FINAL REPORT

Title: What makes for a resilient landscape?
Climate, fire and forests in the Northern Rockies

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List of Abbreviations/Acronyms

CanESM2	Second generation Canadian Earth System Model
FIA	Forest Inventory and Analysis
FVS	Forest Vegetation Simulator
GYE	Greater Yellowstone Ecosystem
HadGEM2-CC	Hadley Centre Carbon Cycle Model, version 2
HadGEM2-ES	Hadley Centre Earth System Model, version 2
iLand	The individual-based forest landscape and disturbance model
IPCC	Intergovernmental Panel on Climate Change
GCM	General circulation model
NRFSN	Northern Rockies Fire Science Network
RCP	Representative concentration pathway, a 21st-century greenhouse gas concentration pathway adopted by the Intergovernmental Panel on Climate Change Fifth Assessment; this study used RCP 4.5 and RCP 8.5
WUI	Wildland-urban interface

Keywords

Abrupt change
Carbon
Climate change
Ecosystem services
Fire regime
Forest loss
Forest resilience
Fire suppression
iLand
Landscape ecology
Machine learning
Postfire regeneration
Simulation model
Subalpine forest
Thresholds
Tipping points
Wildland-urban interface
Wildlife habitat

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Abstract

Determining whether forest landscapes can maintain their resilience to fire–that is, their ability to rebound and sustain their current composition and structure–in the face of rapid climate change and increasing fire activity is a pressing challenge throughout the American West. Many western forests are well adapted to fire, and even subalpine forests that experience infrequent, high-severity fires historically recovered long before they burned again. However, current rates of warming portend a mismatch between historical and future fire regimes. Our project quantified multiple dimensions of resilience for Northern Rocky Mountain forests and developed innovative, widely applicable scientific methods for operationalizing resilience concepts. We engaged fire, fuels and resource managers at the outset through "*Dimensions of Resilience*" workshops in February 2017. We jointly identified multiple desired characteristics to sustain throughout the 21st century and potential simulation landscapes. Informed by this input, we combined state-of-the-art projections of future climate and fire with extensive data on post-fire forest dynamics to model alternative future scenarios and evaluate forest resilience. We asked: (1) How and why might warming climate and changing fire regimes push forest stands over a tipping point? (2) Where and when might projected changes in climate and fire activity interact with management to enhance or erode landscape resilience? (3) How do stand and landscape indicators of resilience scale to the Northern Rockies ecoregion, and what geographical areas are most likely to be vulnerable or resilient to changing climate and fire regimes? We re-convened with stakeholders through "*Learning about Resilient Futures*" workshops in February 2020 to jointly interpret effects of changing climate, fire and management on forest landscape resilience. Objectives were achieved (15 papers published, 5 in progress; 3 MS theses; 3 PhD dissertations), and the in-person workshops fostered excellent communication between scientists and managers.

Under a hotter-drier climate, forest extent is projected to shrink substantially during the 21st century, and remaining forests will be younger and sparser than current forests. Postfire tree regeneration, which is critical for sustaining forest resilience, will decline if more frequent fires reduce local seed availability, larger burn patches exceed effective dispersal distances, and postfire climate conditions are not conducive to seedling establishment. Forests dominated by fire-sensitive tree species (e.g., *Picea engelmannii, Abies lasiocarpa*, *Pinus contorta* var. *latifolia*) are likely to show the greatest declines, whereas forests dominated by fire resisters (e.g., *Pseudotsuga menziesii, Larix occidentalis*) and reprouters (e.g., *Populus tremuloides*) will be more resilient. Declining fire rotations may pass a tipping point after which forest extent sharply declines. Climatically suitable areas for three forest-dependent vertebrates often did not intersect locations where simulated vegetation structure was also suitable; projections based on climate or vegetation alone are likely to misrepresent future habitat availability. Our results also suggested a peak in both high-severity fire and fire risk in the wildland-urban interface (WUI) during the mid-21st century, although annual area burned continued to increase. In the WUI, clustering developments and applying fuels treatments on 10 to 30% of the landscape every 10 years can reduce fire risk across multiple scales. In subalpine landscapes managed for wilderness values, fire suppression is unlikely to alter the trajectory of forest change because forest dynamics will be driven primarily by large fire years and increasingly arid conditions. "Bending the curve" of greenhouse gas emissions to stabilize atmospheric concentrations by mid-21st century will dampen the consequences of climate warming for forest landscapes.

Objectives

Resilient landscapes are a fundamental goal of the National Cohesive Wildland Fire Management Strategy, yet defining, measuring and managing for resilience remain major challenges. *Resilience* refers to the ability of a system to tolerate disturbance without shifting to a qualitatively different state controlled by different processes, yet how to operationalize resilience in actual landscapes is unclear, especially in a no-analog future. Fire and forest managers would benefit from knowing how to measure resilience; where, when and why resilience may be lost; and what management options can promote resilience. We quantified ecological and social dimensions of resilience for Northern Rocky Mountain forests and developed innovative scientific methods for operationalizing forest and landscape resilience concepts at multiple scales. Guided by participatory workshops with stakeholders, we determined how 21st-century climate and fire regimes could alter the resilience of Northern US Rocky Mountain forests and explored management options under a range of possible futures. Our work included three main components (Fig. 1) that addressed specific questions.

Dimensions of Resilience Workshop. *Resilience of what to what? What do stakeholders consider critical components of resilient forest landscapes?* Through workshops and document analysis, we engaged fire, fuels and resource managers and stakeholders at the outset of the project to identify social and ecological dimensions of resilience–i.e., the multiple characteristics they want to sustain throughout the 21st century–given changing climate and fire regimes.

Measuring and Modeling Resilience at Multiple Scales. Informed by stakeholder input, we combined state-of-the-art projections of future climate and fire with extensive data on post-fire forest dynamics to model alternative future scenarios and evaluate dimensions of resilience through the 21st century at three spatial scales (Fig. 1).

(i) *Stand: How and why might warming climate and changing fire regimes push forest stands over a tipping point?* Fire is the dominant disturbance shaping Northern Rockies forests, and post-fire tree regeneration is fundamental to stand-level resilience. We evaluated mechanisms behind tipping points in future climate-fire scenarios, using a next-generation process-based model (iLand) that responds dynamically to novel conditions.

(ii) *Landscape: Where and when might projected changes in climate and fire activity interact with management to enhance or erode landscape resilience?* We simulated 21st-century climate and fire regimes across an array of representative Northern Rockies landscapes, with and without management, using the spatially explicit implementation of iLand.

(iii) *Region: How do stand and landscape indicators of resilience scale to the Northern Rockies ecoregion, and what areas are most likely to be vulnerable or resilient to changing climate and fire regimes?* We developed innovative new approaches using machine learning to project postfire tree regeneration at a regional scale and map the vulnerability of current forests to regeneration failure.

Learning about Resilient Futures Workshop. *What makes for a resilient landscape?* With modeling results comparing resilience outcomes among diverse scenarios in hand, we re-convened with managers and stakeholders to jointly interpret effects of changing climate, fire and management on the dimensions of landscape resilience articulated at the first workshop.

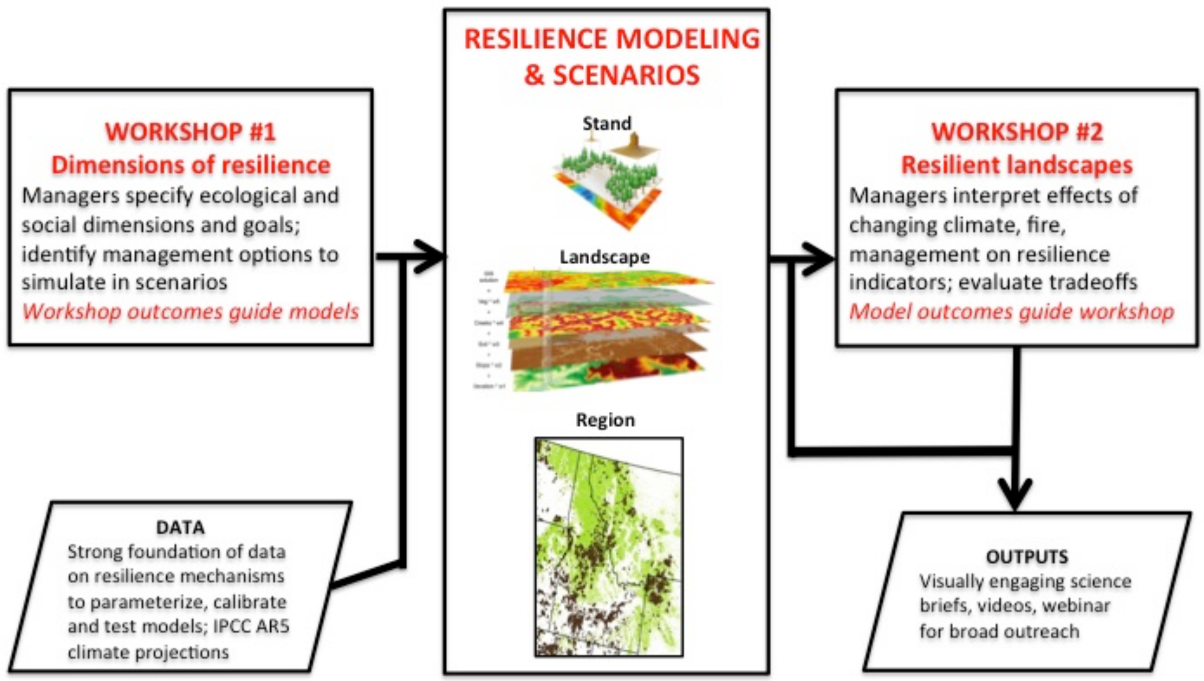


Fig. 1. Flow chart of stakeholder-driven exploration of resilience in Northern Rocky Mountain forests.

Background

Resilient landscapes are a fundamental goal of the National Cohesive Wildland Fire Management Strategy, and federal and state agencies are increasingly mandating that landscapes be managed for resilience. However, defining, measuring and managing for resilience remain major challenges. *Resilience* refers to the ability of a system to tolerate disturbance without shifting to a qualitatively different state controlled by different processes. While ecological resilience theory is well developed (e.g., Scheffer et al. 2015), how to operationalize resilience concepts in actual landscapes is unclear, especially during a time of rapid environmental changes on a path towards a no-analog future. Fire size and severity are already increasing in western North America as climate warms (Westerling 2016, Abatzoglou and Williams 2016, Parks and Abatzoglou 2020, Higuera et al. 2021). The novel climate conditions and fire regimes that are emerging will have profound consequences for forest resilience during the 21st century (Johnstone et al. 2016, Davis et al. 2019, Coop et al. 2020). Yet, fire and forest managers face tremendous uncertainty in how to measure resilience; where, when and why resilience may be lost; and what management options can promote resilience (Stephens et al. 2013).

Applications of resilience concepts to real-world landscapes that incorporate ecological mechanisms and consider land-management options need to be developed, and the challenges associated with such research are daunting. Effects of changing climate and fire regimes on forest resilience play out over decades to centuries and across vast areas; tipping points result from interactions of processes across scales and are difficult to detect before they are passed; and feedbacks and spatial variation can dampen or amplify ecological change. Meeting these challenges requires process-based data-driven models that can assess change trajectories as emergent properties of the interacting drivers, not as phenomena hard-coded into a model. Many current models are purely empirical and thus not well suited to robustly address future no-analog conditions in environmental drivers (Gustafson 2013), and many lack the mechanisms known to underpin forest resilience (Albrich et al. 2020).

Materials and Methods

Study region. We focused on the US Northern Rocky Mountains, a data-rich ecoregion that is served by the Northern Rockies Fire Science Network (NRFSN) and includes well-studied forests in Greater Yellowstone and the Crown of the Continent. Dominant forest types include species with varied fire-related traits, including thick-barked fire resisters (e.g., Douglas-fir, *Pseudotsuga menziesii*; western larch, *Larix occidentalis*), resprouters (e.g., aspen, *Populus tremuloides*), seed bankers (lodgepole pine, *Pinus contorta* var. *latifolia*) and fire-sensitive shade tolerant species (e.g., Engelmann spruce, *Picea engelmannii*; subalpine fir, *Abies lasiocarpa*). Historical fire regimes range from infrequent, stand-replacing regimes in higher elevation mesic forests to mixed-severity regimes in lower montane forests. The frequency of large fires and annual area burned have increased since the mid-1980s (Westerling 2016), and > 400,000 ha of forest burned twice from 1984 to 2010 (Harvey et al. 2016). Land ownership and use vary, and a wide range of management contexts (including extensive wildland-urban interface) are represented.

Stakeholder input. We engaged fire, fuels and resource managers and stakeholders at 1-day *Dimensions of Resilience* workshops in Bozeman and Missoula, MT (co-hosted with the NRFSN) in February 2017. Participants identified social and ecological dimensions of resilience–i.e., multiple characteristics they want to sustain throughout the 21st century–given changing climate and fire regimes and suggested potential simulation landscapes that were of interest. Informed by this input, we combined state-of-the-art projections of future climate and fire with extensive data on post-fire forest dynamics to model alternative future scenarios and evaluate dimensions of resilience through the 21st century at stand, landscape and regional scales.

Model development. Simulation modeling formed the backbone of this project. Our research used iLand, the individual-based forest landscape and disturbance model (Seidl et al. 2012). iLand is a spatially explicit model operating at the grain of individual trees and simulating forest dynamics based on first principles of ecology. Compared to more empirical approaches, process-based models such as iLand can better capture effects of no-analog future conditions (Gustafson 2013). iLand also contains a flexible management interface that allows for the implementation of a wide range of treatments, which interact dynamically with the emergent vegetation development in the simulation (Rammer and Seidl 2015). Wildfire ignitions and maximum potential fire sizes were projected based on fire-climate relationships (extending methods of Westerling et al. 2011), and fire spread was simulated dynamically in iLand at a grain of 20-m cells. Thus, realized fire sizes and perimeters were an emergent property of the simulations, accounting for the influence of fuels, wind, topography and species traits. Fire severity was dependent on fuel load, fuel moisture and both forest structure and composition. For full details on the iLand model, see http://iland-model.org/startpage

In this project, we adapted iLand for the US Northern Rocky Mountains by:

- Parameterizing regional tree species using published empirical studies (Braziunas et al. 2018, Hansen et al. 2018). We began with dominant species in Greater Yellowstone (Douglas-fir, Engelmann spruce, subalpine fir, quaking aspen, lodgepole pine, whitebark pine), then added species present throughout the Northern Rockies (grand fir, ponderosa pine, western hemlock, western larch, western red cedar, and western white pine);
- Tuning and evaluating the performance of tree species, using independent datasets to calibrate and evaluate simulated forest structure and composition (Braziunas et al. 2018);
- Incorporating new parameters to represent forest resilience to fire and climate change, including serotiny (lodgepole pine), resprouting (aspen), and seedling drought tolerance;
- Tuning the iLand fire module to match fire regimes in the Northern Rockies, in terms of burn severity, fire size distribution, and fire shape; and
- Merging future projections of maximum potential fire size based on climate with the fire module in iLand, thereby allowing vegetation feedbacks to realized fire size and severity.

We ensured that stand dynamics aligned well with empirical observations over space and time by comparing simulation results with published field data, forest inventory and analysis (FIA) data, stand development using the Forest Vegetation Simulator (FVS), and existing vegetation maps. Fire regimes were compared against Monitoring Trends in Burn Severity.

We then used iLand to improve understanding of how specific processes (e.g., climate, soils, fire return interval, seed supply, seed dispersal) contribute to forest resilience by conducting stand-level simulation experiments that varied individual drivers. Next, we explored consequences of potential future climate and fire scenarios on forest resilience by conducting spatially explicit model-based scenario analyses in the absence of management and by considering different management options that could affect resilience.

To represent alternative future climate scenarios and generate the potential number, maximum size and location of fires in Northern US Rocky Mountain forests, we selected three general circulation models (GCMs) and two emissions pathways (RCP 4.5 and 8.5) from the IPCC 5th assessment. The three GCMs show similar warming trends but vary substantially in precipitation (Table 1). The CanESM2 model projects warmer temperatures with increased precipitation. The HadGEM2-CC and HadGEM2-ES models both project drier conditions, but they vary in the timing, severity and duration of summer drought. Spatial variation in climate projections, especially for precipitation, is also apparent across the region (Fig. 2).

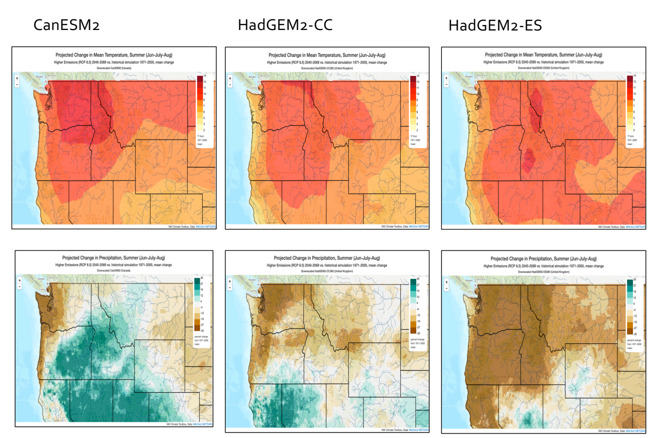


Fig. 2. Mid-21st century change in summer temperature and precipitation across the western US for three general circulation models with RCP 8.5. Data source: https://climate.northwestknowledge.net/MACA/tool_summarymaps2.php.

Table 1. To illustrate the differences among climate scenarios, we summarize historical (1971-2000) and projected future downscaled climate for a region that encompasses the Greater Yellowstone Ecosystem [(42.2262 to 45.4367) N x (-111.4412 to -109.1235) E] for the six CMIP5 scenarios used in this study. Table is from Turner et al. (2021).

Time period	**CanESM2** RCP 4.5	**CanESM2** RCP8.5	**HadGEM2-CC** RCP4.5	**HadGEM2-CC** RCP8.5	**HadGEM2-ES** RCP4.5	**HadGEM2-ES** RCP8.5
			Mean annual temperature (˚C)			
Historical	2.0	2.1	2.1	2.1	2.0	2.2
2010-39	4.2	4.2	3.3	3.8	3.7	3.9
2040-69	5.1	6.1	4.9	6.1	5.1	6.3
2070-99	6.1	8.7	5.5	8.9	6.2	8.8
Net Δ	**4.1**	**6.6**	**3.4**	**6.8**	**4.2**	**6.6**
			Mean annual precipitation (cm)			
Historical	72.6	72.6	70.9	70.9	69.3	69.6
2010-39	78.0	76.7	76.7	71.1	71.6	76.2
2040-69	83.8	90.4	76.5	77.0	73.7	72.1
2070-99	82.6	102.6	76.5	80.5	72.1	76.7
Net Δ	**9.9**	**30.0**	**5.6**	**9.7**	**2.8**	**7.1**
			Mean summer (June–August) precipitation (cm)			
Historical	14.2	14.2	12.4	12.4	12.7	12.4
2010-39	15.0	15.5	14.2	12.7	12.7	14.5
2040-69	15.5	15.5	11.7	10.7	11.9	10.7
2070-99	15.7	17.5	12.4	10.2	10.9	10.2
Net Δ	**1.5**	**3.3**	**0.0**	**-2.3**	**-1.8**	**-2.3**

Data source: https://climate.northwestknowledge.net/MACA/tool_summarymaps2.php

Statistical models relating fire activity to temperature, precipitation and topography were generated by extending methods developed by Westerling et al. (2011) and described in Rammer et al. (2021) and Turner et al. (2021). These statistical models were used to produce 20 probabilistic scenarios of fire number, location, and maximum potential size on a monthly basis through 2100 across the US Northern Rockies for each of the six GCM x RCP combinations. Feedbacks between vegetation and fire were incorporated by driving landscape-level iLand simulations with these statistical projections, such that realized fire sizes and severities depended on fuels, weather and topography. We used our models in a series of studies that were guided by stakeholder input and designed to address specific questions related to forest resilience at stand, landscape, and regional scales.

Interpreting model outcomes. We re-convened with stakeholders at *Learning about Resilient Futures* workshops, co-hosted with the NRFSN, to jointly interpret effects of changing climate, fire and management on the dimensions of landscape resilience articulated at the first workshop. These 1.5-day workshops took place in February 2020, also in Bozeman and Missoula, MT. Participants (n = 30) included personnel affiliated with USDA Forest Service, National Park Service, Bureau of Indian Affairs, Bureau of Land Management, Red Lodge Fire Rescue, Montana State University, University of Montana, and private forestry.

Results and Discussion

Dimensions of Resilience

The *Dimensions of Resilience* workshops fostered spirited discussions about the meaning of resilience, and we subsequently explored its emerging use in a large body of policy and management documents for western forest and fire management produced between 1980 and 2016 (Selles and Rissman 2020). Comparing 1,487 scientific journal articles and 139 western US Forest Service planning documents we asked: (1) How has the use-rate of the word resilience changed over time? (2) Are changes in the use-rate of the word resilience correlated with shifts in terminology associated with environmental values, complex systems theory, or environmental change? (3) How does the use of the word resilience compare between science and management documents? The word resilience has been used in these documents since the 1980s, but its use sharply increased in both contexts between 2009 and 2011 (Fig. 3). The use-rate trends differ between science and management documents and do not appear to be associated complex systems terms but do seem associated with increases in the use of terms "climate change" and "adapt" and biocentric values. Although there are differences in how resilience is used between science and management documents, the shared meaning is a hopeful framing for adapting forests to changing conditions.

A complementary analysis explored how processes related to forest resilience were represented in contemporary forest simulation models (Albrich et al. 2020). By analyzing scientific publications based on forest landscape models, we found a gap between processes that underpin forest resilience to disturbance and processes included in computer models used to assess forest resilience. Important resilience mechanisms associated with tree regeneration, soil processes and disturbance legacies were simulated in less than half of the model applications that we reviewed (publication dates between 1994 and 2019). Thus, many contemporary forest models developed for other goals may be poorly suited for studying forest resilience during an era of accelerating change.

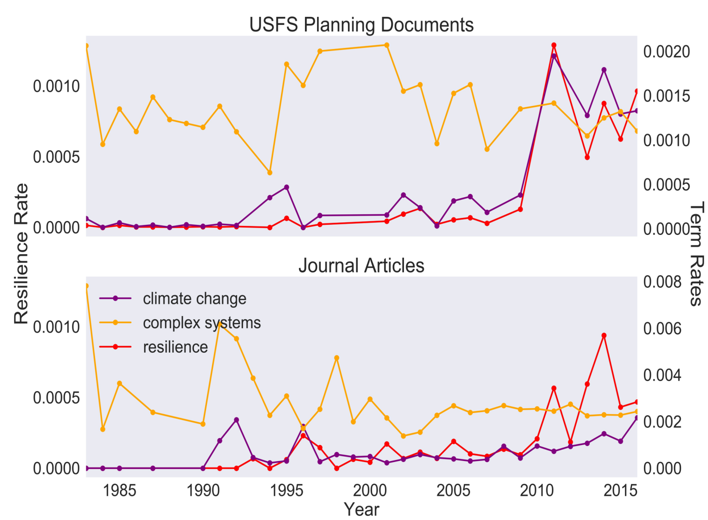


Fig. 3. Resilience (red) use rate in documents has increased, especially tied to climate change adaptation in USFS plans and Environmental Impact Statements. From Selles and Rissman (2020).

Participants at our *Dimensions of Resilience* workshops also guided our work with respect to future scenarios, forest response variables, management options, and focal landscapes:

- Discussions of "*resilience to what?*" led to contrasting scenarios incorporating changing climate, lengthening fire season, and increasing fire size, frequency and severity.

- Discussions of "*resilience of what?*" led us to model postfire tree regeneration, which is critical for potential conversion of forest to non-forest, shifts in tree species composition, and the future of mesic species; forest landscape patterns, including variation in stand structures, stand ages and the extent of old-growth forests; forest wildlife habitat; and carbon storage.
- Myriad fire and forest management options were raised in discussion, and we emphasized two: effects of historical fire suppression vs. wildland fire use; and fire and fuels management in the wildland-urban interface, especially the role of fuels reduction and non-commercial thinning on fire risk and an array of ecosystem services.

Climate, Fire and Forest Resilience - No Management

Drivers of postfire tree regeneration. As the frequency and size of stand-replacing fires increases with climate warming, postfire regeneration is necessary (but not sufficient) for forests to recover and is thus a powerful indicator of forest resilience. However, how postfire tree regeneration will respond to these changes is uncertain. Regeneration could fail if fires re-occur before trees are mature or the sizes of high-severity burn patches exceed dispersal distance. And even if seed is available, trees might not regenerate if postfire climate years are too hot and dry. We conducted a factorial simulation experiment with iLand at the stand level to determine how the success or failure of postfire tree regeneration is influenced by fire-return interval (FRI), distance to seed source (related to fire size), and postfire climate (Hansen et al. 2018). We simulated all combinations of these conditions (with replication, because the model is probabilistic), then assessed lodgepole pine and Douglas-fir regeneration 30 years after stand-replacing fire to allow sufficient time for gradual recovery. We set a conservative density of at least 50 stems/ha (saplings + trees) as the threshold needed for regeneration to be considered successful. Trees regenerated under most combinations, but Douglas-fir was more vulnerable to regeneration failure than lodgepole pine (Fig. 4). When tree regeneration failed, it was usually in stands >500 m from a seed source. Serotinous lodgepole pine stands were very resilient, and regeneration only failed for very short (20 yrs) FRI and long distances (> 500 m) from seed source. Douglas-fir regeneration increased with warming, whereas lodgepole pine regeneration was unaffected by the warmer climates simulated in this study. Changes in the fire regime had a much larger effect on postfire regeneration than did climate (Fig. 4).

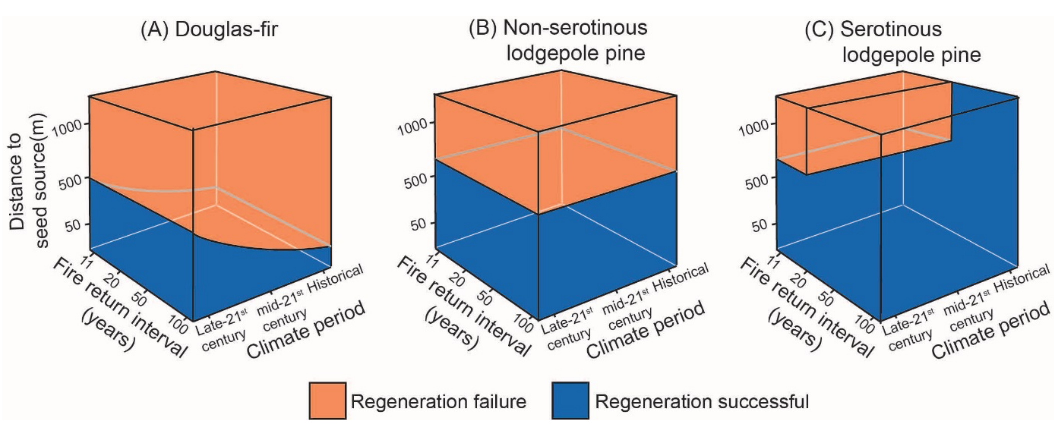


Fig. 4. Combinations of postfire distance to seed source, fire return interval, and climate that can cause regeneration failure for Douglas-fir and lodgepole pine. Regeneration failure generally occurred in stands far from seed for Douglas-fir and non-serotinous lodgepole pine, and following short-interval fires -for serotinous lodgepole pine. From Hansen et al. (2018).

Effect of short-interval reburns. In subalpine forests that historically experienced infrequent (100-300 yr) high-severity fires, short-interval fires can disrupt fire-recovery processes. Our earlier work in Greater Yellowstone suggested that hot, dry weather conducive to large fires would become very frequent by the late 21st century, potentially causing fire rotations to fall below 30 yrs (Westerling et al. 2011). Such short rotations are well outside historical ranges, and what this would mean for forest resilience had not previously been studied. During summer 2016, the Maple and Berry Fires in Greater Yellowstone created a natural experiment for studying effects of short-interval fire. Young stands were merely 16 or 28 years old when they reburned. With separate funding from the National Science Foundation, we conducted field studies during summer 2017 to quantify burn severity, initial tree regeneration and carbon stocks in these reburns (Turner et al. 2019). We also used iLand to simulate carbon recovery with and without the reburn. Following stand-replacing fires, subalpine forests in Greater Yellowstone take about 100 years to recover their carbon stocks (Kashian et al. 2013). We initialized iLand with our field data and ran simulations for 150 years assuming historical climate and no subsequent disturbance. Our model results indicated that recovery of live tree carbon was delayed by about 80 years even in the absence of climate change (Fig. 5; Turner et al. 2019). Further, downed coarse wood and total aboveground C stocks never fully recovered over the 150 year simulation. Short-interval fires disrupt the normal fire-recovery cycle in these subalpine forests, drastically reducing postfire tree regeneration, delaying carbon recovery and eroding forest resilience (Turner et al. 2019).

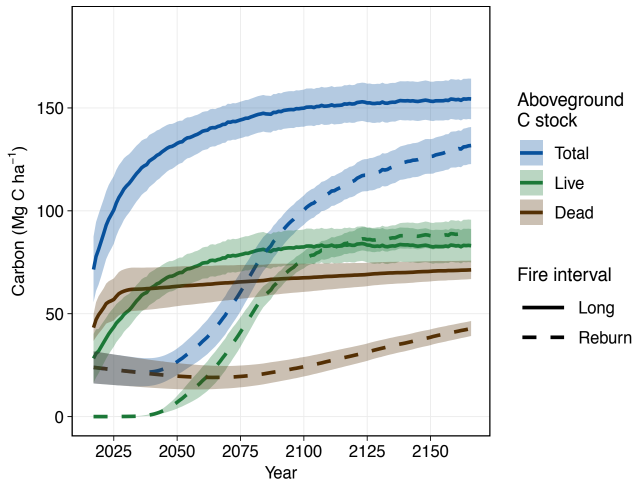


Fig. 5: Simulated recovery of aboveground carbon stocks in young (< 30 yr) lodgepole-pine dominated stands (*n* = 18) with (dashed line) and without (solid line) the 2016 reburns. From Turner et al. (2019).

Magnitude, direction and tempo of landscape change. Despite growing concern that climate change and novel fire regimes are likely to erode the resilience of subalpine forests in the Northern Rockies, the magnitude and tempo of likely changes in species composition, stand-age distributions, forest structure (e.g., tree density, basal area, carbon stocks) and forest extent are difficult to anticipate. How, when and where are forests likely to change? Are particular forest types more vulnerable to loss of resilience? Can indicators of forest change predict forest loss? We addressed these questions in forest landscapes of Greater Yellowstone using iLand (Turner et al. 2021). We simulated fire and forest dynamics spatially through 2100 in five representative landscapes (1-ha resolution; Fig. 6) with the six projected future climates (three GCMs and two RCPs, 4.5 and 8.5; Table 1) and 20 probabilistic scenarios of annual potential fire sizes and locations for each climate-landscape combination (*n*=600 runs). The landscapes were chosen to represent the range of environmental conditions and dominant forest types typical of the region and were guided by stakeholder input at our *Dimensions of Resilience* workshops.

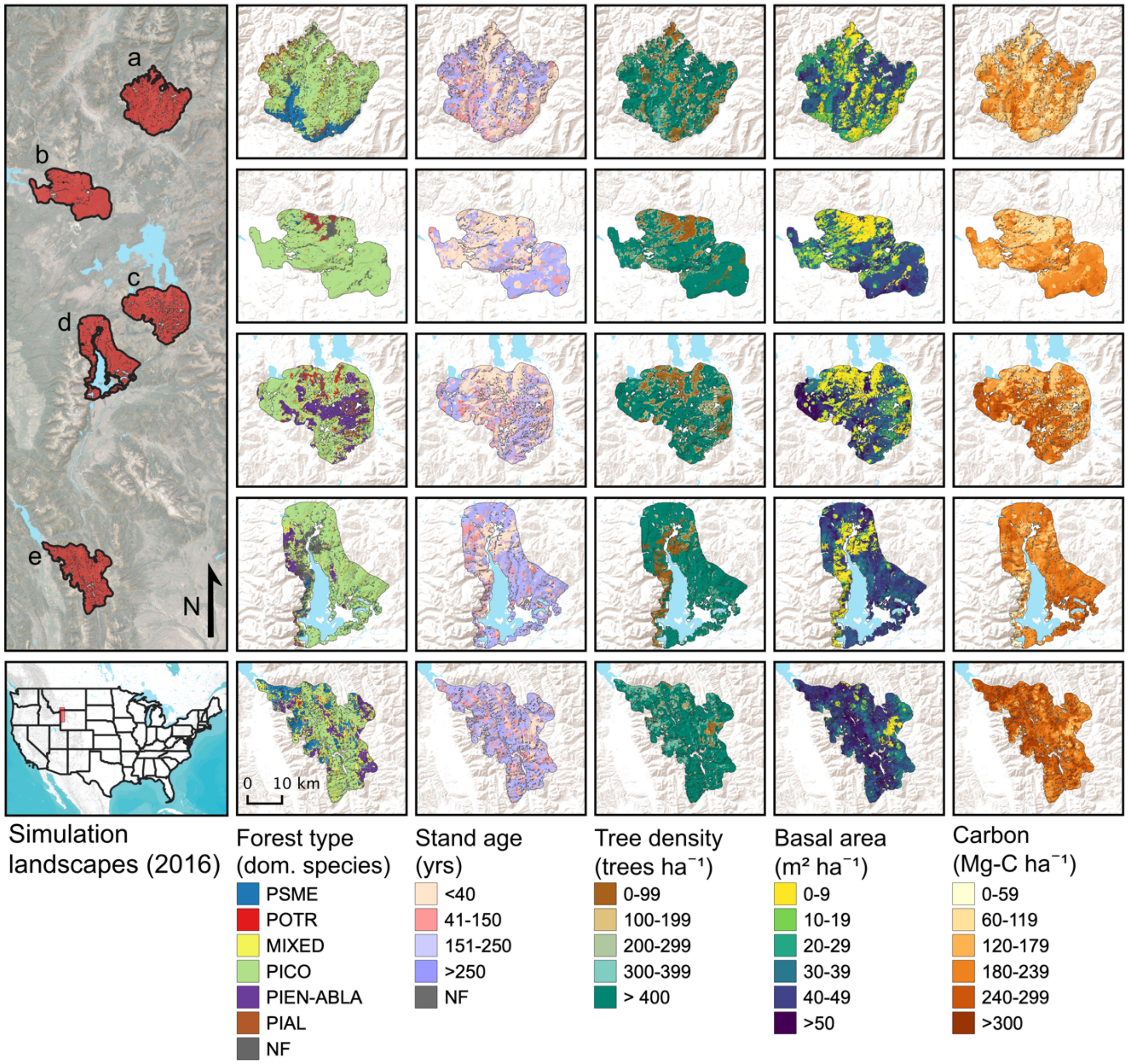


Fig. 6. Location and initial forest conditions as of 2016 in five representative landscapes in which climate, fire and forest dynamics were simulated through 2100. Species codes: Douglas-fir, PSME; aspen, POTR; lodgepole pine, PICO, spruce-fir, PIEN-ABLA; whitebark pine, PIAL. From Turner et al. (2021).

Extensive exploration of future scenarios in diverse landscapes yielded several key results. Annual area burned increased substantially in warmer-drier climate conditions (HadGEM2-CC and HadGEM2-ES models), but forests maintained resilience if increased precipitation accompanied warming (CanESM2 model). With a warm-dry future climate and more fire–which is consistent with current trends and future projections–changes in forest structure were profound. Abrupt declines in tree density, basal area, leaf area index, and aboveground live carbon stocks often occurred prior to 2050, and by 2100, dense conifer forests had become sparse (Fig. 7). Forests shifted toward younger ages, with ages of the oldest stands < 100 yrs by mid-to-late 21st century (Fig. 7). Species range contractions (spruce-fir, lodgepole pine) were often abrupt, but expansions of fire-resistant species (Douglas-fir) or re-sprouters (aspen) were always gradual. Forest extent declined with increased fire, leading to loss of 50-75% of currently forested areas by late century in hot-dry climate scenarios. Forest loss was driven primarily by increased fire, and in individual landscape simulations, abrupt declines in stand structure

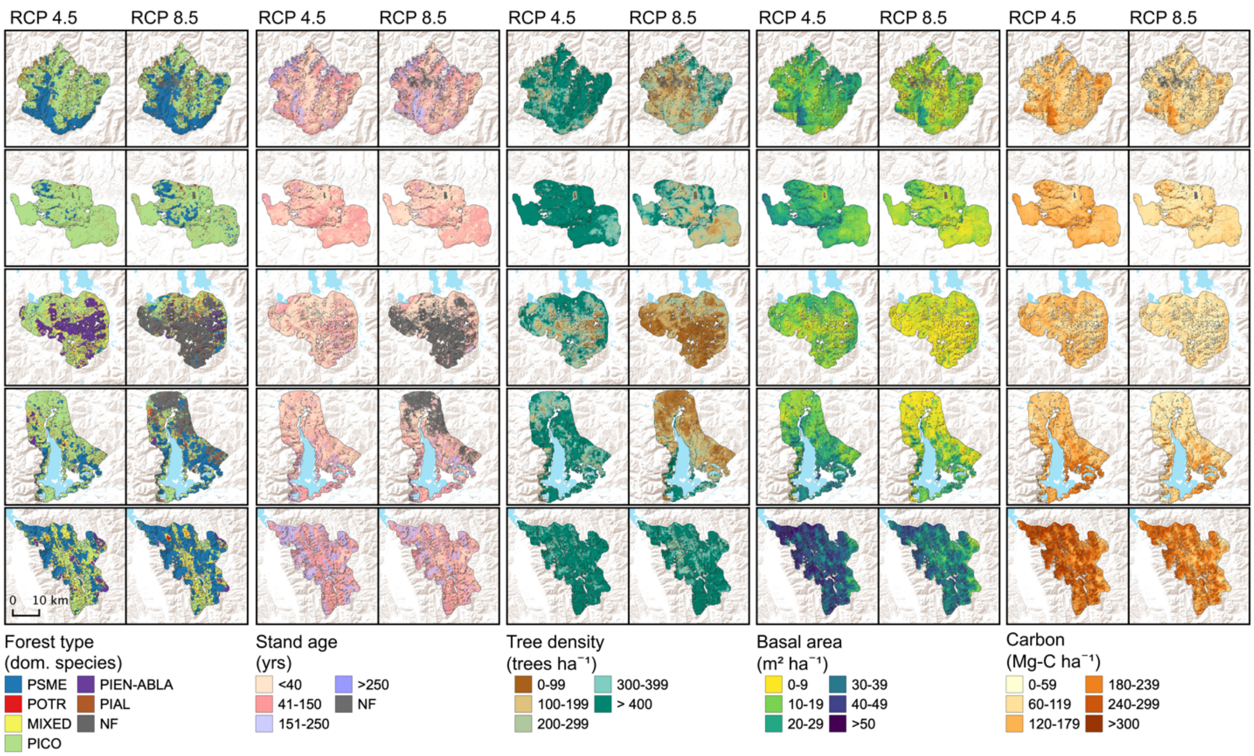


Fig. 7. Simulated forest condition in 2100 for five landscapes in Greater Yellowstone under a dry future climate (the HadGEM2-CC general circulation model) for RCP 4.5 (less warming) and RCP 8.5 (greater warming). Initial conditions as of 2016 are shown in Fig. 6. From Turner et al. (2021).

preceded forest loss by 25-30 years. These results suggest that forest structure may be a measurable and sensitive indicator of forest resilience in subalpine conifer forests, with declines in density and basal area having potential to indicate where forests could be transitioning to non-forest. Our results also demonstrated that stabilizing atmospheric greenhouse gas concentrations by mid-century (i.e., RCP 4.5) can dampen forest decline and enhance forest resilience. Declines in forest attributes by 2100 were diminished considerably when emissions were reduced (RCP 4.5) compared to scenarios in which emissions do not decline (RCP 8.5; Fig. 8).

Fire rotation and tipping points. We further explored whether forests in Greater Yellowstone can exhibit tipping points, where small increases in fire activity result in a loss of forest resilience. Tipping points relate the level of a driver (here, fire activity) to a response variable (here, forest extent). As an integrated measure of fire activity,

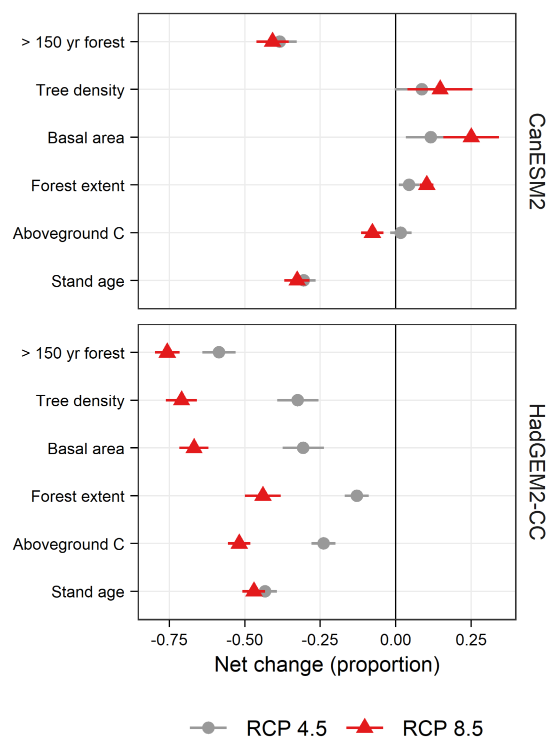


Fig. 8. Relative change in selected forest attributes between initial conditions (2016) and 2100 for RCP 4.5 and 8.5 and two GCMs that project a wet (CanESM2) vs. dry (HadGEm2-CC) future. Error bars ± 2 standard errors. From Turner et al. (2021).

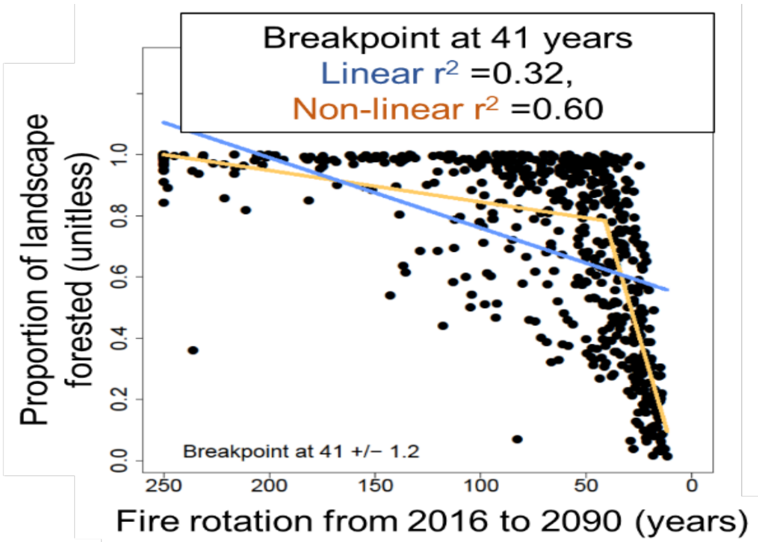


Fig. 9: Relationships between the proportion of simulation landscapes that are forested and fire rotation. Each point is one simulation from one landscape. The blue line is a linear fit, whereas the orange line shows a split-linear model. From Ratajczak et al., *in prep*.

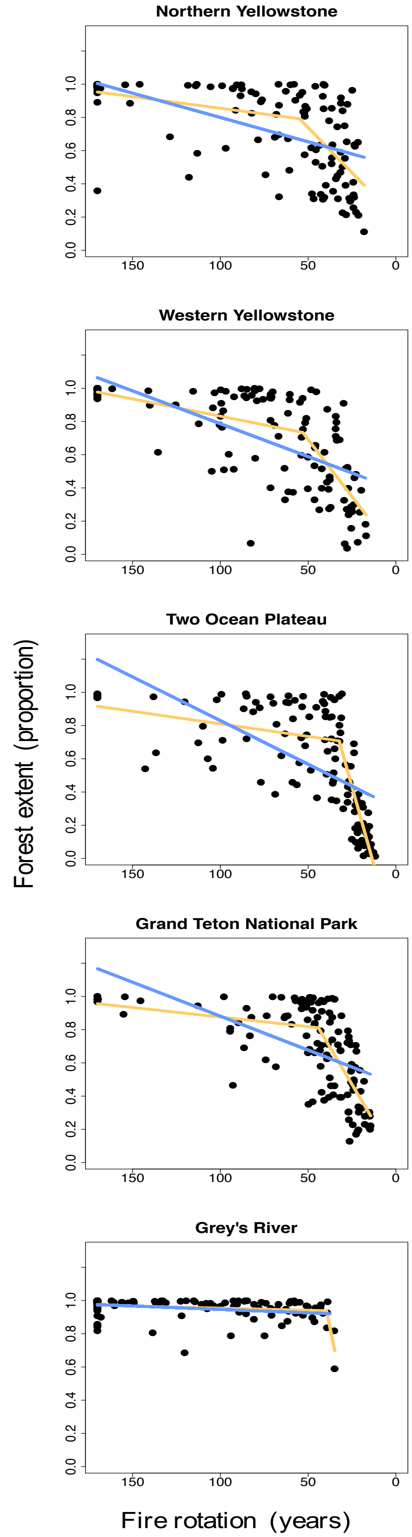


Fig. 10. Linear (blue) vs. split-linear (orange) models of forest extent vs. fire rotation in each of the five GYE landscapes. From Ratajczak et al., *in prep*.

we used fire rotation—the number of years it takes to burn an area equal to each landscape—which ranged from 10 to 250 years in our simulations. We asked whether the relationship between forest extent in the year 2100 and fire rotation was linear or exhibited thresholds, as captured by a split-linear model (Ratajczak et al., *in prep*.). Aggregated across all landscapes and all scenarios, forest extent declined precipitously when fire rotations dropped below 41 years (Fig. 9) suggesting a threshold in fire activity at which forest resilience declines steeply. Simulations in which atmospheric greenhouse gas concentrations stabilized by mid-century (RCP 4.5) were consistently less likely to cross this thresholds compared to those with higher emissions (RCP 8.5; Ratajczak et al., *in prep*.). When the five landscapes were considered separately, fire rotation thresholds varied between 30-50 yrs and were most pronounced in the three landscapes with gentle topography and where fire-sensitive species were prevalent (Fig. 10).

To address forest resilience and tipping points in fire rotation at a more general level, we also developed a model of intermediate complexity–a so-called "Goldilocks model" (Ramadantsoa et al. *in prep*.) Drawing from our understanding of Greater Yellowstone, we modeled three major tree-regeneration strategies: (1) fire-sensitive obligate seeders that rely on seed from live trees to regenerate into burned areas (non-serotinous lodgepole pine), (2) obligate seeders that depend on a canopy seedbank (serotinous lodgeople pine), and (3) species that can resprout following fire (aspen). By exploring a wide range of species mixtures and fire rotation, this general model found that these regeneration strategies were complementary. Each dominated under different combinations of fire size and frequency, and functional diversity in regeneration strategies enhanced forest resilience to declining fire rotations.

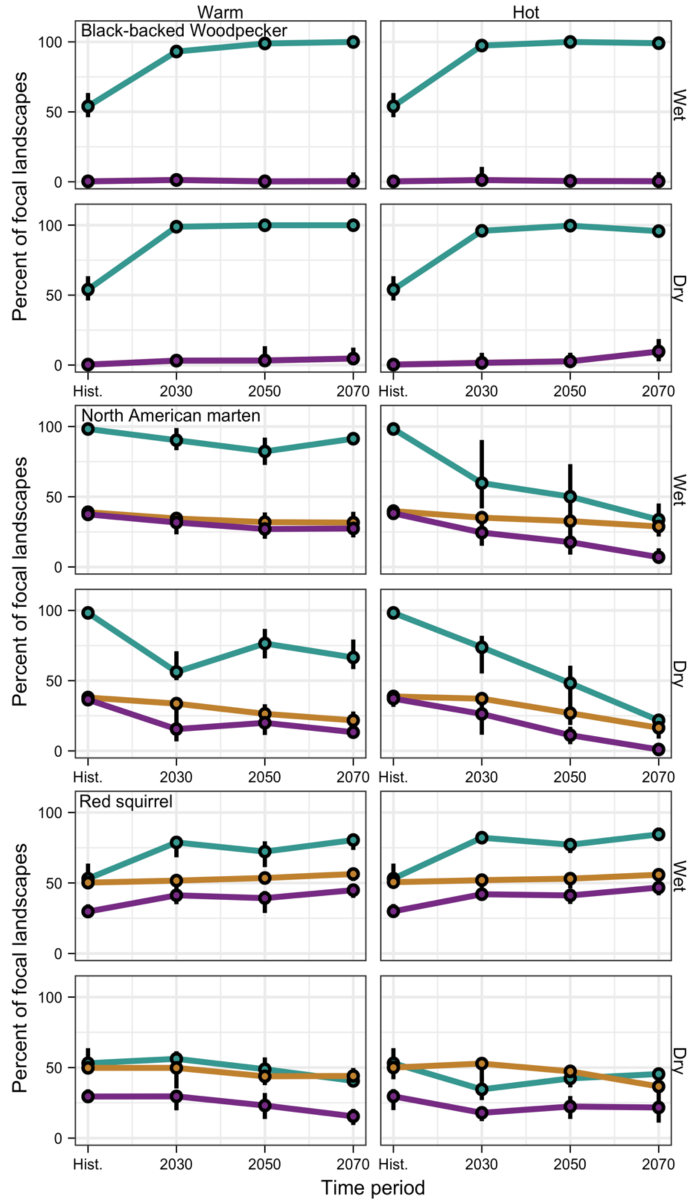


Fig. 11. Estimated habitat area based on climate-only (green), vegetation-only (orange), and joint suitability models (purple) under four CMIP5 future climate projections ("wet" = CanESM2, "dry" = HadGEM2-ES, "warm" = RCP 4.5, "hot" = RCP 8.5). Habitat area is shown as the percentage of the 279,488-ha study area. Error bars indicate 95% confidence intervals based on variability among ensemble models (climate-only), vegetation simulations (vegetation-only) or both (joint model). From Hoecker (2021) and Hoecker and Turner (*in review a*).

Consequences for wildlife habitat. Understanding how 21st-century climate, fire and forest dynamics will affect wildlife habitat was of high interest among the *Dimensions of Resilience* workshop participants. Thus, we used our iLand simulation results to assess how habitat suitability would be affected by changes in climate and forest structure for three forest specialists (Black-backed Woodpecker, *Picoides arcticus*; North American marten, *Martes caurina*; and red squirrel, *Tamiasciurus hudsonicus*) (Hoecker 2021). These species are forest obligates that have contrasting habitat requirements. The Black-backed Woodpecker is a medium-bodied bird native to boreal and cold temperate forests that strongly favors forests burned at high severity within the previous decade. The North American marten is a Mustelid native to boreal and cold temperate forests of North America. Martens are medium-bodied predators that regulate their small mammal prey populations and are themselves influenced by non-consumptive effects (but including competitive killing) of larger predators. The red (or pine) squirrel is a small rodent that feeds primarily on conifer seeds, but also on fruits, leaves and fungi. By extracting and caching conifer seeds and dispersing fungal spores, red squirrels are nodes in trophic webs, mediators of mycorrhizal symbiosis, and agents of selection. For these species, we asked: (1) How does the amount and distribution of potentially suitable habitat for each focal species change during the 21st century based on the independent and joint effects of climate and vegetation? (2) How do spatial patterns of suitable habitat change during the 21st century? We developed separate distribution models for each species based on climate and forest structure, each projected under four climate scenarios (a 2x2 design with moderate and high temperature and precipitation change).

Climatically suitable habitat for the woodpecker increased in all scenarios, and suitable forest structure expanded by a factor of 30 in dry scenarios with more fire (Fig. 11). Climatically suitable habitat for martens declined with warming and drying; the area of suitable vegetation fell >80% with fire-driven losses of mature forest. Red squirrel habitat was maintained in all scenarios, but was sensitive to aridity, and patches were redistributed and compacted. For all three species, we found that suitable habitat based on climate or vegetation alone frequently did not overlap geographically on the landscape (Hoecker 2021, Hoecker and Turner *in review a*). Thus, projections based only on climate may misrepresent future habitat, especially where disturbances accelerate vegetation change. Our results identified substantial consequences of fire-regime change for wildlife in forests dominated by obligate-seeder or fire-sensitive conifers.

Scaling up. Projecting future forest dynamics at a fine spatial resolution (1 ha) but over large geographic regions has posed substantial challenges to current modeling capabilities. Here, we developed a new simulation approach that is able to dynamically scale our stand- and landscape-level projections to larger spatial extents and project regional-scale forest resilience. We began with a state-and-transition approach because these models are efficient at broad spatial scales. However, state-and-transition models are often limited by coarse resolution of the vegetation states that are considered and by inconsistent parameterization of transition probabilities among states. The approach developed here, called SVD (Scaling Vegetation Dynamics; Rammer and Seidl 2019), overcomes these limitations by considering a very large number of current and potential future vegetation states and by basing transition probabilities on simulation results of the process-based model iLand (Seidl et al. 2012). The results of detailed process model runs are assimilated into SVD via deep learning, which is an emerging machine learning approach at the core of many current applications of artificial intelligence. SVD operates at a spatial grain of one hectare and has an annual time step. The model for Greater Yellowstone was driven by the climate and fire projections described above and fire spread is then spatially explicit, as in iLand.

In this first regional application of SVD, we simulated a forest area of 2.9 million ha in the Greater Yellowstone Ecosystem (GYE) and estimated the probability for vegetation transitions during the 21st century (Rammer et al. 2021). We focused again on regeneration failure, i.e. the inability of the prevailing tree species to regenerate after fire, because it is a powerful indicator of the loss of forest resilience. Thus, we (1) quantified the future probability of regeneration failure, (2) identified spatial hotspots of regeneration failure, and (3) assessed how current forest types differ in their ability to regenerate under future climate and fire. By 2100, between 28% and 59% of the forested area failed to regenerate to the prevailing tree species, indicating major loss of resilience (Fig. 12). Areas disproportionally at risk occurred where fires are not constrained by topography and in valleys aligned with predominant winds. Among forest types–and consistent with results from the five representative landscapes (Turner et al. 2021)–high-elevation forest types that are not adapted to fire (i.e., spruce-fir and non-serotinous lodgepole pine forests) were especially vulnerable to regeneration failure (Fig. 12; Rammer et al. 2021).

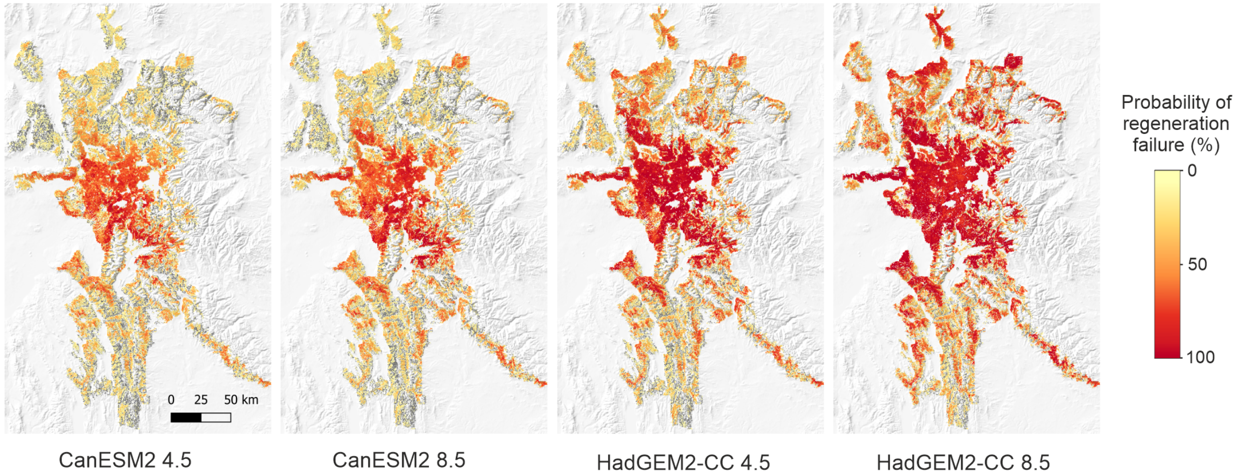


Fig. 12. Spatial distribution of the probability of tree regeneration failure in Greater Yellowstone under four climate change scenarios for the year 2100. The probability is calculated as the average over 20 replicated simulations per scenario. Precipitation increases in the CanESM2 model, whereas aridity increases in the HadGEM2-CC model. For both models, temperature increases by 2100 are lower with RCP 4.5 and greater with RCP 8.5. From Rammer et al. (2021).

Extending to Glacier. While our initial efforts emphasized Greater Yellowstone, a landscape in which we had a long history of research, we are extending this research to other locations–in particular, the more diverse subalpine forests of Glacier National Park. Recent fires in Glacier also offer early examples of expected changes in regional fire regimes that have potential to erode forest resilience, including short-interval fires such as the 2018 Howe Ridge Fire that reburned young forests that regenerated after the 2003 Robert Fire, and high-severity fires such as the 2017 Sprague Fire that burned mesic forests, some as old as 300-400 yrs, not usually exposed to fire. We aimed to anticipate how projected changes in climate and fire will impact forest ecosystems representative of the more diverse forests of the Crown of the Continent. With supplemental funding from the National Park Service, we conducted two years of field study in these recent fires (Hoecker 2021, Hoecker and Turner, *in review b*) that now inform our modeling effort. Extension of iLand to this region is ongoing. Stand-level model runs for the complement of tree species to evaluate simulated stand dynamics against empirical data are underway.

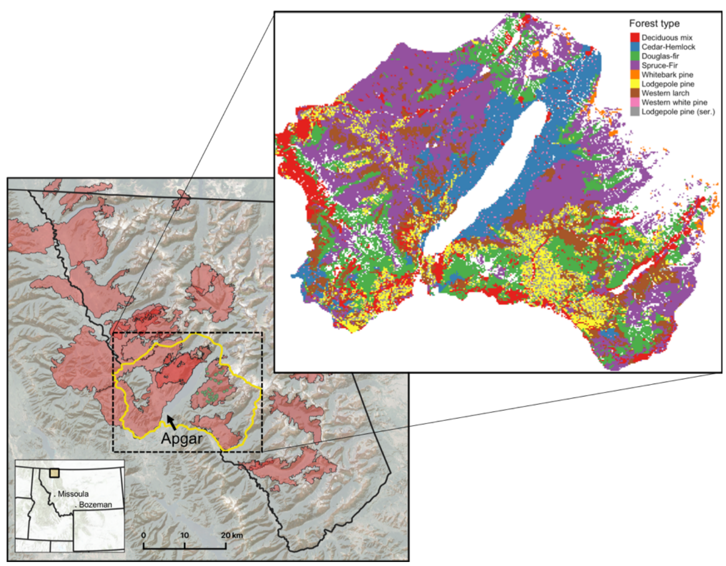


Fig. 13. Location of simulation landscape in Glacier National Park in which climate, fire and forest dynamics will be simulated through 2100. Larger map shows dominant forest types prior to the 2003 Robert Fire (vegetation data from Hop 2007).

With input from Glacier National Park personnel, we identified a ~50,000 ha focal simulation landscape centered on Lake McDonald (Fig. 13). The landscape encompasses a wide range of environmental conditions and forest types, including mesic old-growth cedar-hemlock forests (*Thuja plicata* and *Tsuga heterophylla*), fire-adapted lodgepole pine and western larch, mixed spruce, subalpine fir, and Douglas-fir stands, and treeline stands of whitebark pine (*Pinus albicaulis*). Once iLand is fully calibrated for the suite of tree species, we will explore consequences for forest resilience of the future climate-fire scenarios (3 GCMs x 2 RCPs x 20 realizations of potential future fire activity) generated for this region (Hoecker et al. *in prep*.). Our tree regeneration data suggest that fire-adapted species, including lodgepole pine and western larch, are likely to increase in abundance in a warmer climate with more fire, whereas fire-sensitive mesic species may be vulnerable to decline.

Climate, Fire and Forest Resilience–With Management

Effects of fire suppression on subalpine forests. Fires are suppressed in the Northern Rockies for a variety of reasons, and historical fire suppression in dry forest types (e.g., southwestern ponderosa pine forests) has contributed to the size and severity of some recent fires. However, whether the suppression of subalpine fires in subalpine forests has altered forest landscapes and how future fire suppression might mediate 21st-century climate-fire trends has not been evaluated–and this topic was also raised in our early workshops. Fire managers can effectively suppress smaller fires under average weather conditions, but larger fires that burn under extreme conditions of drought and severe winds are not suppressible. Twentieth-century observations suggest that suppression of subalpine fires has not influenced subsequent fire size or forests–unlike in dry conifer forest types. We used iLand to assess whether 20th-century observations hold under 21st-century conditions by characterizing how a contemporary subalpine landscape would be different if fires had not been suppressed over the last three decades and how letting fires burn affects 21st century fire and forests (Hansen et al. 2020). We simulated a ~60,000-ha forest landscape in Grand Teton National Park from 1989-2099 then contrasted one scenario in which all fires were suppressed when weather conditions were average with another scenario where all fires burned without suppression. We compared cumulative area burned, percent non-forested area, forest age, and tree-species composition.

On average, 200 more ha yr^{-1} burned when fires were not suppressed between 1989 and 2017, but forests changed little, with or without fire suppression (Hansen et al. 2020). In the 21st century, the cumulative area burned increased more rapidly when fires were not suppressed. By 2099, almost twice as much area had burned in the absence of suppression. However, climate change, via its effect on fire, had a much stronger effect on 21st-century forests than did fire suppression. By 2099, stands that were less than 100 yrs old occupied ~85% of forested area, irrespective of suppression. Lodgepole pine dominance declined as Douglas-fir dominance increased (Fig. 14). Most strikingly, approximately 35% of stockable area became non-forested

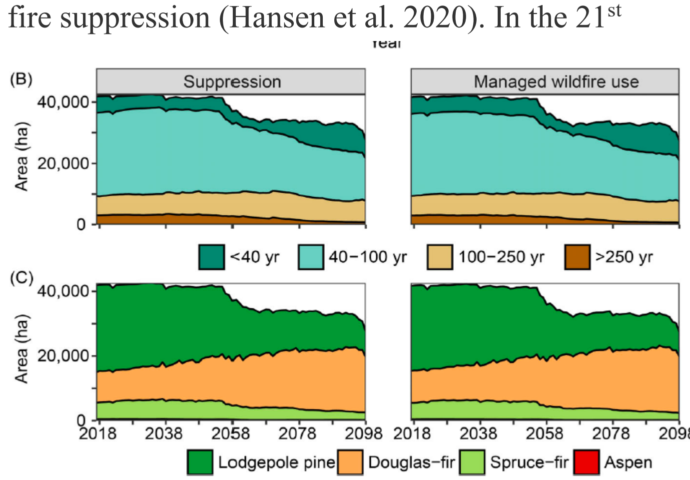


Fig. 14. Stand age and dominant forest type in Grand Teton National Park through 2100under a hot-dry future climate scenario as simulated with and without fire suppression. From Hansen et al. (2020).

by 2099 regardless of whether or not fires were suppressed. Thus, fire suppression could reduce 21st-C burned area but have only a small effect on forest structure and extent. These results suggest management flexibility to suppress subalpine fires strategically for resource benefit (e.g., protection of wildlife habitat or seed sources), with few long-term consequences for 21st-century forests.

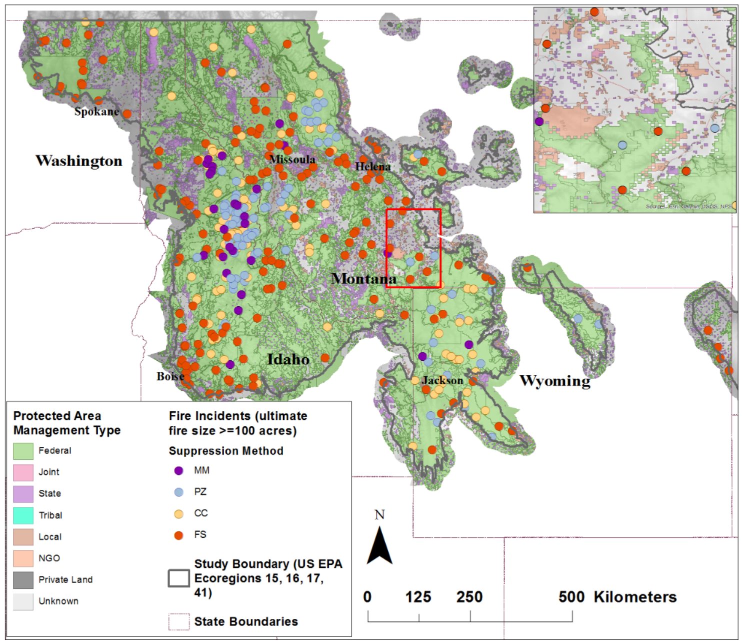
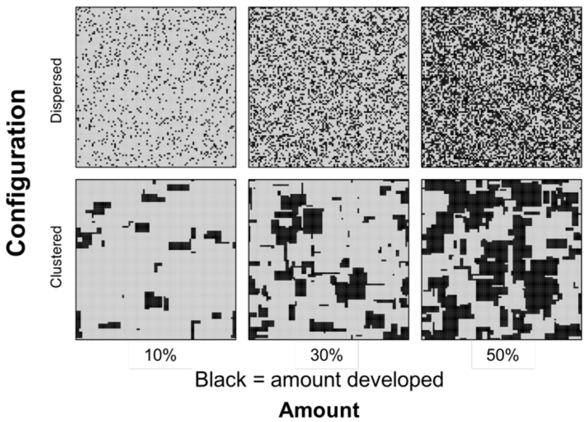


Fig. 15. Locations of fire incident reports used to assess the context of fire suppression decisions. From Daniels (2019).

Fire suppression decisions in the northern US Rockies. When fires ignite, management response decisions are made quickly and re-assessed throughout the fire. Threats to human safety, property, and resources, along with public pressures and agency cultures, often lead to full-suppression decisions. However, managers may select other than full suppression to promote responder safety, reduce firefighting costs, and enhance ecological benefits of fire. In the US, suppression methods are described in publicly available daily incident status summary reports, which also provide detailed information about the fire and its context, including weather and fire behavior outlook and resource status. We used incident reports from the US northern Rocky Mountains to assess the management, socioeconomic, environmental, and fire characteristics associated with full suppression, point-zone protection, confinement/containment, and maintain/monitor suppression methods (Daniels 2019). Regression analyses were developed using fire incident reports from 374 fires between 2008 and 2013 (Fig. 15). Results revealed that full suppression was associated with non-federal land jurisdiction, regional and national incident management teams, earlier report dates within the fire season and human-caused ignitions; full suppression was also more likely in areas of higher housing density, gentle to moderate terrain, grass and shrub fuels, and greater fire size (Daniels 2019). In addition, interviews conducted with revealed the needs, pressures, and incentives that commanders face and how they influence what is reported. Future efforts to encourage less-than-full suppression should address the complex management context faced by incident commanders in addition to the biophysical context of fire.

Resilience in the wildland-urban interface. Fire in the wildland-urban interface (WUI) remains among the most challenging issues in contemporary fire management. As climate conditions and fire activity depart from historical baselines, strategies that enable adaptive resilience in forested WUI landscapes will become increasingly important but are not yet well developed or tested. *Adaptive resilience* is the ability of people to manage for change and therefore maintain resilience in social-ecological systems. The rapidly growing wildland-urban interface (WUI), where structures meet or intermingle with undeveloped wildlands, comprises 10% of the land



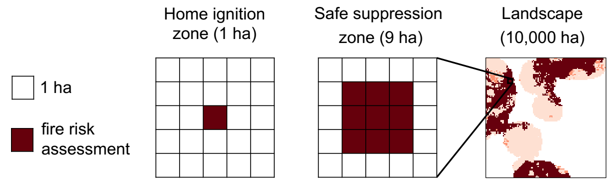


Fig. 16. We simulated six development scenarios differing in amount and configuration (left). We then quantified fire risk at 3 scales to represent potential structure ignition due to direct flame contact or radiant heat (home ignition and safe suppression zones) or due to embers (landscape). From Braziunas et al. (2021).

and one-third of the population of the contiguous US. Fire is expected to increase in nearly 40% of existing western US WUI in the next 20 years, and recent years have underscored the vulnerability of many communities to fire. Removing fuels in defensible space can reduce fire intensity, decreasing firebrand production and likelihood of structure ignition from radiant heat. Housing density and arrangement can also affect likelihood of structure loss. However, it is unclear how treatment effectiveness might change under future climate and fire conditions, and we targeted modeling studies to address this knowledge gap and advanced the capability to link forest dynamics with fire behavior. We used established fire behavior modeling methods to estimate fire intensity at the resolution of a 1-ha grid cell based on fire weather and fuels characteristics derived from iLand outputs (Braziunas et al. 2021). By estimating fire intensity as a dynamic response to changes in forest conditions and environmental drivers, we capitalized on the strengths of iLand to characterize future conditions. Canopy fuel characteristics, surface fire behavior fuel model classification, fire spread rates and intensities, and crown fire occurrence were similar to comparison data and responded appropriately to variation in fuel loads, fuel moisture, and wind speed (Braziunas et al. 2021). We also used fire intensity (flame length, m) to assign fire intensity class (low, moderate, or high). High intensity fire corresponds to flame lengths ≥ 2.4 m, at which point fire control is unlikely to be effective and, as flame lengths increase, extreme fire behavior is likely.

For a subalpine forested landscape (10,816 ha) in the Northern Rockies, we first developed our approach using neutral landscapes, process-based modeling, and custom fire intensity and risk calculations to determine which scenarios of WUI development minimize fire risk over the course of the 21st century. We simulated defensible space treatment scenarios differing in the amount of landscape developed and therefore treated (10%, 30%, or 50%) and in development configuration (dispersed based on rural sprawl, clustered based on conservation development) under three 21st-century climate projections (Fig. 16). We then assessed fire risk to structures at each of three spatial scales (Fig. 16). Home ignition zone risk was quantified as fire intensity within the 1-ha treated area of defensible space around each structure, with higher fire intensities implying increased risk. Safe suppression zone fire risk was quantified as the percentage of structures exposed to high intensity fire in at least one of the eight neighboring grid cells in a given year. Fire risk in the home ignition zone and safe suppression zone were averaged across areas classified as developed and containing structures in the simulation each year, an approach that assumed houses are rebuilt after fire. Fire risk for the entire landscape was quantified by using three landscape metrics calculated for high intensity area burned: percentage of landscape burned at high intensity, largest patch index, and area-weighted mean patch size.

Our simulations using neutral landscapes indicated that area burned always increased during the 21st century, regardless of fuels treatment. Under the warm-dry climate scenarios, the proportion of area that burned at high intensity declined by the end of the 21st century, coinciding with decreasing surface and canopy fuel loads across the landscape. Importantly, defensible space treatments consistently reduced fire risk in the home ignition zone regardless of amount and configuration. However, clustered development configurations were more effective than randomly dispersed configurations at reducing safe suppression zone exposure. At landscape scales, treating 30% of the landscape was required to reduce fire risk. Overall, our results showed that defensible space management plays an increasingly important role in altering local and landscape-level fire intensity and structure exposure as fire activity increases in western subalpine WUI (Braziunas et al. 2021).

Wildfire risk and ecosystem services in the WUI under future climate and management scenarios. We are currently extending our models of fire in the WUI to real-world landscapes and exploring the synergies and trade-offs that may ensue between threats, such as fire risk, and ecosystem services, which are the benefits people derive from nature. We will simulate proposed management strategies for maintaining resilience under 21st-century climate and fire in forested landscapes surrounding two WUI communities in the US Northern Rockies: West Yellowstone, MT and Hamilton, MT (Fig. 17; Braziunas et al. *in prep*.). These landscapes are emblematic of the mixed ownership and diverse forest types that are common in the Northern Rockies. In this analysis, we ask (1) Which management strategies support adaptive resilience under future climate and fire? and (2) How do trade-offs and synergies among threats and services change over time and vary among management scenarios?

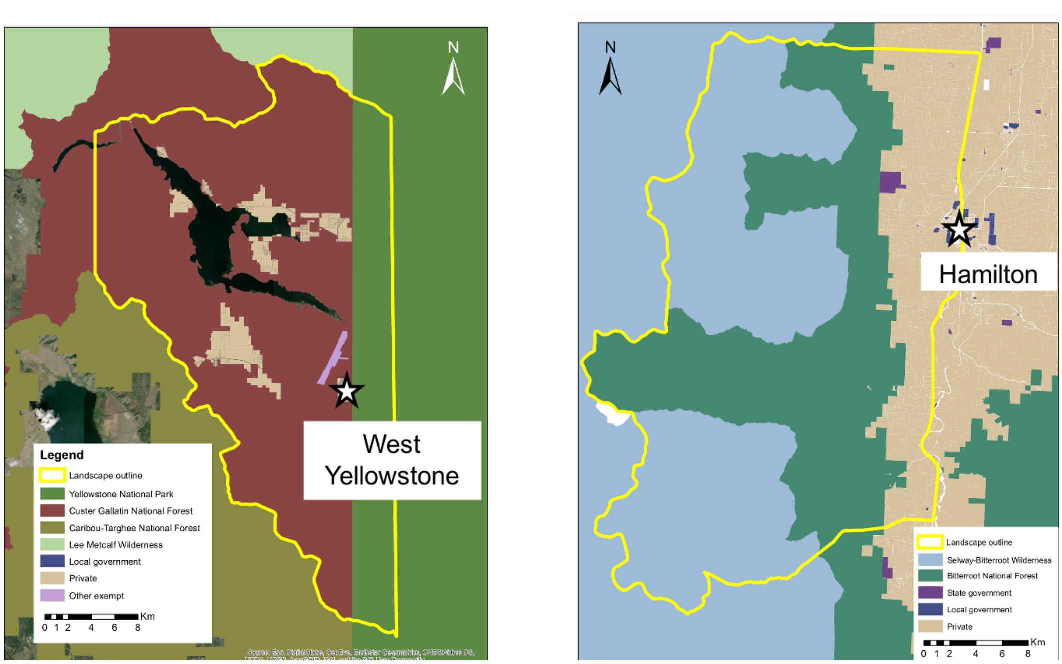


Fig. 17. WUI landscapes in this study are oriented around West Yellowstone, MT in Greater Yellowstone (left) and Hamilton, MT in the Bitterroot Valley (right). These landscapes have different mixes of land ownership, forest types, and fire regimes but share similar challenges in managing fire-prone forests for multiple objectives.

This study is in progress (Braziunas et al. *in prep*.) Input was obtained from participants at our February 2020 workshops, *Learning About Resilient Futures*, and from silviculturists on the Custer-Gallatin and Bitterroot National Forests to design this study. Future climate, fire and forest dynamics will be simulated under 21st century climate scenarios as described above. Initial results illustrate differences in the risk of high-intensity fire in the West Yellowstone landscape under contrasting future climate scenarios (Fig. 18). We will implement management strategies that differ in broad-scale landscape configuration (e.g., fuels treatments dispersed throughout the landscape versus concentrated close to WUI) and in treatment intensity (e.g., business-as-usual versus five times the amount of area treated). Simulation results will be used to assess tradeoff and synergies among a portfolio of ecosystem services that contribute to

Table 2. Focal threats and ecosystem services in to be simulated in the West Yellowstone and Bitterroot forested landscapes, identified in workshops with fire and land managers in February 2017 and 2020 and in Forest Plans. The term baseRV refers to the baseline range of variation, used here as a proxy for current conditions or “status quo”. BaseRV will be quantified over simulated historical period (1980-2020) for comparison with future conditions.

Threat or service	Measurable indicator(s)	Desired conditions
Threats: Fire risk to...		
Structures	High intensity fire near structures	Minimal number of structures exposed to moderate to high intensity fire
Privately-owned or non-federal land	Fire spread and severity on privately-owned or non-federal land, even if no structures present	Minimal fire spread; Minimal area burned at high severity
Critical infrastructure, other resources	Fire spread and intensity near infrastructure (e.g., communication systems, power lines, roads) or other resources (e.g., archaeological)	Minimal fire spread; Minimal area burned at high intensity
Evacuation routes and centers	Overlap of fire spread with critical bottlenecks for evacuation routes (similar to recreation indicator) and designated evacuation centers	Maintain at least 1 evacuation route; Evacuation centers not exposed to moderate to high intensity fire
Water supply, watersheds	High severity fire in municipal watersheds, other watersheds of interest	Minimal area burned at high severity
Ecosystem services		
Timber and fuelwood production	Harvest volume	Sustained yield
Climate regulation	Total live and dead aboveground carbon stocks, net primary productivity	Within baseRV
Microclimate regulation	Canopy cover in recreation areas (campgrounds, fishing areas, lakes, trails, etc.) for shade, local cooling	Maintain canopy cover within baseRV
Recreation	Proportion recreation areas open (Inverse of area burned in campgrounds, other recreation areas). Proportion roads/trails open [Inverse of road/trail closure based on overlap of fire spread with key access points (e.g., trailheads)]	Maximum area open; maximum roads/trails open and accessible
Scenic character	Forest cover, proportion of forest in structure/age classes, proportion of forest by forest type, forest patch size	Maintain forest characteristics within baseRV

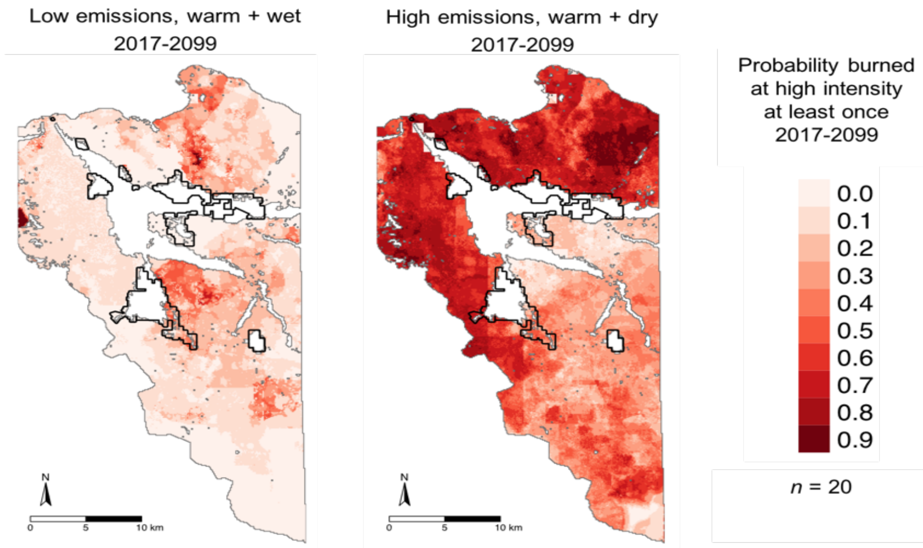


Fig. 18. Example simulations of 21st-century fire in West Yellowstone, MT, under two contrasting climate scenarios. From Braziunas et al. (*in prep.*)

resilience of WUI landscapes in the Northern Rockies (Table 2). We will also evaluate whether resilience is maintained relative to desired conditions, which we based on input from forest plans, workshop participants, and local experts (Table 2).

Learning About Resilient Futures

At the 2020 workshops in Bozeman and Missoula, our research team shared our simulation results at the stand, landscape and regional scales through the 21st century. In response to feedback from our 2017 workshops, these were each 1.5 days rather than 1 day to allow for informal evening discussions and added time for participants to reflect on and react to the materials that we presented. Our results stimulated much discussion that focused a lot on future research directions. Participants were receptive to the results of these models, and they appreciated the role of models as complementary to what is learned from observations, experiments and experience. Many commented that models help to fill gaps in knowledge, and they "open the door" to thinking seriously about the range of possible futures. Participants also noted the value of heterogeneous forest structures on the landscape and were especially interested in the fate of forest lands that transition to non-forest vegetation. What will replace the forests? There was substantial interest in tipping points, and why some forest types or landscapes were more or less resilient to climate change and fire than others. That effects of climate change and fire could overwhelm effects of forest management challenged assumptions, and uncertainty about the natural role of fire in a changing world was discussed. Many questions were raised. What should the future objectives of fire management be? What do climate-adapted fire regimes look like? If a goal is to maintain forest, how should that be done? How can tree regeneration failure be avoided? Is resilience even attainable, given the expected rates of environmental change? What are the consequences of losing old-growth forests? Is active management or the lack of management a greater threat to persistence of old-growth? How can flexibility in management be increased as challenges are becoming more complex?

Participants also emphasized the importance of communicating results of this study widely and the importance of making liberal use of pictures, graphs, visualizations and stories. The importance of communicating tradeoffs was also emphasized, recognizing that it is "impossible to have it all." Participants appreciated the value of scenarios that explored a range of futures without attempting to predict the future; the salient point was that managers will likely need to prepare for a range of alternatives, as there are multiple possible futures. Participants agreed that the sense of urgency was clear, but that lack of appreciation for the rate and magnitude of likely changes in forested landscapes was widespread.

Conclusions (Key Findings), Implications for Management/Policy and Future Research

Key Findings

- Use of the word "resilience" in relation to western forests has risen in both scientific publications and management documents since about 2010, and despite some differences in use, there is common ground associated with climate change.
- Most contemporary forest models–often developed to reach other goals–lack important resilience mechanisms and may not be well suited to explore forest resilience during an era of rapid change.
- Climate-driven change in fire regimes rather than climate change *per se* is likely to be the proximate cause of substantial 21^{st}-century changes in US Northern Rocky Mountain forests.
- Postfire tree regeneration, which is critical for sustaining forest resilience, is projected to decline if more frequent fires reduce local seed availability, larger burn patches exceed effective dispersal distances, and postfire climate conditions are not conducive to seedling establishment.
- After integrating climate-based statistical models with dynamic fire spread and accounting for uncertainty in future scenarios, our results suggest a mid-21^{st} century peak in high-severity fire and WUI fire risk in Greater Yellowstone, although annual area burned continues to rise.
- Under a hotter-drier climate, forest extent is projected to shrink substantially during the 21^{st} century, and remaining forests will be younger and sparser than current forests.
- Forests dominated by fire-sensitive tree species (e.g., Engelmann spruce, subalpine fir, lodgepole pine) are likely to show the greatest declines, whereas forests dominated by fire resisters (e.g., Douglas-fir, larch) and reprouters (e.g., aspen) will be more resilient.

- In Greater Yellowstone, fire rotations < 40 yrs may pass a tipping point associated with sharp decline in forest extent.

- Forest losses during the 21st century are more likely in landscapes with little topographic relief compared to those with steep elevational gradients.

- Monitoring changes in forest structure (e.g., tree density and basal area) may serve as an operational early warning indicator of impending forest loss.

- During the 21st century, climatically suitable areas for three forest-dependent wildlife species often did not intersect with locations where simulated vegetation structure was also suitable. Projections based on climate or vegetation alone are likely to misrepresent future availability of suitable habitat.

- Fire suppression is unlikely to alter the trajectory of 21st-century forest change in subalpine landscapes managed for wilderness values because forest dynamics will be driven primarily by large fire years and increasingly arid conditions.

- In areas of wildland-urban interface (WUI), clustering developments and applying fuels treatments on 10 to 30% of the landscape every 10 years can reduce fire risk across multiple scales.

- Rising temperatures alone are insufficient to produce landscape-level changes in forest structure, composition and extent; rather, it is the combined effects of rising temperature, increased aridity, and fire.

- "Bending the curve" of greenhouse gas emissions to stabilize atmospheric concentrations by mid-21st century will dampen the consequences of climate warming for forest landscapes.

- Collaboration among managers, scientists and academics was extremely fruitful. Early input on study design, face-to-face meetings with follow-up, and joint interpretation of study results and model output strengthened ties between research and application.

Management Implications

Key objectives of federal fire management in the western United States include (1) ensuring people and property are protected from wildfire, and (2) maintaining natural fire regimes and fostering mosaics of forest structure, stand age, and tree species composition. Results of our studies help managers to consider longer time frames, to imagine a range of plausible futures that account for future uncertainties, and to anticipate the magnitude of changes that could affect their forest landscapes during the 21st century. Our study suggests that future fire activity in the Northern Rockies will differ substantially from the historical past. The shorter fire rotations observed in today's forest landscapes may be the longest rotations observed by the end of the century. Results suggest that areas of high-severity fire may peak in the middle third of the century then decline even as annual area burned continues to rise. In response to these changes, forests could shift in extent, structure and composition more than they have for thousands of years; not all forests will be resilient. Communicating these dynamics to the public will become increasingly important. However, forest attributes will not change at the same rates, and we identified indicators of forest structure that may be harbingers of subsequent forest loss. It is also important to recognize that some species may benefit from these changes and extend their ranges. For example, Douglas-fir and aspen are likely to expand in forests of Greater Yellowstone, and western larch may expand in Glacier. Compositional change in forest communities may allow forest cover to persist, and habitat may be maintained for some wildlife species. Workshop attendees concluded that plans to manage for forest resilience in the decades ahead should consider multiple possible outcomes.

Fire suppression and fuels treatments will likely slow rather than prevent change, and long-term forest outcomes may not be changed. However, such actions could buy more time for ecosystems to adjust. Fire should and will continue to shape landscape mosaics of forest structure, age and composition. Nonetheless, strategic use of fire suppression in subalpine forests might be warranted not only for protecting high-value assets (e.g., buildings and infrastructure) but also for maintaining valued ecosystem attributes (e.g., old growth forest, wildlife habitat) that are at risk. Forest transitions can be irreversible for thousands of years if seed sources are depleted by frequent fire (e.g., especially for fire-sensitive species). Thus, fuels management might be desirable in areas where forest recovery could be in jeopardy, or where protecting certain forests is important. In addition, factors limiting postfire regeneration could be countered by management. Assisted migration of genetic ecotypes or species likely to thrive in a changing climate might be worth considering in areas not managed for wilderness values. However, it is equally important to allow ecological processes to play out without interference in wilderness landscapes. Our study relied critically on data from long-term study of such areas, and new lessons remain to be learned from lightly managed forest landscapes.

In forested WUI landscapes, fire risk to structures will increase in the coming decades, and some exposure to high intensity fire is likely unavoidable even when defensible space is treated. However, fuels reduction in the WUI has potential to substantially reduce fire risk to structures, with effectiveness of different actions varying with scale. Our study offers a template for assessing fire risk to structures at multiple scales to better incorporate different mechanisms of structure ignition due to wildfire.

Ultimately, our results suggest that managers should consider the potential effects of reduced forest cover and younger, sparser forests for wildlife habitat, aesthetics, timber production and recreational use in the northern Rocky Mountain region. Minimizing additional stresses on forest ecosystems (e.g., invasive species) may become increasingly important. Monitoring postfire tree regeneration in recent and future fires will be critical for determing whether postfire recovery has been compromised. Ongoing analyses of repeated surveys (e.g., FIA plots) will allow forest managers to track regional change in forest structure and composition and determine whether forests are approaching a threshold. Finally, the in-person workshops conducted as part of this project fostered effective communication and valuable discussions that shaped the research. Results could catalyze forward-looking discussions about resource management and research priorities among the agencies.

Future Research Directions

Our project results suggest several important directions for future research.

Vegetation-fire feedbacks. Feedbacks from vegetation (fuels) to fire regimes warrant additional research. Interest in this topic is considerable, yet studies have produced conflicting results, in part because of variation in forest and fuel conditions and fire weather. When and where are fires likely to be self-limiting, and when and where are sequential fires likely to amplify or dampen fire severity?

Tipping points. How do tipping points vary among different forest types and fire regimes? Threshold relationships deserve further attention, with the particular need to distinguish changes that are abrupt in time (e.g., Turner et al. 2021) from changes that are abrupt relative to a driver variable, such as fire rotation (e.g., Ratajczak et al. 2018, Turner et al. 2020, Ratajczak et al. *in prep.*).

Vegetation dynamics. How are postfire regeneration and forest structure changing during stand development relative to historical baselines? What will be the fate of forests that convert to sparse woodlands or non-forest? How will ecosystem services change across forested landscapes in the decades ahead? Our results highlight the importance of tracking forest change over time, with particular emphasis on patterns of postfire tree regeneration because these can establish stand development trajectories for decades to centuries.

CO_2 fertilization, forest dynamics and fuels. How increasing atmospheric CO_2 concentrations will affect tree growth and water use efficiency in western forests during coming decades is not well understood. Could elevated atmospheric CO_2 lead to more fuels on the landscape, and what is the effect of CO_2 fertilization relative to the myriad factors that constrain forest productivity? Our approach was conservative, but future research–both field and modeling studies–on effects of CO_2 fertilization are warranted.

Cascading consequences of more fire. Many more topics and questions were raised at our workshops than could possibly be addressed by any individual research project. Beyond what we have considered, there remains keen interest in projecting the consequences of changes in climate, fire and forests for aquatic resources, including water supply, flood risk, and fisheries; recreation; aesthetics; and wildlife. There was especially high interest in understanding how invasive species (e.g., cheatgrass, *Bromus tectorum*, which has altered fire regimes throughout the Great Basin; Fusco et al. 2019) will respond to forest landscape change and whether new vegetation-fire feedbacks could emerge in the Northern Rockies. In addition, how increased fire activity will affect disturbance interactions throughout the 21st century–considering compound and linked disturbances, and amplifying and dampening effects (Simard et al. 2011, Harvey et al. 2013, Seidl et al. 2016)–is also an important area for future research.

An evolving role for fire management. Managing wildfires for resource benefit has been an important management option in forests of the Northern Rockies. Whether and how fire management for resource benefit should evolve as climate and fire regimes change is of growing interest. For example, can fire management be used by "buy time" for forest ecosystems to adapt to climate change? What amounts and configurations of fire and fire suppression are most effective at meeting management objectives? Can fire suppression or fuels management protect forests identified as crucial wildlife habitat or key seed sources for postfire tree regeneration or species expansion?

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Turner, M. G., K. H. Braziunas, W. D. Hansen, T. J. Hoecker, W. Rammer, Z. Ratajczak, A. L. Westerling, and R. Seidl. 2021. The magnitude, direction and tempo of forest change in Greater Yellowstone in a warmer world with more fire. Ecological Monographs (In press)
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Appendix A: Contact Information for Key Project Personnel

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery

1. Articles in peer-reviewed journals

Published or in review (n = 15)

Albrich, K., W. Rammer, M. G. Turner, Z. Ratajczak, K. H. Braziunas, W. D. Hansen, and R. Seidl. 2020. Simulating forest resilience: a review. Global Ecology and Biogeography 29:2082-2096.

Braziunas, K. H., W. D. Hansen, R. Seidl, W. Rammer, and M. G. Turner. 2018. Looking beyond the mean: Drivers of variability in postfire stand development of conifers in Greater Yellowstone. Forest Ecology and Management 430:460-471.

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Hansen, W. D., D. Abendroth, W. Rammer, R. Seidl, and M. G. Turner. 2020. Can wildland fire management alter 21st-century fire patterns and forests in Grand Teton National Park? Ecological Applications 30(2), e02030.

Hoecker, T. J., and M. G. Turner. Interactions between climate and fire-driven vegetation change constrain the distributions of forest vertebrates during the 21st century. Diversity and Distributions (*In review)*.

Rammer, W., K. H. Braziunas, W. D. Hansen, Z. Ratajczak, A. L. Westerling, M. G. Turner, and R. Seidl. 2021. Widespread regeneration failure in forests of Greater Yellowstone under scenarios of future climate and fire. Global Change Biology 27:4339-4351.

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Rissman, A. R., K. D. Burke, H. A. C. Kramer, V. C. Radeloff, P. R. Schilke, O. A. Selles, R. H. Toczydlowski, and C. B. Wardropper. 2018. Forest management for novelty, persistence, and restoration influenced by policy and society. Frontiers in Ecology and the Environment 16:1-9.

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Selles, O. A., and A. R. Rissman. 2020. Content analysis of resilience in forest fire science and management. Land Use Policy 94:104483.

Sommerfeld, A., C. Senf, B. Buma, A. W. D'Amato, T. Després, I. Díaz-Hormazábal, S. Fraver, L. E. Frelich, A. G. Gutiérrez, S. J. Hart, B. J. Harvey, H. S. He, Tom´s Hlásny, Andrés Holz, T. Kitzberger, D. Kulakowski, D. Linednmayer, A. S. Mori, Jörg Müller, J. Paritsis, G. Perry, S. Stephens, M. Svoboda, M. G. Turner, T. T. Veblen, and R. Seidl. 2018.

Patterns and drivers of recent disturbances across the temperate forest biome. Nature Communications 9:4355.
Turner, M. G., K. H. Braziunas, W. D. Hansen, and B. J. Harvey. 2019. Short-interval fire erodes the resilience of subalpine lodgepole pine forests. Proceedings of the National Academy of Sciences 116:11319-11328.
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Turner, M. G., K. H. Braziunas, W. D. Hansen, T. J. Hoecker, W. Rammer, Z. Ratajczak, A. L. Westerling, and R. Seidl. 2021. The magnitude, direction and tempo of forest change in Greater Yellowstone in a warmer world with more fire. Ecological Monographs (*In press*).

Planned articles with tentative titles (n = 5)

Braziunas, K. H., T. J. Hoecker, R. Seidl, W. Rammer, A. R. Rissman, and M. G. Turner. Managing wildland urban interface landscapes to minimize wildfire risk and maintain ecosystem services under future climate and fire. (*In prep*.)
Daniels, M. C., K. H. Braziunas, T. F. Ma, K. C. Short, M. G. Turner, and A. R. Rissman. Multiple social and environmental factors affect wildland fire response of full or less-than-full suppression. (*In prep*.)
Hoecker, T. J., K. H. Braziunas, R. Seidl, T. Simensen, W. Rammer, and M. G. Turner. Anticipating 21st-century forest dynamics in Glacier National Park. (*In prep*).
Ramiadantsoa, T., Z. Ratajczak, and M. G. Turner. Regeneration strategies and forest resilience to changing disturbance regimes: insights from a Goldilocks model. (*In prep)*.
Ratajczak, Z., K. H. Braziunas, W. Rammer, R. Seidl, A. L. Westerling, and M. G. Turner. Tipping points in Greater Yellowstone forests with increasing wildfire activity. (*In prep.*)

2. Technical reports

None.

3. Text books or book chapters

None.

4. Graduate theses

Braziunas, K. H. 2018. Looking beyond the mean: Drivers of variability in postfire stand development of Rocky Mountain conifer forests. MS Thesis, Department of Zoology, University of Wisconsin-Madison, Madison, WI.
Braziunas, K. H. *In progress*. Operationalizing resilience of social-ecological systems to changing climate and fire in US Northern Rocky Mountain forests. PhD Dissertation, Department of Integrative Biology, University of Wisconsin-Madison, Madison, WI. (December 2021 defense).

Daniels, M. C. 2019. Complexities in decision-making by natural resource managers: a study of fire suppression decisions in the Northern Rockies. MS Thesis, Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, Madison, WI.

Hansen, W. D. 2018. Resilience to changing climate and wildfire in subalpine forests of Greater Yellowstone. PhD Dissertation, Department of Zoology, University of Wisconsin-Madison, Madison, WI.

Hoecker, T. J. 2021. Anticipating subalpine landscapes of the future: Response to climate and fire-regime change in the northern US Rocky Mountains. PhD Dissertation, Department of Zoology, University of Wisconsin-Madison, Madison, WI.

Selles, O. A. 2018. The use of the work "resilience" in forest and fire management and science in the western United States. MS Thesis, Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, Madison, WI.

5. Conference or symposium proceedings

None.

6. Conference or symposium abstracts

Braziunas, K. H., R. Seidl, W. Rammer, and M. G. Turner. 2019. Can we manage a future with more fire? Effects of climate, fuels treatment, and spatial configuration on fire risk in the wildland urban interface. US-IALE Annual Landscape Ecology Symposium, Fort Collins, CO.

Braziunas, K. H., W. D. Hansen, R. Seidl, W. Rammer, and M. G. Turner. 2017. Age alone is not enough: Multiple drivers control postfire stand development in Rocky Mountain conifers. Annual Meeting of the Ecological Society of America, Portland, Oregon.

Hansen, W. D., K. H. Braziunas, W. Rammer, R. Seidl, and M. G. Turner. 2017. A perfect storm: Multiple stressors interact to drive postfire regeneration failure of lodgepole pine and Douglas-fir forests in Yellowstone. Annual Meeting of the Ecological Society of America, Portland, OR.

Hansen, W. D., W. Rammer, R. Seidl and M. G. Turner. 2018. Fire suppression in 21st century subalpine forests of Greater Yellowstone. Annual Meeting of the Ecological Society of America, New Orleans, LA.

Hoecker, T. J., Z. Ratajczak and M. G. Turner. 2020. Fire-driven changes in subalpine forest landscape reduce habitat for forest wildlife during the 21st century. Annual Meeting of the Ecological Society of America (virtual).

Rammer, W., Z. Ratajczak, A. L. Westerling, M. G. Turner, and R. Seidl. The scaling of resilience: projecting regeneration failure under future climate and fire regimes for Greater Yellowstone. International Congress for Landscape Ecology, Italy.

Ratajczak, Z., K. H. Braziunas, W. D. Hansen, W. Rammer, R. Seidl, and M. G. Turner. 2018. Does functional diversity increase resilience to more extreme fire regimes in a subalpine forest? Annual Meeting of the Ecological Society of America, New Orleans, LA.

Ratajczak, Z., K. H. Braziunas, W. Rammer, R. Seidl, A. L. Westerling, and M. G. Turner. 2020. Tipping points in Greater Yellowstone forests with increasing wildfire activity. Annual Meeting of the Ecological Society of America (virtual).

Turner, M. G., B. J. Harvey, W. D. Hansen, and K. H. Braziunas. 2018. Is increased fire frequency likely to erode resilience of lodgepole pine forests in Yellowstone? US-IALE annual landscape ecology symposium, Chicago, IL.

Turner, M. G., B. J. Harvey, W. D. Hansen, and K. H. Braziunas. 2018. Changing fire regimes and resilience of lodgepole pine forests in Yellowstone. Annual Meeting of the Ecological Society of America, New Orleans, LA.

Turner, M. G., Z. Ratajczak, K. H. Braziunas*,* W. D. Hansen, T. J. Hoecker, W. Rammer, R. Seidl, and A. L. Westerling. 2020. Abrupt changes in subalpine forest landscapes in a warmer world with more fire. American Geophysical Union annual meeting (virtual, invited).

Turner, M. G., Z. Ratajczak, K. H. Braziunas*,* W. D. Hansen, T. J. Hoecker, W. Rammer, R. Seidl, and A. L. Westerling. 2021. The magnitude, direction and tempo of mountain forest change in a warmer world with more fire. International Association for Landscape Ecology - North America (IALE-NA) annual meeting (virtual).

Turner, M. G., Z. Ratajczak, K. H. Braziunas*,* W. D. Hansen, T. J. Hoecker, W. Rammer, R. Seidl, and A. L. Westerling. 2021. The magnitude, direction and tempo of forest change in Greater Yellowstone in a warmer world with more fire. Ecological Society of America Annual Meeting (virtual, invited).

7. Posters

Braziunas, K. H., W. D. Hansen, R. Seidl, and M. G. Turner. 2016. Adapting the process-based model iLand to simulate subalpine forest dynamics in Greater Yellowstone. 13th Biennial Scientific Conference of the Greater Yellowstone Ecosystem. October 4-6, 2016, Jackson Lake Lodge, Moran, WY. Poster presentation.

Braziunas, K. H., W. D. Hansen, R. Seidl, W. Rammer, and M. G. Turner. 2018. Looking beyond the mean: Drivers of variability in postfire stand development of Rocky Mountain conifers. US-IALE Annual Meeting, Chicago, IL, April 8-12.

Braziunas, K. H., R. Seidl, W. Rammer, A. R. Rissman, and M. G. Turner. 2018. Can we manage a future with more fire? Effects of defensible space and spatial configuration on local and landscape-level fire severity. Ecological Society of America Annual Meeting, New Orleans, LA, August 5-10.

8. Workshop materials and outcome reports

2017 Organized and led 1-day workshops for forest and fire managers in the Northern US Rocky Mountains on “Dimensions of forest resilience”, one day in Bozeman, MT and one day in Missoula, MT. Workshops were co-sponsored by the Northern Rockies Fire Science Network.

2020 Organized and led 1.5-day workshops for forest and fire managers in the Northern US Rocky Mountains on “Learning about resilient futures”, workshops held in both Bozeman, MT and Missoula, MT. Workshops were co-sponsored by the Northern Rockies Fire Science Network.

9. Field demonstration/tour summaries

None.

10. Website development

None.

11. Presentations/webinars/other outreach/science delivery materials.

NRFSN Research Brief

"What makes a resilient landscape? Climate, fire and forests in the northern Rockies." Northern Rockies Fire Science Network Research Brief 9. July 2021. Authored by Monica Turner, editing and layout by Cory Davis and Signe Leirfallom.

Public Presentations Related to this Project

Braziunas, K. H. 2019. Western forests in an uncertain future: How will changing climate and increasing fire activity affect forested and human landscapes in the Greater Yellowstone Ecosystem? Environmental Studies and Biology, Oberlin College, Oberlin, OH. Public talk (Invited).

Turner, M. G. 2018. Fires in the West and forests of the future: Lessons from Yellowstone. Crossroads of Ideas (public lecture), Wisconsin Institute for Discovery, Madison, WI. 20 March (Invited).

Turner, M. G. 2018. Yellowstone Fires and the American West. Public lecture and discussion for *Science on Tap* held at the Nomad World Pub, Madison, WI. 5 September.

Turner, M. G. 2019. Fire in Yellowstone and forests of the future. Hood Lecture (public), School of Environment, University of Auckland, New Zealand. 7 March.

Turner, M. G. 2019. Forest and fire in Greater Yellowstone: What does the future hold? American Alpine Club Climber's Ranch, Grand Teton National Park, public talk for guests, 19 July.

Turner, M. G. 2021. A fiery future: Are widespread megafires the new normal? Facebook Live event, programmed by The Franklin Institute, Philadelphia, PA. Viewable on YouTube: https://youtu.be/SkHY8OXsTPc

General Audience Articles

Turner, M. G. 2019. Fire in Yellowstone. Ranger 35(4):10-12.
Invited article for the journal of the Association of National Park Rangers, Fall 2019

Video

Fires in the West may be changing the future of forests. YouTube video featuring members of this team discussing changing fire regimes, field research and models in Greater Yellowstone. Released by the University of Wisconsin-Madison in August 2018.
https://youtu.be/dD8VLS5F2Xo

Selected Media Coverage

McDermott, Amy. 2020. News feature: Foreseeing fires. PNAS September 8 117:21834-21838. (Highlights PhD work by W. D. Hansen in the Turner lab and quotes Turner). https://www.washingtonpost.com/climate-environment/2020/09/16/fires-climate-change/

Koshmrl, Mike. 2020 What's in the forecast? Lots of fire, less forest. Jackson Hole New & Guide, September 23. https://www.jhnewsandguide.com/special/conservation/what-s-in-the-forecast-lots-of-fire-less-forest/article_d3f7328c-bb3b-59c3-8868-bf4d0b5c7bfb.html

Pennisi, Elizabeth. 2020. As wildfires continue in western United States, biologist fear for vulnerable species. Science 370(6512):18-19, 2 October. https://www.sciencemag.org/news/2020/09/wildfires-continue-western-united-states-biologists-fear-vulnerable-species

Appendix C: Metadata

All data and full metadata associated with publications based on primary research from this project have been archived in publicly available databases as indicated below. We followed standards specified in the Ecological Metadata Language (EML), and data and metadata are published with assigned DOIs or on github, which is used commonly for modeling studies. Relative to empirical data, archiving model versions, simulation outputs, and analysis codes is more complex. The Environmental Data Initiative (EDI; https://environmentaldatainitiative.org/), funded by the National Science Foundation, has become one of the best repositories for ecological data. EDI is well positioned to accept data from simulation studies, provides excellent support for both deposit and search, and will be curated into the future. We have provided the archived data below to the Forest Service Research Data Archive so that data from this project will be available through that platform and linked to the appropriate DOIs. Data and metadata will continue to be archived in association with forthcoming publications. The URLs for all published data are listed below by publication.

Albrich et al. 2020
Data and code used in the analysis are available at https://doi.org/10.6084/m9.figshare.12958166

Braziunas et al. 2018
The model output data that support the findings of this study and files to recreate model simulations are openly available in the Environmental Data Initiative (EDI) at DOI https://doi.org/10.6073/pasta/152ed98663904892d9d11903949cadb7

Braziunas et al. 2020
Data, code, and software used for model simulations and analyses are available on the EDI Data Portal:
https://doi.org/10.6073/pasta/696e59acecd0bd289dae1afe3316c09c

Hansen et al. 2018
All data and metadata are available on the EDI Data Portal:
https://doi.org/10.6073/pasta/77c3807c43dedd0acd0ed65d097d0077

Hansen et al. 2020
All data and metadata are available on the EDI Data Portal:
https://doi.org/10.6073/pasta/0107f11a3fe019de1d61fdfe88d72118

Rammer et al. 2021
The code and data that support the findings of this study are openly available at https://github.com/SVDmo del/SVD (https://doi.org/10.5281/ zenodo.4810960), and https://github.com/SVDmo del/models (https://doi.org/10.5281/zenodo.4811079).

Turner et al. 2019
All data and metadata are available on the EDI Data Portal:
https://doi.org/10.6073/pasta/a1b7791376a04ce8c6ea9043547bb6af

Turner et al. 2021
All data and metadata are available on the EDI Data Portal:
https://doi.org/10.6073/pasta/e0c3aaa9b49478f9ebea8fce93b14fe7