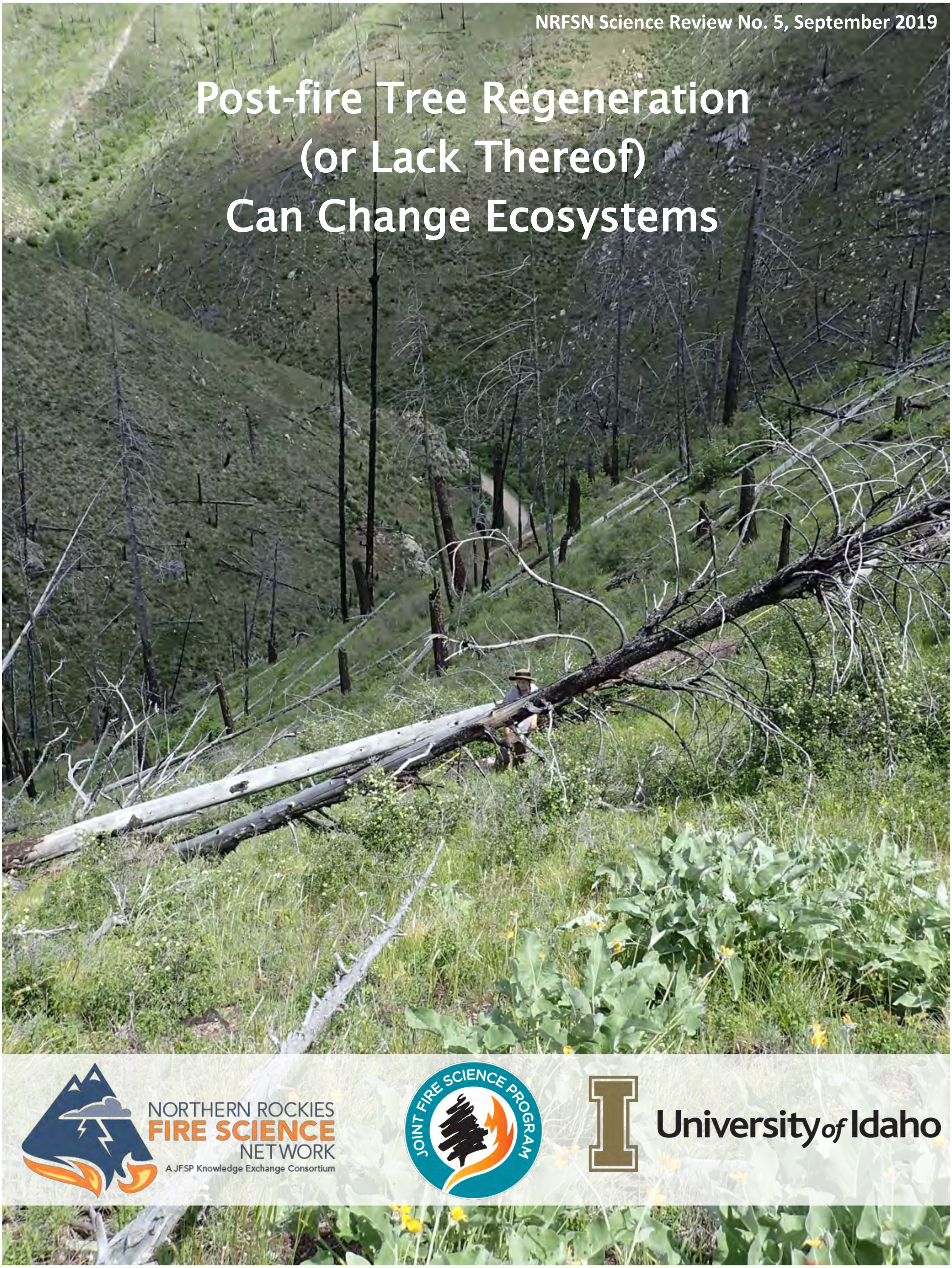
NRFSN Science Review No. 5, September 2019

Post-fire Tree Regeneration (or Lack Thereof) Can Change Ecosystems



NORTHERN ROCKIES FIRE SCIENCE NETWORK
A JFSP Knowledge Exchange Consortium

JOINT FIRE SCIENCE PROGRAM

University of Idaho

Post-fire Tree Regeneration (or Lack Thereof) Can Change Ecosystems

Camille Stevens-Rumann[1], Penelope Morgan[2], Kimberley Davis[3], Kerry Kemp[4], Jarod Blades[5]

[1]Forest and Rangeland Stewardship Department, Colorado State University
[2]Forest, Rangeland, and Fire Science Department, University of Idaho
[3]Department of Ecosystem and Conservation Sciences, University of Montana
[4]The Nature Conservancy of Oregon
[5]Department of Natural Resources and Society, University of Idaho

For questions and comments about this Fire Science Review, contact first author, C. Stevens-Rumann, C.Stevens-Rumann@colostate.edu.

Citation: Stevens-Rumann, C., P. Morgan, K. Davis, K. Kemp, and J. Blades. 2019. Post-fire tree regeneration (or lack thereof) can change ecosystems. Northern Rockies Fire Science Network Science Review No. 5.

Acknowledgements: We would like to thank reviewers: Shelagh Fox, Silviculturist, USDA FS Region 1, Monique Wynecoop, Fire Ecologist, USDA FS Colville National Forest, and Linda Mutch, Science Communication Specialist, NPS, for their time and contributions to this paper. We would also like to thank the USDA FS Rocky Mountain Research Station, University of Idaho Department of Forest, Rangeland, and Fire Sciences, and the University of Montana W.A. Franke College of Forestry and Conservation's Restoration Ecology and Forest Ecology Labs for their support of the Northern Rockies Fire Science Network and this science review. We are grateful for funding from the Joint Fire Science Program Projects 11-S-3-2, 16-1-01-20, 12-3-1-13, and 16-1-01-15.

Layout and Managing Editor: Signe Leirfallom

Science Reviews published by the Northern Rockies Fire Science Network (NRFSN) summarize and review the state-of-knowledge on current topics of importance for fire and fuels management in the Northern Rockies. To view additional science products, find out about upcoming fire- and fuels-related events, and/or contact us with your ideas to facilitate networking and knowledge exchange between scientists and managers, **visit the NRFSN at nrfirescience.org.**

On the cover —
High severity burn in the Frank Church Wilderness Area with little tree regeneration post-fire. Photo courtesy of Ashley Durham.

Introduction

High severity disturbances, such as high severity wildfires, are likely to become major catalysts of forest ecosystem change in response to climate change (Stevens-Rumann et al. 2018, Walker et al. 2018, Davis et al. 2019). As large, uncharacteristic fires become more prevalent, scientists are starting to document a lack of tree regeneration (Fig. 1). In many locations worldwide, but especially across the western US (see review by Stevens-Rumann and Morgan 2019), concern among researchers and managers is mounting given that decades after large fires, many formerly forested sites have so few tree seedlings that the likelihood these locations return to forests is minimal. Instead, these formerly forested sites appear to be transitioning to shrublands, grasslands, or woodlands. There is a combination of events – large patches burned with high severity, few seed source trees nearby, and poor post-fire climate windows – that can often lead to poor regeneration. These events are becoming more frequent, decreasing the windows of opportunity for successful tree regeneration, especially if regeneration doesn't occur soon (within 10 years) post-fire. Postponing replanting at least a couple years post-fire allows for both observations of natural regeneration establishment and the development of some nurse structures such as downed logs or shrub growth that may improve planted seedling survival.

Ecosystems appear to be transitioning most often in recently burned areas on sites that were already relatively warm and dry. Much of the research we present here from the northern Rockies has focused on lower elevation tree species such as ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*); however, in places like Glacier National Park and the Greater Yellowstone Ecosystem, species such as lodgepole pine (*Pinus contorta*), western larch (*Larix occidentalis*), fir (*Abies spp*.) and Engelmann spruce (*Picea engelmanii*) have been studied.

Research Highlights -

- Few trees seedlings have established 9 to 13 years after many large forest fires, especially to replace pre-fire tree densities. Key environmental influences vary.
- Fewer tree seedlings established far (>270 ft (90m)) from living tree seed sources, especially for species with wind or gravity-dispersed seeds.
- Hot, dry climatic conditions in the years after fires resulted in lower tree regeneration.

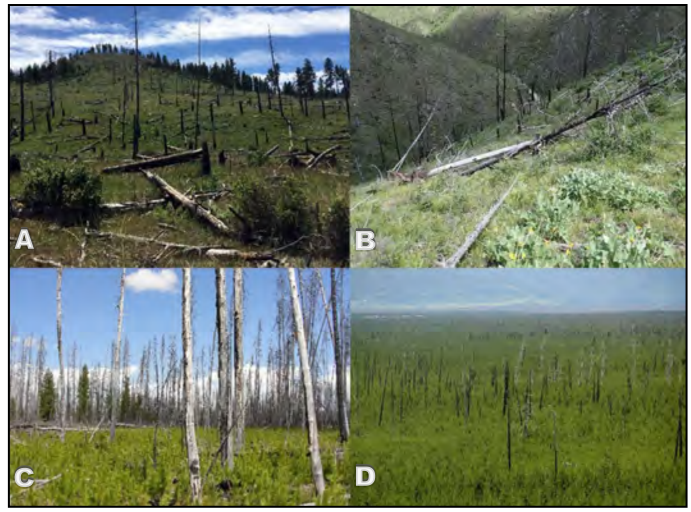


Figure 1. (A) On many warm, dry sites, no or very few tree seedlings have regenerated following large fires. (B) This is sometimes related to distance to seed source, but trees are less likely to successfully establish if climate is too warm and dry. (C) and (D) For lodgepole pine with serotinous cones and for tree species with small, light seeds, seedlings establish in abundance post fire. Photos courtesy of Kimberley Davis.

Why focus on tree regeneration?

This review is focused on tree seedling regeneration for several reasons. First, a high mortality event, like a high-severity wildfire, kills the mature trees needed to maintain forest cover. When fire-caused mortality is minimal, we are less concerned about tree regeneration, but a high severity fire creates the need for tree regeneration if long-term forest cover is desired. Second, high mature tree mortality limits seed availability for the regeneration of most species, especially those that are not serotinous. Third, young trees are more sensitive to soil temperature and drought than established trees (Jackson et al. 2009, Andrus et al. 2018). Older trees may persist through multiple droughts or other suboptimal conditions that kill immature trees. Finally, with changing fire regimes and the potential for increasing frequency of fires, seedlings are more vulnerable to death from subsequent surface fires than are established trees with thicker bark and crowns that may be further above the heat from flames (Agee 1993). We recognize that in many locations forests have increased in density or expanded into areas that were historically persistent meadows and shrublands, representing an unnatural condition where abundant tree regeneration may not be optimal or representative of the historical forest structure (then loss of forests may or may not be of concern). However, with drought, bark beetles, fires and other disturbances resulting in extensive mortality of large trees, the lack of tree regeneration remains a concern.

Where has a lack of tree regeneration been found?

The absence of tree regeneration and a reduction in tree density are occurring at many elevations and latitudes. In the northern Rockies, limited tree regeneration has been documented post fire in sites that range from low elevation ponderosa pine to high elevation subalpine forests (Table 1, Fig. 2), although many areas, particularly at higher elevations, still have sufficient tree regeneration. Other regions around the West also have experienced limited post-fire conifer regeneration in certain forest types, but with a lot of variability between sites (Fig. 3). For example, in mixed conifer forests of southern Oregon and California, different studies have found that between 0-61% of study plots had no conifer regeneration 5 to 28 years following fire (Shatford et al. 2007, Welch et al. 2016, Tepley et al. 2017). Limited post-fire conifer regeneration has also been found in the Colorado Front Range (59% of sampled plots in lower montane forest had no conifer regeneration; Rother & Veblen 2016) and Southwestern ponderosa pine forests (e.g. Savage & Mast 2005; Roccaforte et al. 2012).

Table 1. Studies of post-fire regeneration in the northern Rockies show variability in the percent of plots without conifer regeneration. Differences between studies may arise due to differences in fire severity, forest type, or climate (see below), with some differences arising because of differences in methods, plot size, and time since fire.

Study	Forest Type	Years Since Fire	Plots without conifer regeneration
Kemp et al. 2016	Dry mixed conifer	5-13	26%
Donato et al. 2016	Lower montane	24	13%
Urza & Sibold 2017	Lower subalpine	7-22	7%
Harvey et al 2016	Subalpine	10-19	2%
Stevens-Rumann and Morgan 2016	Dry and moist mixed conifer	7-25	14%

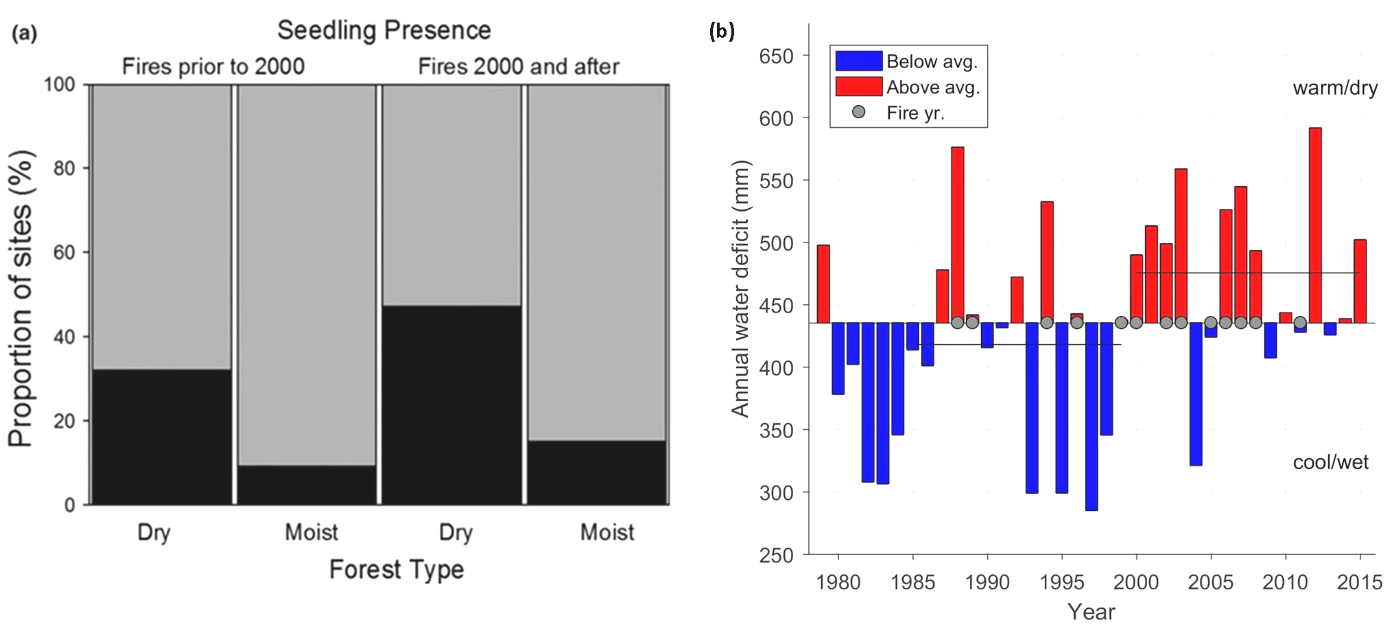


Figure 2. (a) For 62 forest fires in the northern Rocky Mountains in the US sampled 3-28 years since fires occurred, tree seedlings were absent (black) disproportionately in dry forest types, though all forest types had some sites with the presence of seedlings (gray) post fire. Proportion of sites without seedlings increased in dry forests from 30% pre-2000 to 45% post-2000; in moist forests, the change was a 10% increase. Tree regeneration was less successful in dry forests than in moist forests, but especially for fires that burned since year 2000. (b) Sampled sites were warmer and drier after 2000 compared to before. The graph shows 30-yr average mean annual water deficit; red is above average, blue is below average, and gray circles indicate when sampled fires burned; lines above and below indicate 15 year means (1984-1999 and 2000-2015). Adapted from Stevens-Rumann et al. 2018.

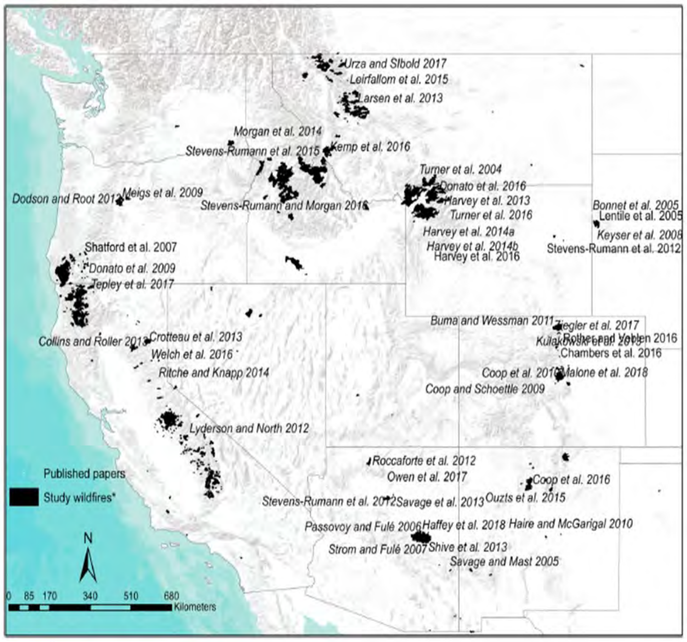


Figure 3. West-wide, assessments of where and when natural regeneration (seedlings not planted) has established 9 to 46 yr after large forest fires. From Stevens-Rumann and Morgan (2019) and see this paper for citations. This was current as of January 2019, though additional papers have been published since.

What is driving the lack of tree regeneration?

Studies documenting low tree regeneration densities are numerous across the West. Although the key environmental influences vary, several major factors emerged. First, the distance a site was from a living tree was very important. At distances >270ft (90m) tree regeneration density was low, especially for species that rely on wind and gravity-dispersed seeds (see examples in Kemp et al. 2016, Urza and Sibold 2017, Stevens-Rumann et al. 2018). Large patches that are burned with high severity often result in long distances to seed sources, suggesting that these patches are less likely to regenerate than small patches burned with high severity. Because they have more surviving tree seed sources, areas burned with moderate (20-70% tree mortality) and low severity (< 20% tree mortality), are more likely to have tree seedlings growing after fires. In this way both burn severity and the size of patches of different burn severities can influence post-fire tree regeneration.

Climate is also an important factor in predicting tree regeneration. Several researchers have documented low tree seedling densities where moisture stress is high. For example, Davis et al. (2019) used ages of tree seedlings from sites across the western US to determine that the warm, dry conditions of recent years have exceeded the thresholds for successful post-fire establishment of ponderosa pine and Douglas-fir tree seedlings on warm, dry sites (Fig. 4 and 5). Using current post-fire establishment patterns, Kemp et al. (2019) predicted that the elevational range of both ponderosa pine and Douglas-fir will need to shift upwards by 300+ ft (100+ m) to keep up with climatic changes over the next 40 years. Even subalpine species can be influenced by climate. Post-fire regeneration densities of both subalpine fir (*Abies lasiocarpa*) and Engelmann spruce were lower in areas that experienced dry conditions in the first three years following fire than in areas that had wetter post-fire weather (Harvey et al. 2016).

Repeated disturbances, microsite conditions, competing vegetation, and topography (aspect, slope, and elevation) also influence tree regeneration, but the relationships of these variables to tree regeneration are less consistent across the western US. Repeated disturbances, especially repeated high severity fires, present a challenge in ecosystems where the time between fires is too short for trees to reach maturity for seed production following a high severity fire (e.g. Turner et al. 2019) and for fire-resistant species to grow to a substantive size to avoid mortality from a low intensity fire (see Prichard et al. 2017 and Stevens-Rumann et al. 2014 for more details on repeated fires). However, to date few places in the western US have experienced extensive reburning, thus the impact of repeated fires is limited in extent, and our knowledge of the ecological effects in many systems is unknown. Competing vegetation, like shrubs, can influence tree regeneration success and growth (e.g. Lyderson and North 2012, Savage et al. 2013, Tepley et al. 2017), especially if tree seedlings don't establish soon after fires. However, in the northern Rockies, studies have not documented as much of an effect from competing vegetation. Topography influences microsite suitability for seedlings. In dry, low elevation forests, post-fire tree seedlings were more abundant on north-facing aspects and at higher elevations (Dodson and Root 2013, Chambers et al. 2016, Lopez-Ortiz et al. 2019), but regeneration patterns may be the opposite in cold forests, where snowpack and colder temperatures are often observed at the highest elevations and on north-facing aspects.

What are the consequences?

The replacement of forests by grasslands or shrublands results in less carbon stored (Liang et al. 2018), shifts habitat for many birds or other organisms, and may impact important local and regional societal values. While we focused here on wildfires, mature trees on many sites globally are

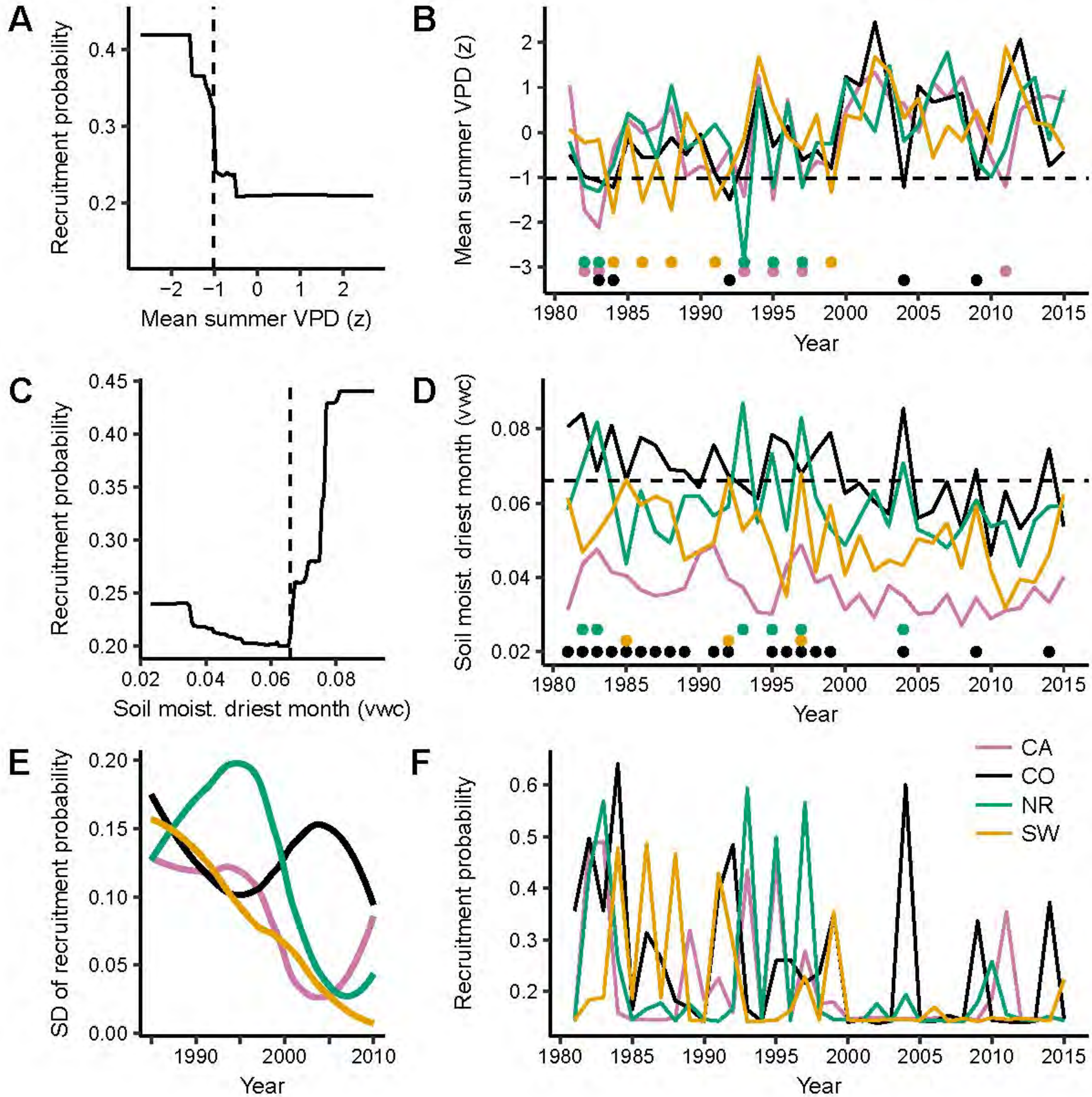


Figure 4. Ponderosa pine seedlings were absent or low in density on many of the sites at low elevations within 33 large fires sampled in California (CA, pink), Colorado (CO, black), the US northern Rockies (NR, green), and the southwestern US (SW, orange) because drought (summer vapor pressure deficit VPD, z score) and soil moisture during the driest month (volumetric water content, vwc) have exceeded thresholds for successful recruitment (A and C), in many years. This is increasingly so in recent years (dots indicate conditions favorable for recruitment, B and D). As a result, recruitment probability of tree seedlings is highly variable year to year (E and F), and very low in recent years. Analyses accounted for effect of burn severity and distance from seed source. From Davis et al. (2019)

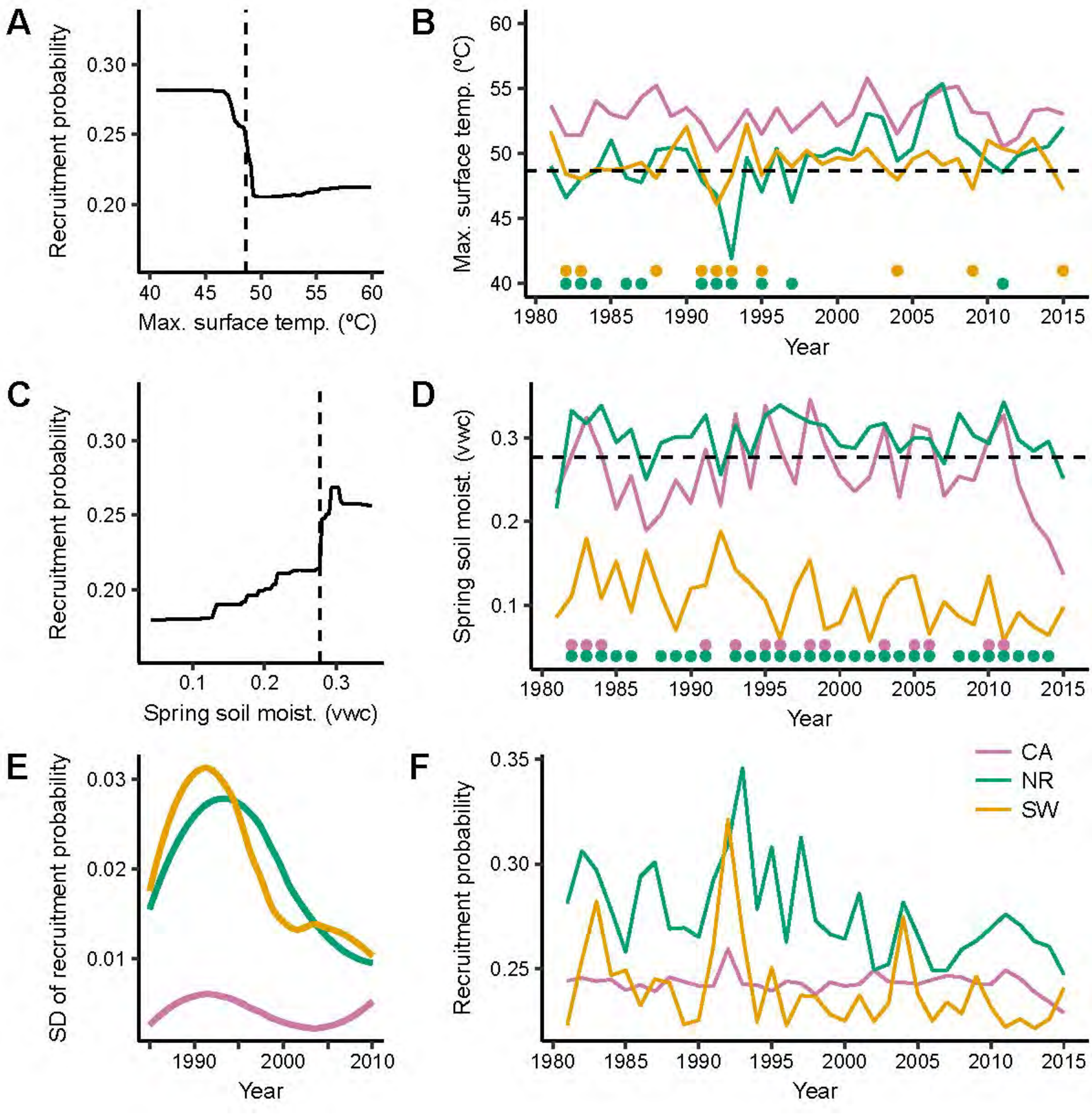


Figure 5. Douglas-fir seedlings were absent or in low density on some of the sites at low elevations within 33 large fires sampled in California (CA, pink), the US northern Rockies (NR, green) and the southwestern US (SW, orange). These sites have poor regeneration of Douglas-fir after large fires because surface temperature (maximum during the growing season, °C) and spring soil moisture (March-May, volumetric water content, vwc) have exceeded thresholds for successful recruitment (A and C), in many years. This is increasingly so in recent years (dots indicate conditions favorable for recruitment, B and D). As a result, recruitment probability of tree seedlings is highly variable year to year (E and F), and lower in recent years in the NR and SW. Analyses accounted for effect of burn severity and distance from seed source. From Davis et al. (2019)

experiencing high levels of tree mortality from drought and insects, even in the absence of fires (Allen et al. 2010, Hicke et al. 2016); thus many of our forests will only continue to function as forested ecosystems if tree regeneration can establish. With changing climate and shifting suitable habitat for trees, we are likely to continue to see the loss of forests. As wildfires burn more areas, with a greater proportion burning at high severity, alternate ecosystems are likely. These changes have the potential to be most prevalent on relatively warm and dry sites and at the lower treeline, but some ecosystem reconfiguration is likely to occur in most forests. We are experiencing, and likely to continue to experience, species composition shifts due to differential species responses to disturbances and life history traits (ex: lodgepole pine and serotiny versus minimal seed dispersal distance of ponderosa pine).

What can be done?

Disturbances can be the catalyst for abrupt ecosystem changes. However, this is not inevitable, and land managers can minimize and perhaps mitigate some of these changes in some places. For example, there are many steps that can be taken before, during, and after a wildfire to mitigate the losses of forest cover.

Research-management partnerships and interactive forums: The ability to advance effective action by land managers often depends on their understanding of emerging research and having open and reasoned discussions among researchers, land managers, and other relevant stakeholders (Kemp et al. 2015). Research-management partnerships and interactive regional workshops have been effective for synthesizing, visualizing, and translating complex science, as

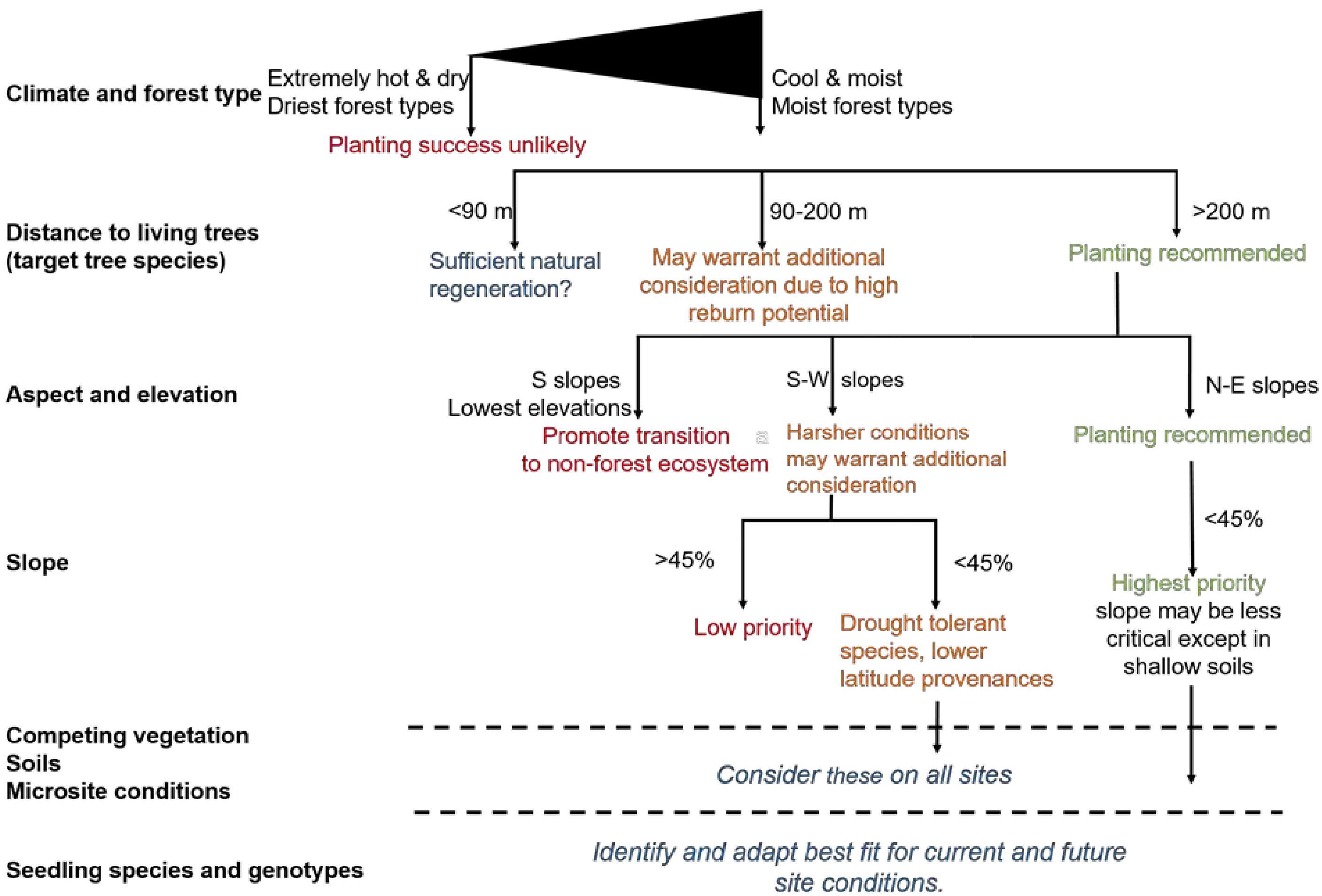


Figure 6. This decision tree, developed by scientists and managers working together, suggests that on the warmest and driest sites, post-fire tree regeneration is unlikely whether trees are planted or not, and where climate is very favorable planting may not be needed either. On intermediate sites, managers could strategically target sites beyond the reach of seed sources, as well as beyond the edge where reburns are more likely to occur (Stevens-Rumann and Morgan 2019).

well as coproducing management strategies to address findings of climate change and tree regeneration science (Blades et al. 2016). These interactive interdisciplinary settings have been shown to increase and reinforce participant understanding and risk perceptions related to post-wildfire climate influences on tree regeneration, regeneration failure mechanisms, forest vulnerability, and how fuels change over time post-fire. Research-management partnerships and interactive forums will continue to be imperative in the face of increasing agency barriers to using emerging science in land management decisions (e.g., lack of time, reduced funding, dynamic politics). The coproduction of research-management strategies and tools (Fig. 6) holds great promise for understanding, minimizing, and mitigating the effects of disturbances and rapid ecosystem change.

Planning before and managing during fires: Extensive work has been done to help project where fires are most likely to occur and to burn severely (Dillon et al. 2011, Parks et al. 2018). Combining this with climate projections and management objectives will be important to assess where and what management actions are needed to foster forest resilience to future fires. Managing forests and fires to foster survival of the trees that will provide seed sources for future regeneration is important. Strategies include managing so that more areas burn under less extreme conditions and with smaller patches of high burn severity, implementing prescribed burns to limit accumulation of fuels and increase the likelihood of tree survival in subsequent wildfires (Walker et al. 2018), and thinning to foster development of larger trees more likely to survive fires.

After fires: Stevens-Rumann and Morgan (2019) developed a decision tree in conjunction with land managers to assist in their strategic decisions about where and what to plant post fire to foster forests. They suggest that managers avoid planting trees on sites that are so warm and dry that planted trees are unlikely to survive, and also on cooler and wetter sites where trees will naturally regenerate post-fire (Fig. 6). This must be tempered by local knowledge and experience. Additionally, North et al. (2019) focused on the need to alter planting patterns and locations to increase resilience and decrease the potential for future fires. As various tree species respond differently to warm and dry conditions (Davis et al. 2018, 2019), planting multiple species and seeds for different seed zones (if allowed by local land management policy), as well as fire-resistant trees likely to survive future fires, is potentially advisable and is currently being researched in common garden studies.

In Other Words-

Mature trees are needed to increase the number of seedlings. If mature trees are far away, fewer seeds result in fewer seedlings. If we can manage to have more mature trees resilient to future fires, and have fewer parts of burned areas far from live seed sources, forests are more likely to persist into the future. When large patches have burned with high severity, North et al. (2019) recommend planting trees in clumps far from surviving trees.

We can expect more, large fires in forests in the future. Sustaining forests in the face of large fires will require innovative coordination and management before, during and after fires that encourages forests that are resilient and able to recover from fires.

More research is needed: All the research presented here is on natural tree regeneration. More studies on the success of planted seedlings would increase our understanding of the contributors of regeneration success on sites that do not naturally regenerate. Additionally, studies presented here predominantly focused on seedling establishment, more studies on seedling growth in relation to climate and other factors would improve our understanding of the future of burned landscapes.

Management Recommendations -

- Management before and during wildfires to promote smaller high severity burned patches to maintain live seed source trees could favor more successful tree seedling establishment and survival on sites that are not too warm and dry.
- Consideration of climate and future site suitability in both planting location and species selection can increase survival of planted seedlings in post-fire landscapes.
- Planting at distances far from seed sources can optimize resources; locations closer to live seed sources may have sufficient natural regeneration.
- When large patches have burned with high severity, planting trees in clumped patterns far from surviving trees creates a more heterogeneous forest structure into the future.
- Research-management partnerships and interactive forums are crucial for synthesizing, visualizing, and translating complex science, as well as coproducing management strategies to address findings of climate change and tree regeneration science.

Additional information sources include -

[Northern Rockies Fire Science Network]

- Post-fire Tree Regeneration Hot Topic Webpage
- Research & Publications Database

Literature cited

Agee, JK (1993) Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg ET, Gonzalez P (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259:660–684. https://doi.org/10.1016/j.foreco.2009.09.001.

Andrus RA, Harvey BJ, Rodman KC, Hart SJ, Veblen TT (2018) Moisture availability limits subalpine tree establishment. Ecology 99:567–575.

Blades JJ, Klos PZ, Kemp KB, Hall TE, Force JE, Morgan P, Tinkham WT (2016) Forest managers' response to climate change science: evaluating the constructs of boundary objects and organizations. Forest Ecology and Management 360: 376–387. https://doi.org/10.1016/j.foreco.2015.07.020.

Chambers ME, Fornwalt PJ, Malone SL, Battaglia MA (2016) Patterns of conifer regeneration following high severity wildfires in ponderosa pine dominated forests of Colorado Front Range. Forest Ecology and Management 378: 57-67.

Davis KT, Higuera PE, Sala A (2018) Anticipating fire-mediated impacts of climate change using a demographic framework. Funct Ecol 32(7):1729-1745.

Davis KT, Dobrowski SZ, Higuera PE, Holden ZA, Veblen TT, Rother MT, Parks SA, Sala A, Maneta MP (2019) Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. PNAS. DOI: 10.1073/pnas.1815107116.

Dillon G, Morgan P, Holden Z (2011) Mapping the potential for high severity wildfire in the western United States. *Fire Management Today*. 71(2): 24-27.

Dodson EK, Root HT (2013) Conifer regeneration following stand-replacing wildfire varies along an elevation gradient in a ponderosa pine forest, Oregon, USA. Forest Ecology Management 302: 163-170.

Harvey BJ, Donato DC, Turner MG (2016) High and dry: Postfire tree seedling establishment in subalpine forests decreases with post-fire drought and large stand-replacing burn patches. Global Ecology and Biogeography 25:655–669.

Hicke J, Meddens AJH, Kolden C (2016) Recent tree mortality in the western united states from bark beetles and forest fires. For Sci 62:141-153.

Jackson ST, Betancourt JL, Booth RK, Gray ST (2009) Ecology and the ratchet of events: Climate variability, niche dimensions, and species distributions. Proceedings of the National Academy of Sciences USA 106:19685–19692.

Kemp KB, Blades JJ, Klos PZ, Hall TE, Force JE, Morgan P, Tinkham WT (2015) Managing for climate change on federal lands of the western United States: perceived usefulness of climate science, effectiveness of adaptation strategies, and barriers to implementation. Ecol Soc 20(2).https://doi.org/10.5751/ES-07522-200217.

Kemp KB, Higuera PE, Morgan P (2016) Fire legacies impact conifer regeneration across environmental gradients in U.S. northern Rockies. Landscape Ecol 31(3): 619-636. http//dx.doi.org/10.1007/s10980-015-0268-3.

Kemp KB, Higuera PE, Morgan P, Abatzoglou JT (2019) Climate will increasingly determine post-fire tree regeneration success in low-elevation forests, Northern Rockies, USA. Ecosphere 10:1, e02568.

Liang S, Hurteau MD, Westerling AL (2018) Large-scale restoration increases carbon stability under projected climate and wildfire regimes. Frontiers in Ecology and the Environment (April 4), online. https://doi.org/10.1002/fee.1791.

Lopez Ortiz MJ, Marcey T, Lucash, MS, Hibbs D, Shatford JPA, Thompson JR (2019) Post-fire management affects species composition but not Douglas-fir regeneration in the Klamath Mountains. Forest Ecology and Management 432: 1030-1040.

Lydersen J, North M (2012) Topographic variation in structure of mixed-conifer forests under an active fire regime. Ecosystems 15:1134-1146.

North MP, Stevens JT, Greene DF, Coppoletta M, Knapp EE, Latimer AM, Restaino CM, Tompkins RE, Welch KR, York RA, Young DJ, et al. (2019) Tamm Review: Reforestation for resilience in dry western US forests. For Ecol Manage 15 (432):209-24.

Parks SA, Holsinger LM, Panunto MH, Jolly WM, Dobrowski SZ, Dillon GK (2018) High-severity fire: evaluating its key drivers and mapping its probability across western US forests Environmental Research Letters. 13(4): 044037.

Prichard S, Stevens-Rumann CS, Hessburg P (2017) TAMM Review: Wildland fire-on-fire interactions: management implications under a changing climate. Forest Ecology and Management. 396: 217-233.

Roccaforte JP, Fulé PZ, Chancellor WW, Laughlin DC (2012) Woody debris and tree regeneration dynamics following severe wildfires in Arizona ponderosa pine forests. Canadian Journal of Forest Research 42:593–604.

Rother MT, Veblen TT (2016) Limited conifer regeneration following wildfires in dry ponderosa pine forests of the Colorado Front Range. Ecosphere 7:12, e01594.

Savage M, Mast JN (2005) How resilient are southwestern ponderosa pine forests after crown fires? Canadian Journal of Forest Research 35: 967-977.

Savage M, Mast JN, Feddema JJ (2013) Double whammy: high-severity fire and drought in ponderosa pine forests of the southwest. Can J For Res 43:570-583.

Shatford, JPA, Hibbs DE, Puettmann, KJ (2007) Conifer regeneration after forest fire in Klamath-Siskiyous: how much, how soon? J For 105:139-146.

Stevens-Rumann CS, Prichard S, Morgan P (2014) The effect of previous wildfires on subsequent wildfire behavior and post-wildfire recovery. Northern Rockies Fire Science Network, Technical Synthesis.

Stevens-Rumann CS, Kemp K, Higuera P, Harvey B, Rother M, Donato D, Morgan P, Veblen T (2018) Evidence for declining forest resilience to wildfires under climate change. Ecology Letters. 21: 243-252.

Stevens-Rumann CS, Morgan P (2019) Tree regeneration following wildfires in the western US: A review. Fire Ecology 15. doi:10.1186/s42408-019-0032-1

Tepley AJ, Thompson JR, Epstein HE, Anderson-Teixeira KJ (2017) Vulnerability to forest loss through altered postfire recovery dynamics in a warming climate in the Klamath Mountains. Glob Change Biol 23:4117-4132.

Turner MG, Braziunas KH, Hansen WD, Harvey BJ (2019) Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. Proceedings of the National Academy of Sciences of the United States of America 116 (23):11319-11328.

Urza AK, Sibold JS (2017) Climate and seed availability initiate alternate post-fire trajectories in a lower subalpine forest. Journal of Vegetation Science. 28: 1–14.

Walker RB, Coop JB, Parks SA, Trader L (2018) Fire regimes approaching historic norms reduce wildfire-facilitated conversion from forest to non-forest. Ecosphere 9:4.

Welch KR, Safford HD, Young TP (2016) Predicting conifer establishment post wildfire in mixed conifer forests of the North American Mediterranean-climate zone. Ecosphere 7:e01609.

The Northern Rockies Fire Science Network is actively engaged in a variety of science delivery partnerships in the Northern Rockies. Partners include both science and management organizations. For more about the NRFSN and its many partners, please visit:

NRFireScience.org.