.E.M., 2017. Visions of restoration in fire-adapted forest landscapes: lessons from the collaborative forest landscape restoration program. Environ. Manag. 59, 338–353.
USDA Forest Service, 2022. Confronting the wildfire crisis: a strategy for protecting communities and improving resilience in America's forests. 〈https://www.fs.usda.gov/sites/default/files/Confronting-Wildfire-Crisis.pdf〉.
USDI National Park Service, 2003. Fire monitoring handbook. Fire Management Program Center, National Interagency Fire Center, Boise.
Vaillant, N.M., Noonan-Wright, E.K., Reiner, A.L., Ewell, C.M., Rau, B.M., Fites-Kaufman, J.A., Dailey, S.N., 2015. Fuel accumulation and forest structure change following hazardous fuel reduction treatments throughout California. Int. J. Wildland Fire 24, 361–371.
Vakili, E., Hoffman, C.M., Keane, R.E., Tinkham, W.T., Dickinson, Y., Vakili, E., Hoffman, C.M., Keane, R.E., Tinkham, W.T., Dickinson, Y., 2016. Spatial variability of surface fuels in treated and untreated ponderosa pine forests of the southern Rocky Mountains. Int. J. Wildland Fire 25, 1156–1168.
Wasserstein, R.L., Schirm, A.L., Lazar, N.A., 2019. Moving to a world beyond "$p < 0.05$.". Am. Stat. 73, 1–19.
Woolsey, G.A., Tinkham, W.T., Battaglia, M.A., Hoffman, C.M., 2024. Constraints on mechanical fuel reduction treatments in United States forest service wildfire crisis strategy priority landscapes. J. For. 1–17.
Wozniak, S.S., Strand, E.K., Johnson, T.R., Hulet, A., Roundy, B.A., Young, K., Wozniak, C., Strand, E.K., Johnson, T.R., Hulet, A., Roundy, B.A., Young, K., 2020. Treatment longevity and changes in surface fuel loads after pinyon–juniper mastication. Ecosphere 11, e03226.
Wynecoop, M.D., Morgan, P., Strand, E.K., Sanchez Trigueros, F., 2019. Getting back to fire sumés: exploring a multi-disciplinary approach to incorporating traditional knowledge into fuels treatments. Fire Ecol. 15, 1–18.
Youngblood, A., Wright, C.S., Ottmar, R.D., McIver, J.D., 2008. Changes in fuelbed characteristics and resulting fire potentials after fuel reduction treatments in dry forests of the Blue Mountains, northeastern Oregon. For. Ecol. Manag. 255, 3151–3169.
Zald, H.S.J., May, C.J., Gray, A.N., North, M.P., Hurteau, M.D., 2024. Thinning and prescribed burning increase shade-tolerant conifer regeneration in a fire excluded mixed-conifer forest. For. Ecol. Manag. 551, 121531.