Western Fire & Forest Resilience Collaborative

Science Vision

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Abstract

The frequency and size of forest fires in the western United States (US) are rapidly increasing as climate changes. Concurrent with anthropogenic drying, a century of fire suppression and exclusion of Indigenous cultural burning has also led to fuel densification in some western forests, causing proliferation of high-severity fire where burning was historically low intensity. Together, climate change and legacies of fire suppression signal an even more fiery future. Projections indicate that extreme drought risk could grow 300% by 2100 over a pre-industrial baseline. Models of future fire suggest the record-breaking area burned in 2020 will become the annual average by mid-century. If projections are accurate, western US forests will reorganize to fundamentally different ecosystem types, and the west US will be an unsustainable place to live. Decision makers are tasked with stewarding western forests during this period of profound environmental change. Innovative approaches are emerging, like the Resist, Accept, Direct framework, which helps them conceptualize the complete domain of potential responses to ecosystems undergoing rapid change. However, such frameworks require rigorous science to underpin them. Here, we describe our efforts to partner with decision makers and co-produce the science vision for a new multi-year program called the Western Fire and Forest Resilience Collaborative (WFFRC).

The three questions that guide the science vision of WFFRC are:

1. How and why are forests and fire regimes in the western US changing, and how will they change in coming decades under different scenarios of management and climate change?
2. What are the consequences of current and future forest and fire trajectories for critical ecosystem services including biodiversity, forest carbon storage, air quality, human-settlement vulnerability to fire, and provision of water?
3. What innovative management strategies and adaptation efforts are needed to respond to projected changes and at what spatial and temporal scales?

We will address these questions in all forests in the western United States by pursuing the following objectives:

1. Build a community of practice that ensures the research agenda is responsive to decision-maker needs and that the best available science guides decision making and adaptation.
2. Understand and predict where and when the risk of non-reversible forest reorganization or transition to grasslands and shrublands is greatest and identify the mechanisms that may underpin forest change.
3. Quantify how fire regimes and resulting forest structure and function are changing across the western US.
4. Quantify the drivers of observed trends in forest fire, project how forests and fire regimes will continue to change in the future, and determine how current and future stewardship actions may shape future outcomes.
5. Quantify current and future consequences for people, biodiversity, and ecosystem services essential to human well-being and economies.

By combining field sampling, remote sensing, process-based simulation, and geospatial data synthesis, WFFRC could collectively address the trans-disciplinary and cross-cutting challenges of understanding and anticipating forest ecosystem change in the large fire era.

PROJECT DESCRIPTION

1. Background and vision

The frequency, size, and severity of forest fires in the western United States (US) have increased at astonishing rates over the last four decades [1–4]. Annual burned forest area grew more than 1,000 percent since the early 1980s [5], culminating, thus far, in the fire seasons of 2020 and 2021 that both shattered previous records [6,7]. Intensifying fire regimes are in large part attributable to ongoing human-caused climate change [3,8,9], which manifests as warming and drying in the western US [10–14]. In fact, much of the region just recently emerged from the driest 22-year period in 1,200 years [15,16]. Concurrent with anthropogenic drying, a century of near universal fire suppression and exclusion of Indigenous cultural burning has led to a densification of fuels in some western forests, causing the proliferation of high-severity stand-replacing fire where burning was historically frequent but low intensity [17–22].

Together, climate change and fuel densification situate modern western US fire regimes in a new large-fire era, many elements of which are likely unprecedented since pre-Euro American settlement [23,24]. Beneficial fire, tuned to the historical range of variability, still regularly occurs and even dominates western US fire regimes. However, we are now increasingly experiencing “catastrophic" fires that are uncharacteristically frequent and high-severity. We are also seeing massive increases in annual burned area. In parallel, changing climate and increased fire have profound implications for the resilience of western forests and human communities [25–28]. We define resilience as the ability of a system to absorb, recover, or adapt to disturbance without losing its fundamental identity [29].

Fire is an essential Earth system process, and conifer forests like those found in the western US burned in high-severity fires as early as 350 million years ago [30,31]. Many tree species in the western US are evolutionarily adapted to burning [32]. However, intensifying fire regimes are beginning to overwhelm key mechanisms that previously ensured robust forest recovery [25,33,34]. For example, tree regeneration is a resilience lynchpin following high-severity fire [35]. Seedlings that establish in the first few years to decades postfire dictate forest structure and functions, sometimes for centuries [26,36–38]. More frequent high-severity fire, larger severely burned patches, and an increasingly hostile climate can individually or collectively constrain seedling establishment and even cause tree regeneration failure [28,33]. Modern climate is likely already too dry across vast swaths of the western US to support robust postfire tree regeneration [26], including 20% of forests in the iconic Sierra Mountains of California [39]. In fact, wildfires in 2020 and 2021 caused the loss of as many as 19% of all the giant sequoias on Earth [40,41]. Given current and expected trends, we are likely on the precipice of abrupt and widespread transitions from forest to grasslands and shrublands.

Catastrophic fires also threaten people and communities in the western US. The wildland urban interface (WUI), areas where houses meet or intermingle with often flammable natural vegetation, was the fastest growing land cover type in the US between 1990 and 2010 [42]. While WUI expansion has slowed nationally, substantial regional variation in growth rates persist. For example, expansion of WUI accelerated in Texas during the 2010s, with ~93 % of all new homes in the state being built within or abutting wildlands[43]. People start most fires, and they are most likely to ignite them in the WUI [44,45], meaning homes are often at high risk. Most homes that burn in the western US WUI are destroyed by grassland and shrubland fires, like the 2021 Marshall Fire in the Front Range of Colorado and the 2023 Smokehouse Creek Fire, the largest in Texas history at the time of writing this document. However, homes are more likely to be destroyed by forest fires, when they do occur in the WUI, than by grass fires. An extremely tragic example is the 2018 Camp Fire that consumed the entire community of Paradise, CA. Damage to homes, loss of life, and suppression costs to protect people have reached extraordinary levels. For example, the US Federal government’s mean annual expenditures on fire suppression over the last decade was approximately 11 times larger than the annual cost of suppression from 1985-1994 (~$2.2 billion vs $193 million when adjusted to 2022 real U.S. dollars using the consumer price index to account for inflation) [46]. Growing expenditures were driven by the large increase in the mean annual acres burned and a nearly 5-fold increase in the suppression expenditure *per* acre burned [46], highlighting the intensification of suppression efforts. The private sector is also rapidly adapting to new realities of the large fire era; a number of major insurance companies have begun to pause or restrict homeowner's insurance in California, due to exploding fire risk [47].

Fires also negatively impact people by affecting the provision of critical ecosystem services. Temperate forests are a large carbon sink [48] that have already helped society avoid the worst of climate change [49]. Western US forests, particularly those in the Pacific Northwest, have some of the highest aboveground carbon densities in North America [50,51]. This means they will play an important role in climate mitigation efforts, either as carbon sinks if storage potential is maintained, or as massive carbon sources if future climate-fire trends continue unabated. Recent analyses demonstrate that live forest carbon storage across much of the arid western US already started to decline as early as 2005 with increased burning and drought [52,53]. Major forested western US watersheds are also approaching thresholds of burned area that when crossed could lead to marked changes in runoff and water quality that challenge our water management systems [5,54]. This is important because human communities across much of the western US are experiencing acute water stress. For example, the city of Phoenix, AZ has begun to limit new home construction due to dwindling groundwater [55]. Smoke regularly blankets rural communities and urban centers, alike, with profound consequences for human respiratory health, including exacerbation of asthma and respiratory infections like COVID-19, as well as increased respiratory-related mortality [56]. While links are not as well established, wildfire smoke may also adversely affect birth outcomes, mental health, and cause increased incidence of various cancers [57]. Western US forests serve as important habitat for myriad species, and fire-induced forest conversion to grassland will alter species and functional diversity in complex and unpredictable ways.

Together, climate change and the legacy of suppression portend an even more fiery future. Warming and drying is expected to continue through this century. Projections indicate that the risk of extreme drought could grow as much as 300% by 2100 [58]. Models that project how fire and forest dynamics might change in the future are only beginning to mature and uncertainty is pronounced. However, the models agree that intensification of fire regimes will accelerate under all climate change scenarios. In fact, the record-breaking area burned in 2020 could become the annual average by 2050, even under moderate emissions scenarios [59]. If fire and forest projections are accurate, the western US will become an increasingly inhospitable and unsustainable place to live, with smoky summers, the constant destruction of homes, and an abrupt widespread loss of western forests and the ecosystem services we rely on.

Even as uncertainty abounds, decision makers are tasked with stewarding western US forests during this period of profound environmental change [60]. State and federal agencies, politicians, land managers, and the public alike face impossible choices and tradeoffs with complex and long-lasting social-ecological consequences [61]. While challenges are extraordinarily daunting, innovative approaches to stewardship are emerging like the Resist, Accept, Direct (RAD) framework, which helps practitioners conceptualize the complete domain of potential responses to ecosystems undergoing rapid irreversible change [61]. However, such frameworks require good science to underpin them. In fact, the critical role for science in fire and forest management was codified in the recent report from the Wildland Fire Mitigation and Management Commission [62]. As the report highlights, many streams feed into policy and management decisions, but fundamentally, decision makers must know more clearly where, when, how, and why our forest ecosystems and fire regimes are changing, what the consequences might be, and how available tools could influence outcomes. The need for best-in-class science to inform decisions is reinforced by the fact that the US Forest Service [63], National Aeronautics and Space Agency [64], National Science Foundation [65], Bureau of Land Management and US Fish and Wildlife Service [66], and National Oceanic and Atmospheric Agency [67] all have ongoing and/or newly launched programs focused on understanding and better measuring fire and ecosystem change. State agencies such as CALFIRE are also investing heavily in fire and forest research [68].

As a process, however, fire cuts across the domains of climate, society, and ecosystems in ways that profoundly challenge traditional scientific methods and mission-driven agency research [23]. To live more sustainably with fire, we desperately need transdisciplinary insights into its causes and consequences that will only emerge at the intersections of fields like earth system science, ecology, conservation biology, economics, and public health. Fire research is also a uniquely applied area of study with the potential to directly influence stewardship decisions. Thus, partnership between fire researchers and decision makers is critically important, a skill set most scientists have little to no training in. Further, most disciplinary based research is carried out at spatial and temporal scales that are fundamentally misaligned with providing effective guidance to decision makers, and studies are often heavily concentrated in just a few states with most of the resources, leaving vast swaths of the western US lacking for data and scientific understanding. Unfortunately, if left to traditional approaches, the "data-discovery-decision" pathway might never mature due to the complex and wicked nature of fire as a cross-cutting biophysical and social-ecological process [69]. Society needs new research approaches unconstrained from the common barriers of innovation to accelerate the pace of discovery, collection of crucial data across all of the western US, and generation of actionable scientific insights that can become immediately available for decision making. Given their pragmatic and nimble nature, philanthropic sources of funding may be uniquely poised to overcome constraints with the traditional pathways to scientific advancement.

Generously seed-funded by the Gordon and Betty Moore Foundation and Lyda Hill Philanthropies, The Western Fire and Forest Resilience Collaborative (WFFRC) is a new research program designed to fill this need. The goal of WFFRC is to accelerate advancements in fire ecology and forest resilience for ALL of the western US that will ensure fire science is sufficiently mature to help address the fire crisis. This will be accomplished by empowering some of the world's most creative scientists to conduct convergent, transdisciplinary research guided by and developed in partnership with decision makers. Further, WFFRC will serve as an innovation catalyst for the broader research community through discovery, convening, open-science best practices, and a culture of inclusive collaboration. Together, WFFRC's actions will lead to a deeper understanding of biophysical, ecological, and social dynamics that could underpin a strategic portfolio of innovative fire management and community adaptation efforts across the western US by addressing the following questions:

1. How and why are forests and fire regimes in the western US changing, and how will they change in coming decades under different scenarios of management and climate change?
2. What are the consequences of current and future forest and fire trajectories for critical ecosystem services including biodiversity, forest carbon storage, air quality, human-settlement vulnerability to fire, and provision of water?
3. What innovative management strategies and adaptation efforts are needed to respond to projected changes and at what spatial and temporal scales?

Our study domain is all forests in the western United States defined as any forested area in the contiguous United States, west of the 100th meridian (Fig. 1). By combining field-based empirical work with remote sensing, process-based simulation, and geospatial data synthesis, WFFRC focuses on five objectives designed to collectively address the trans-disciplinary and cross-cutting challenges of understanding and anticipating ecosystem change in the modern era of fire.

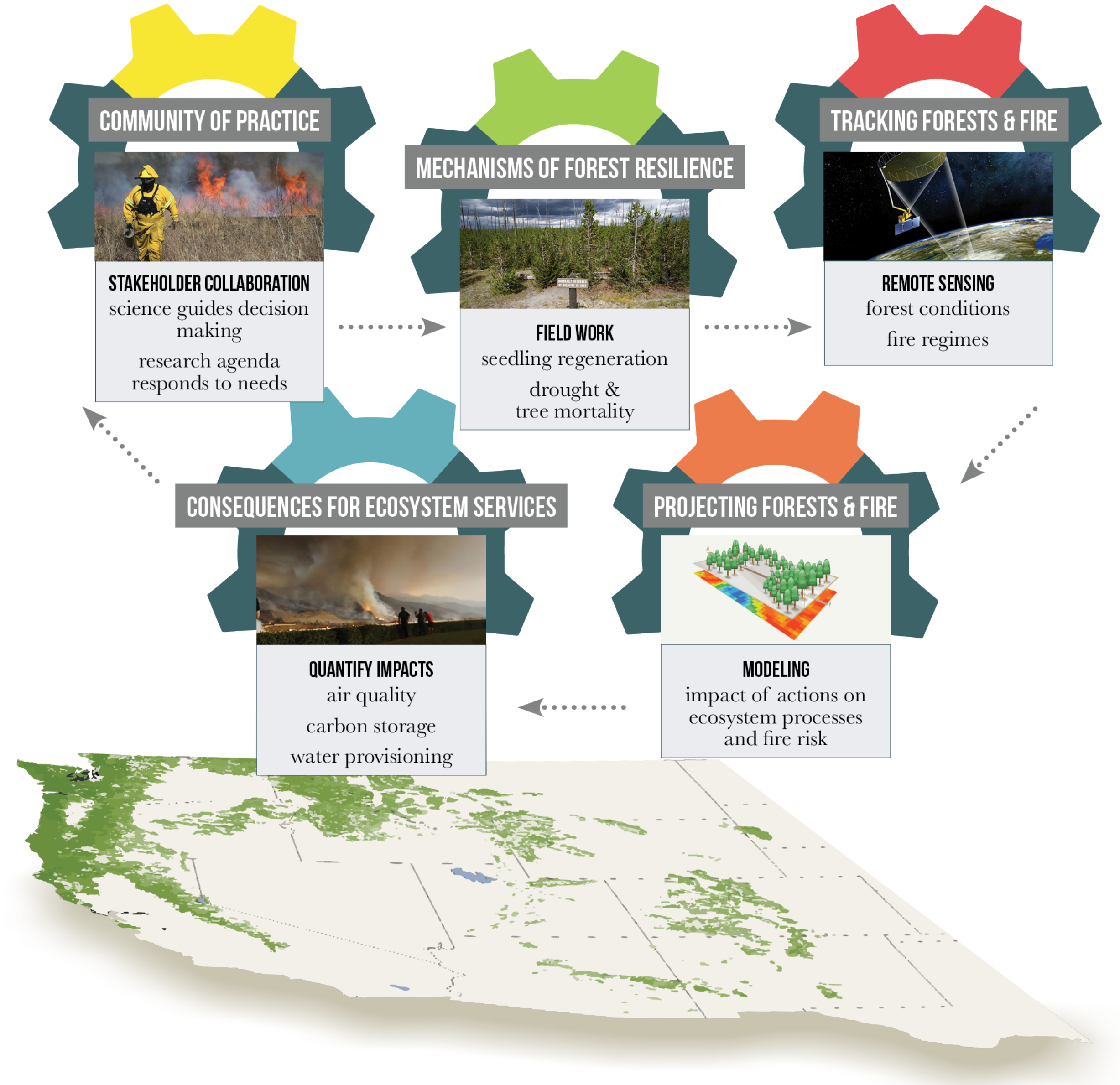

Figure 1. The objectives of the Western Fire and Forest Resilience Collaborative are organized around stakeholder engagement and four research themes that provide insights on the changing nature of forests and fire and consequences of those changes for people, from individual trees to the continent and over coming months to decades into the future. Our study domain includes western US forests (defined as forested areas west of the 100th meridian).

2. Objectives

The Western Fire and Forest Resilience Collaborative is organized around five objectives that encapsulate the research program and our efforts to cultivate and nurture a community of practice with stakeholders, so the science is immediately used to inform decision making and the science agenda is responsive to decision maker needs (Fig. 1). The objectives are:

1. **Build a community of practice** that ensures the research agenda is responsive to decision-maker needs and that the best available science guides decision making and adaptation.

2. **Understand and predict where and when the risk of non-reversible forest reorganization or transition to grasslands and shrublands is greatest and identify the mechanisms that may underpin forest change.** We will combine field surveys and hypothesis testing leveraging a suite of process-based vegetation models to ask:

    a. How does energy versus moisture limitation modify postfire forest resilience in seedlings and mature trees?

    b. Which vegetation traits influence pathways of ecosystem reorganization and how?

    c. How could elevated atmospheric CO_2 modify postfire ecosystem resilience?

3. **Quantify how fire regimes and resulting forest structure and function are changing across the western US.** We will use a combination of field and remotely sensed datasets and landscape analyses to address the following questions:

    a. How do remotely sensed burn severity metrics translate into quantitative ecological effects in forests of the western US, and how is burn severity changing over time and space?

    b. What are the trends and drivers of functional landscape patterns of burn severity over time and space across forests of the western US?

    c. How are key fire behavior metrics (e.g., fire intensity, rate of spread) changing over the last 20 years in the western US?

    d. When, where, and why is there spatial congruence or divergence between fire behavior and functional measures of burn severity in the western US?

    e. How are forest structure, function, and cover changing in response to fire and proactive forest management?

4. **Quantify the drivers of observed trends in forest fire, project how forests and fire regimes will continue to change in the future, and determine how current and future stewardship actions may shape future outcomes.** Building off management strategies developed with stakeholders, we will use an ensemble of state-of-the-art process-based simulation models to ask:

    a. How have human-caused climate change and natural variability combined to contribute to western US forest-fire trends over the last several decades?

    b. How will western US forest-fire regimes change between now and 2100 based on projections from 27 climate models and various emissions scenarios?

    c. Where, when, and why will forests change fundamentally in response to unprecedented climate extremes including drought and fire across a range of spatial scales, from landscapes to the entire western US? When, where, and at what spatial scales do self-regulating vegetation-fire feedbacks emerge and how strong are they?

    d. Where and how might management and policy strategies, designed with decision makers, affect trajectories of change in forests and fire regimes, and at what spatial and temporal scales do interventions have impact?

5. **Quantify current and future consequences for people, biodiversity, and ecosystem services essential to human well-being and economies.** This includes human smoke exposure, fire risk in the WUI, species and functional diversity, carbon storage, and provision of water. Living more sustainably with fire and the secure provision of ecosystem services during a time of profound change will only occur with improved ecological understanding. We will interrogate model outputs from objective 4 and a variety of geospatial datasets to ask:

    a. How have human smoke exposure, WUI dynamics, biodiversity, water quantity, and forest carbon storage changed in response to fire and other drivers in recent decades?

    b. How will human smoke exposure, WUI dynamics, biodiversity, provision of water and forest carbon storage change over the next century with projected burning?

    c. Where are the current and future areas of robust ecosystem services and areas of degraded services? Where and when do inflection points emerge during the 21st century that cause ecosystem services to rapidly degrade or disservices to accelerate?

    d. What are the synergies and trade-offs between current and future ecosystem services and disservices? What are the direct and indirect drivers of these synergies and trade-offs?

The overarching goal of WFFRC is to build a science program guided by and developed in consultation with decision makers. Objectives 2-5 were informed by an extensive and ongoing stakeholder engagement process as part of objective 1. The questions within objectives 2-5 either address the knowledge gaps identified by stakeholders so far, or they provide foundational scientific insights that are necessary for rigorously addressing these knowledge gaps. Moving forward, we also expect stakeholder needs to evolve as our community of practice widens and stewardship challenges evolve.

3. Research Plan

3.1 Objective 1: **Build a community of practice** that ensures the research agenda is responsive to decision-maker needs and that the best available science guides decision making and adaptation.

3.1.1 Initial stakeholder engagement efforts

Development of this research vision has been informed by an extensive and in-depth stakeholder engagement process. We began by engaging a policy and management liaison, Dr. Kristina Bartowitz, who initially assembled a stakeholder database of 150 individuals and 61 organizations. Using the database, she then conducted 20 1-on-1 interviews with stakeholders from across the western US asking open-ended questions to ensure we did not bias answers.

Interview notes were synthesized by the research development team of the Climate and Wildfire Institute at UCLA (CWI @ UCLA) to identify key knowledge gaps and barriers to using science for informing decisions.

Box 1. Stakeholder Interviews and Synthesis of Knowledge Gaps

In summer 2023, we conducted 20 1-on-1 interviews with stakeholders. We asked the following open-ended questions:

- How useful are modeling and remote sensing products for informing short-term vs long-term thinking?
- What do you think are the greatest barriers to effectively addressing the large fire crisis?
- At what scale should strategies to address the large fire crisis be implemented and how should approaches vary across human and ecological geographies?
- In what ways could scientists improve ecological insights/data/outputs (or make more accessible) that are easiest to incorporate into the decision-making stream?
- In what ways could stakeholders engage with shaping the science being done (or how could it be improved or be more inclusive)? How would those interactions operate most effectively?

Upon conclusion of interviews, the CWI @ UCLA Research Development team distilled notes from the interviews into key points and organized them into spreadsheet format with responses in rows, grouped by question. This allowed for interviews to be analyzed based on the frequency of comments relative to the diversity of participants and organizations. To avoid reducing complex statements into overgeneralized takeaways, a single response to a prompt was often segmented to isolate multiple points. Breaking down statements in this way allows distinct themes to be identified. The following are the results that emerged from this analysis.

Knowledge gaps

1. A need exists for metrics to differentiate between "good" and "bad" fire across multiple dimensions including:
    a. Improving acceptance of prescribed burns by using bad fire vs good fire metrics to communicate their social and ecological benefit.
    b. Understanding consequences of human exposure to smoke.
    c. Measuring post-fire impacts, particularly on critical ecosystem services.
    d. Differentiating landscapes that are less resilient or not adapted to fire, or made more vulnerable by climate change.
2. A need exists to determine reliable and measurable indicators of resilient pre-fire forests, in particular, to evaluate the effectiveness of interventions such as thinning across space and time.
3. A need exists to address spatial and temporal scale mismatches between:
    a. Modelers and practitioners. Current mismatches between the scales at which models produce outputs and the scales at which forest and fire management is implemented can limit the utility of models.

b. Modelers and other researchers. Often model scales are not well aligned with remote sensing products, empirical ecology, and the scales at which social science is conducted. This can lead to frustration, lack of understanding, difficulty in communication and collaboration.

4. A need exists to identify which scale is most important for particular questions, to develop robust frameworks for scaling up or down ecological information, and to identify the limits of scaling. This is particularly important for understanding the limitations of models that are available at different scales and for different geographies, and how relying on these models might lead to misguided decisions, especially when translating between scales and geographies.

Additional themes that emerged

1. A need exists for strategies that can foster behavioral change and improve social acceptance for fire. This theme encapsulated multiple dimensions, including:

    a. Building support for mechanical thinning and prescribed fire, including increased tolerance of smoke.

    b. Need for change in people's behavior, including the reduction of human-ignited fires, improved hardening of existing homes in the WUI, and changing where new homes are built to reduce WUI expansion.

    c. Addressing the "fear of fire" and how messaging that focuses on social narrative can too easily dissuade the public from embracing the guidance of scientifically vetted practices.

2. Policy and funding were often cited as the greatest barriers to confronting the wildfire crisis. The two were often linked in the discussions.

    a. Policy was often cited as a barrier to implementing scientifically vetted interventions, and generally this criticism was associated with claims that policy-makers do not engage with the science. The process of writing or changing policy was also perceived as opaque and difficult.

    b. While there is an influx of funding into fire and forest management, there were concerns of it being used haphazardly. There was a perceived lack of coordinated, focused strategy about where to invest funding.

These knowledge gaps and barriers formed the foundation for a two-day town hall meeting at UCLA, facilitated by CWI @ UCLA. We brought together more than 40 scientists and decision makers for conversations to deepen our understanding of how science could help address knowledge gaps and what approaches might help us overcome barriers to using science in the decision-making process. Participants included representatives from the US Forest Service, Idaho Conservation League, Washington State Department of Natural Resources, California Natural Resources Agency, the Nature Conservancy, Pacific Forest Trust, and California Council on Science and Technology, among others. Findings from the UCLA town hall served as the foundation for developing and writing this science vision (Fig. 2). We requested feedback on initial drafts of the science vision from a subset of stakeholders.

Figure 2. Top panel: A town hall at UCLA in September 2023 with more than 40 scientists and decision makers helped us interrogate and refine knowledge gaps that were identified during more than 20 1-on-1 interviews with stakeholders. Those insights formed the foundation for developing our science implementation plan, which was kicked off with a meeting of science teams at Cary Institute of Ecosystem Studies in November 2023 (bottom panel).

We also convened four regional focus groups (Pacific Northwest, Southwest, central Rockies, and northern Rockies) with 3 to 10 practitioners that had not previously participated in our stakeholder engagement process. Participants represented a range of organizations including State Forestry Divisions or Departments of Natural Resources, US Forest Service, US National Park Service, US Bureau of Land Management, and the Nature Conservancy. Where possible, we included boundary-spanning organizations like the Southwest Ecological Restoration Institutes, Southwest Fire Science Consortium, Northwest Fire Science Consortium, Southern Rockies Fire Science Network, Northwest Climate Adaptation Science Center, University of Washington Climate Impacts Group, and the Watershed Center. During these meetings, we solicited feedback on the science proposed in the rough draft of this science vision, its relevance to regional issues of forest resilience and fire management, and how it could be refined to better fit their needs. We used questions and discussions to generate a synthesis of regional perspectives on our proposed science. We will use the process of engaging stakeholders and revising our science vision as a model for iteratively soliciting and incorporating feedback on our science from stakeholders throughout the lifespan of WFFRC.

3.1.2 Addressing identified knowledge gaps

The science vision described in subsequent sections directly addresses the knowledge gaps identified by stakeholders.

Stakeholders identified a need for metrics that differentiate good vs bad fire including smoke, postfire impacts, and landscape vulnerability assessment. In reality, the benefits and consequences of fire are complex in multiple social-ecological dimensions. A single fire could have good qualities in some dimensions and damaging in others. Our science vision is designed to unpack and quantify the multiple dimensions of fire impacts by providing a seamless workflow for identifying the underlying mechanisms of change (objective 2), tracking fire- and forest-change in real time (objective 3), modeling current and future fire regimes and forest-ecosystem responses (objective 4), and quantifying the associated consequences for smoke, fire risk in the WUI, and ecosystem services (objective 5). As a result of this uniquely integrated set of activities that span from "the whys to the consequences", we will be well poised to produce clear and concrete metrics through which the social-ecological impacts of fire can be assessed on a spectrum from beneficial to catastrophic.

Stakeholders identified a need for reliable indicators of resilient pre-fire forests to evaluate effectiveness of interventions across space and time. Effective indicators of prefire forest resilience must accurately predict whether a forest will successfully resist or recover from fire if it were to burn, outcomes that are influenced by myriad processes and that can play out over decades to centuries. Thus, reliable indicators of prefire forest resilience must either rely on some method of forecasting or make use of space-for-time extrapolation. Projection with mechanistic process-based models is preferable, given the rapid rate of change and potential for statistical relationships that underpin space for time substitution to break down in novel climate conditions. Our research program emphasizes identifying the mechanisms that will determine whether and how forests prove resilient to fire (objective 2). We will build those mechanisms into state-of-the-art, process-based models that can robustly project postfire forest recovery trajectories (objective 4) at multiple spatial scales. This combination of mechanism and best-in-class modeling will allow us to identify the most promising indicators of forest resilience. We can then leverage our advances in real-time tracking of forests and fires (objective 3) to produce wall-to-wall annualized maps of resilience.

Stakeholders identified a need to address spatial and temporal scale mismatches among modelers, practitioners, and other researchers. Our research vision addresses this knowledge gap in two key ways. First, we have brought together 10 research teams with diverse but complementary sets of expertise and are designing an integrated multi-scale workflow that allows for seamlessly sharing products and insights within and across groups (objectives 2-5). This will provide opportunities for other researchers to tap into the framework, catalyzing innovation beyond our teams. Second, we are building a community of practice from the beginning with stakeholders, which allows us to better understand the different spatial and temporal scales at which they need scientific information to make decisions (objective 1). For instance, we were challenged at the UCLA Town Hall to not just quantify forest and fire trajectories decades into the future but to also emphasize forecasts over a near-term horizon of 5-10 years, which we plan to embrace.

Stakeholders identified a need for frameworks to rigorously scale insights up and down and to determine the limits to scaling, particularly when translating across geographies. No single tool can address all questions at all spatial and temporal scales, and one must exercise great caution when applying social-ecological insights gathered in one place to a new geography. For example, dry forests of eastern WA, where fire is frequent, are not a good model system for wet productive forests in western WA, less than 50 miles away. Our research plan explicitly addresses these challenges because we have designed the remote sensing (objective 3), modeling (objective 4), and quantification of social-ecological consequences (objective 5) to be scalable by leveraging multiple sensors and tools, and by aggregating outputs to multiple social and ecological domains (pixel/stand, watershed, ecoregion, county, state, all of the western US). We also address the challenge of translating insights across geographic domains because our mechanistic work (objective 2) and ecosystem modeling (objective 4) include landscapes that are representative of the immense social-ecological diversity found across western US forests. Thus, this framework will allow us to explicitly quantify what insights can be broadly applied and where and when important and management-relevant differences in ecosystem dynamics emerge.

3.1.3 Next steps in stakeholder engagement

Accomplishing objective 1 is a long-term and ongoing process that will continue through the lifetime of this project. Leveraging the strong momentum we built in our planning year, we anticipate a number of key next steps in building a community of practice. First, we are hiring 2 FTEs, including a Deputy Director of Policy and Management (see section 5.3). Over the next year, the Deputy Director will be responsible for leading the development of a stakeholder engagement and knowledge-transfer strategy. This strategy will successfully build a national community of practice with relevant stakeholders to understand their needs and to ensure the best science informs stewardship of western forests and fire. The Deputy Director will use feedback provided by stakeholders during the regional focus groups as a framework for the creation of this strategy. As part of the strategy, we anticipate continuing to build relationships with key boundary spanning organizations, such as the Climate and Wildfire Institute and CWI@UCLA, the Fire Science Exchange Networks and Consortiums, USDA Climate Hubs, Climate Adaptation Centers, and the Climate Impacts Group at University of Washington. We will consider assembling a stakeholder external advisory committee to help guide this effort.

3.2 Objective 2: **Understand and predict where and when the risk of non-reversible forest reorganization or transition to grasslands and shrublands is greatest** and identify the mechanisms that may underpin forest change. We will combine field surveys and hypothesis testing, leveraging a suite of process-based vegetation models, to ask:

3.2.1 Sub-objective 1: How does energy versus moisture limitation modify postfire forest resilience in seedlings and mature trees?

The frequency, size, and ecological impacts of forest fires across the western US vary markedly both with mean climate and local climate variability. This is because prevailing climatic conditions and climate variability interact to shape vegetation communities [26,27], fuel abundance [70], and fuel moisture content [71]. Mean climate is a dominant control of biome distributions. However, variability in key drivers, like precipitation, often underpin intra-annual and inter-annual patterns in forest dynamics [72,73]. For example, fuel loads in arid forests are often highest following unusually wet years. Conversely, trees are generally most stressed (and live fuel moisture is lowest) during anomalously dry years. Trees are prone to mortality in dry years because they often produce too much biomass during wet years (structural overshoot) [74]. Furthermore, mature trees are less likely to successfully survive a fire event or recruit after fire when it is dry. To anticipate future wildfire impacts on forest resilience (objective 4) and the cascading effects on ecosystem services (objective 5), we need to better understand (a) the vegetation recovery trajectories that have already been set in motion by current record setting fires and severe droughts, (b) how recovery prognosis is modified by local mean climate, and (c) how variability in climate interacts both with wildfire risk and ecosystem resilience after fire. Such insights are fundamentally important to implementing innovative management strategies like the Resist-Accept-Direct (RAD) framework [61]. We will pursue two efforts for better understanding forest response to fire in the 21st century: (1) intensive forest inventory measurements across climate and burn severity gradients and (2) vegetation modeling that explores alternate hypotheses about the effects of climate variability and change on post-fire tree regeneration and mature tree survival. This work will inform model development to support objectives 4 and 5. Forest inventory measurements will be directly assimilated into remotely sensed fire tracking products developed in objective 3.

Remotely sensed metrics for assessing wildfire impacts are critical for tracking the current state of ecosystems after fire, but they rely on ground-based plot surveys for rigorous calibration and ground truthing. In collaboration with objective 3, we will extend the current networks of plots previously published by collaborators [27] (see objective 3) and developed by co-PI Harvey in the Pacific Northwest US and co-PI Balch in the central Rocky Mountains of Colorado to cover additional ecosystems in the western US, potentially including the Sierra Nevada Mountains in California and the southern Rocky Mountains in New Mexico. All plots will be systematically established and measured using the same protocol: Plots will be oriented in a 30-m diameter circle and follow established protocols for measuring burn severity (e.g., surface charring, tree mortality, canopy cover change, scorch height) [75,76] and post-fire vegetation trajectory (e.g., tree species, height, estimated age of post-fire tree seedlings and plant functional groups) [77–79]. Data in each plot will be collected on physical site characteristics, pre-fire stand structure, burn severity, post-fire vegetation conditions, and post-fire trees (residual live trees and post-fire seedlings). Elevation (m), slope (deg), and aspect (compass azimuth) will be recorded from the plot center. Pre-fire stand structure will be characterized by measuring diameter at 1.35 m (DBH), species, and live/dead status of all pre-fire overstory trees (>15 cm DBH live, dead/standing or dead/fallen since fire) rooted in the plot. Distance to the nearest patch (>1 ha) of live and pre-fire mature tree(s) will be measured from the plot center with a laser rangefinder. Additionally, we will measure post-fire understory vegetation cover (percent cover of herbs, graminoids, and shrubs; plus shrub layer height) in four 2 x 5 m subplots, spaced 5 m from plot center in cardinal directions. For established tree seedlings (trees < 1.5 cm DBH), we will record every individual in variable-sized subplots according to establishment density [77,80,81]. Default subplot size will be four 2 x 15 m rectangular subplots (120 m^2 total area) configured in cardinal directions. Subplot size will be decreased to four 0.5 x 15 m belt plots or increased to the entire 0.07 ha circular plot if visual inspection indicates >200 or <10 tree seedlings would be captured in the default subplot size, respectively. Based on stakeholder input, we will consider additional variables like downed fuels.

Plot scouting and establishment will take place in years 1-2 of the project and the field team will perform plot inventories over years 2-3 of the project. An additional subset of plots will likely be outfitted with temperature/relative humidity sensors and additional plant physiological measurements to inform specific model hypotheses on postfire tree prognosis, particularly for plots recovering during dry years. Collectively, these plots will provide valuable data on how fire severity affects post forest recovery in ecosystems that span the energy- to moisture–limitation gradient, with a focus on unprecedented high severity fires, providing new data on a major unknown.

The individual-based forest landscape and disturbance model (iLand) will be used to understand the impacts of fire severity and droughts, compounded with fire, on post-fire tree recruitment success and forest recovery [82,83]. iLand is a detailed process-based forest landscape model that simulates individual trees and their interactions in spatially explicit landscapes with a 2 m to 100 m spatial resolution and daily to annual temporal resolution (depending on process). The model was designed to address questions about how climate and disturbance affect forest resilience. Thus, it includes key processes like fire-induced tree mortality, postfire seed dispersal, and the effects of climate stress on individual seedling recruitment and long-term tree survival. Given this emphasis, the detailed level of process representation, and its focus on forest landscapes, iLand is an ideal testbed for exploring the mechanisms that underpin forest resilience in the western US.

Some of the key forested regions in the western US have already been parameterized and well tested in iLand, including landscapes in the northern Rocky Mountains and Pacific Northwest [82–87]. We will expand these rigorous parameterization and benchmarking efforts to three additional test bed regions (central Rocky Mountains of CO, Sierra Nevada Mountains of CA, and the southern Rocky Mountains of New Mexico). Co-PI Trugman's lab will lead parameterization of the Sierra Nevada region, leveraging ongoing field surveys, physiological measurements made in Sequoia National Park from a different project, and demographic plot data available through collaboration with the USGS for model validation/hypothesis testing. PI Hansen's lab, in collaboration with co-PI Harvey's and co-PI Trugman's labs will lead parameterization of the other regions, using functional trait databases, the literature, and empirical sources. New species parameterizations will be benchmarked using remotely sensed observations, USDA Forest Service Forest Inventory and Analysis plots, and synthesis of other geospatial products.

We will initialize landscapes using the best available data, including tree species maps, lidar data, and fire database that includes all observed fires greater than 100 ha [1], and plot-level tree data collected in our field campaign. Models will be forced with daily downscaled climate data. Climate variables include minimum and maximum temperature, precipitation, VPD, solar radiation, and day length. The model can simulate fire dynamically, but it can also ingest fire products such as those produced by us in objective 4, which are then spread in the iLand landscapes based on fuel availability.

After successful parameterization and benchmarking of iLand in testbed regions, simulation experiments will target the sensitivity of seedling recruitment success to drought severity and frequency post fire across a large gradient of energy and moisture limitation, as well as the sensitivity of recruitment success to fire severity through its impact on seed availability. Then, we will examine the relative importance of drought on recruitment success and failure versus drought impacts on large tree mortality from a carbon budget perspective. We will conduct a simulation experiment to understand the relative impact of postfire recruitment dynamics vs mature tree mortality on resulting forest structure and total biomass. To do this, we will run the model with forced elevated mature tree mortality, decreased recruitment success, or the combination (both within observational ranges gained from our forest inventories and beyond as a 'hammer' to see what might initiate tipping point dynamics) and compare outcomes to a baseline control simulation.

In years 1-3, we will produce a paper examining the impacts of fire severity and post-fire climate on vegetation recovery. Further, plot measurements will inform basic theory on recovery from disturbance that will be incorporated and tested in process-based vegetation models used in this project. Field plots will also form a core component of the remotely-sensed burn severity product described in objective 3, and ultimately enable skillful projections by models used in objectives 4 and 5. We also anticipate (1) a representative parameterization of iLand for the Sierras and the central and southern Rocky Mountains that will be critical for objectives 4 and 5 and (2) publications examining the effects of drought post fire and how climatic variability and fire severity interact to drive risk of non-reversible forest reorganization such as transitions to non-forest ecosystems across a gradient of energy to moisture limitation.

Over 5-10 years, we aim to advance understanding of the climate conditions and plant physiological processes that may initiate irreversible transitions to grasslands and shrublands by causing recruitment failure and mature tree mortality after fire. With testbeds in the central and southern Rocky Mountains, we aim to improve understanding of the drivers of transitions in arid forests, an ecosystem type that has been relatively understudied. This is critically important for developing reliable indicators of resilient prefire forests, a key knowledge gap identified by stakeholders (as described in objective 1). Such insights can also be used to inform forest management strategies that are designed to bolster forest resilience to increasing drought, including postfire tree planting efforts.

3.3.2 Sub-objective 2: Which vegetation traits influence pathways of ecosystem reorganization and how?

Physiological and ecological traits mediate tree responses to climate and disturbance. Differences in local environmental conditions strongly affect which traits and community trait assemblages are successful. Community trait assemblages also directly impact ecosystem carbon uptake during average years and mortality risk and ecosystem resilience during droughts and after fire. Extreme events linked to climate change have resulted in substantial shifts in tree-species dominance [88] and tree-species' geographic range limits [89,90], particularly in water-limited biomes like the western US [91], but it is still poorly resolved what traits are most important in forest reorganization, how this varies across climate gradients, and how fire might tip the balance in favor of different plant functional strategies. Here, we will build off the forest inventory measurements and model work described in sub-objective 1 to understand which traits may be most influential in ecosystem reorganization after fire.

In the forest inventory measurements described in sub-objective 1, we will leverage data on post-fire understory vegetation cover (percent cover of herbs, graminoids, and shrubs; plus shrub layer height) to understand how competition/facilitation by shrubs and grasses varies across western US forests and to constrain where and when shrubs may facilitate forest recovery versus initiate regeneration failure by outcompeting seedlings. In the process-based model sensitivity experiment described in sub-objective 1, we will perturb specific plant parameters such as seed dispersal kernels, seedling water potential threshold requirements for recruitment, parameters governing plant allometric growth curves, and parameters governing susceptibility to stress driven mortality to see how sensitive forest structure is to each of these traits and how this varies by forest type. These traits will also be measured in the field surveys described in sub-objective 1, allowing for a seamless crosswalk between empirical data and the modeling experiment.

In years 1-3, we anticipate these results will contribute to the publications detailed in sub-objective 1 on vegetation trait controls influencing forest reorganization or transitions to non-forest ecosystems. Over 5-10 years, this research could synergistically combine with that from sub-objective 1 to improve our understanding of how plant physiology and physiological diversity modify vegetation recovery responses to climate after fire. This diversity lens will add critical insights into our understanding of how biodiversity and disturbance interact when assessing risk of irreversible biome transitions with escalating climate change and increased disturbance. Such trait-based insights into diversity-function relationships will also be essential for informing new management strategies, such as assisted migration, to bolster resilience through facilitating ecosystem adaptation.

3.2.3 Sub-objective 3: How could elevated atmospheric CO_2 modify postfire ecosystem resilience?

Regeneration of western US forests following fire can take decades to centuries, with tree recruitment rates dependent on fire severity, seed availability, and post-fire water balance [27]. Following high-severity fire, the first few years is a critical window of resilience that strongly dictates the likelihood of successfully established trees in ecosystems ranging from Sierra mixed conifer forests [92] to Yellowstone National Park [35]. In some locations, tree-seedling sensitivity to early post-fire climate is due in part to competition with shrubs and grasses, which may slow tree growth or promote reburning [93]. At the same time, increasing atmospheric CO_2 concentration has been shown to increase growth rates of some tree species [94–97] with potential for greater effects on evergreen than deciduous species [98]. Further, elevated CO_2 has been shown to increase tree reproductive output in some experiments [99]. However, the effects of CO_2 on post-fire forest resilience – particularly in the context of competition with grasses and shrubs – is not known. To improve our ability to predict the future distribution and structure of forests, and associated fire regimes, we will pursue modeling that explores the effects of enhanced CO_2 on rates of post-fire tree regeneration, using a framework that explicitly represents plant physiology and mechanisms of CO_2 growth enhancements, including allocation to reproduction. We will use the modeling to probe the limits of understanding and to guide future development of field experiments that may be needed to constrain or evaluate the model. This work will inform efforts in objective 4 understanding the future of fire in the western US with climate change.

Site-scale modeling will use the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) [100], which explicitly represents plant physiological response to CO_2 concentrations, to dynamically adjust plant carbon status, water use and growth, mortality and reproduction rates. This work will leverage model parameterizations developed under prior funding for California mixed conifer [101], grassland [102] and oak woodland ecosystems and Colorado subalpine forest, as well as a new seedling recruitment scheme [103] that requires testing in the western US and development to reflect alternative hypotheses regarding CO_2 effects on seed production, seedling survival and growth, and sensitivity to water stress. Given literature suggesting that CO_2 effects can depend on other constraints (temperature, soil fertility) [104], we will further develop the model framework to enable testing interactions between these factors. Our aim is to explore the range of environments throughout the project domain where elevated CO_2 may be expected to have contrasting effects based on theory and prior research. We will use site-observed climate drivers as well as a dynamically downscaled version of a historical observationally constrained reanalysis climate dataset [105] from Alex Hall's group [106]. Our focal outputs will be recruitment rates, tree carbon status (e.g., storage), and growth rates; forest composition and rate of stand development; and return interval, biomass loss, and size of fires. The model experiments will be an examination of alternate hypotheses related to how seedlings may respond to elevated CO_2.

The effect of CO_2 on post-fire tree regeneration in the western US is a gap in our understanding and therefore ability to predict outcomes at warm forest edges in the coming decades, areas of primary management concern. It is difficult to infer CO_2 effects from distributed observations as can be done for climate constraints (see sub-objective 1), therefore, modeling will be used to probe mechanisms that are consistent with theory and prior experimental findings; the need for new experiments to fill gaps in understanding will be assessed through this work.

In the first two years of the project, we anticipate results from the model hypothesis tests in California mixed conifer forests and oak woodlands, where we already have done significant parameterization work. In years 3-5, we expect completion of model experiments across key sites in the western US, and multiple publications. On a 10-year horizon, these results will inform the need for further experiments and monitoring efforts that can help quantify how CO_2 fertilization modifies post-fire tree regeneration and may either amplify or dampen processes driving biome transitions with escalating disturbance, major scientific unknowns that are yet to be included in future wildfire risk forecasts. These insights will improve our ability to model future forests and fire in objective 4 and provide important mechanistic context for developing reliable indicators of prefire forest resilience, a knowledge gap identified by stakeholders (See objective 1). Fundamentally, this research will help determine where forests may be most at risk of transitioning to non-forest states after future fires.

3.3 Objective 3: Quantify how fire regimes and resulting forest structure and function are changing across the western US. We will use a combination of field and remotely sensed datasets and landscape analyses to address the following objectives and research questions.

3.3.1 Sub-objective 1: How do remotely sensed burn severity metrics translate into quantitative ecological effects in forests of the western US, and how is burn severity changing over time and space?

Forest fire regimes are rapidly changing due to the combined effects of climate warming and land use. Burn severity (i.e., the ecological effect of fire) is a critical dimension of fire regimes that is commonly measured in the field and then extrapolated spatially using satellite remote sensing indices. However, the indices available from remote sensing instruments currently do not directly translate into the ecological effects of fire measured from the ground. To address this gap, we will use a broad network of intensive field measurements of multiple dimensions of burn severity, satellite indices of fire-induced change, and cutting-edge statistical models to develop the first-of-its-kind atlas of quantitative measures of burn severity in forests of the western US.

The characterization and tracking of burn severity in US forests has advanced in recent decades thanks to a suite of satellite indices derived from publicly available Landsat products [107,108]. For example, the Normalized Burn Ratio (NBR) and derived indices of change caused by fire (e.g., dNBR, RdNBR, RBR), are commonly calibrated with field-based ordinal estimates of burn severity (e.g., the Composite Burn Index, or CBI), [109]. While these approaches enable wall-to-wall mapping of fire effects across ecoregions, the translation of burn severity indices (either field or satellite) into quantitative ecological effects that are meaningful to a manager on the ground has remained elusive. Our group has led several advances in quantifying ecological effects of fire and connecting them to satellite indices [75,76,110] that can now be extended to a broader suite of metrics and spatial domains. We will refine the approach for generating a burn severity atlas of on-the-ground fire effects in the Pacific Northwest, and extend this approach to create a quantitative burn severity atlas of forests and woodlands of the western US.

First, using the models that support the burn severity atlas we developed for the Pacific Northwest (PNW) and used in subsequent analyses [111,112], we will refine models that connect NBR-derived indices of burn severity to on-the-ground measures of burn severity including nine burn severity metrics (CBI, canopy cover change, dead needle retention, proportion tree basal area killed, proportion above-ground biomass (AGB) killed, proportion tree stems killed, bole scorching, char height, deep wood charring, surface charring) by incorporating additional covariates shown to be important in other studies [75,109]. These include latitude, topographic position (slope, aspect, heat load), pre-fire forest conditions (species composition, pre-fire NBR, quadratic mean diameter (QMD), basal area, density), previous disturbance interval and severity (fire, insect outbreak, harvest). Using the best performing models that incorporate these covariates and following established approaches [75,109], we will update the PNW burn severity atlas as a template for an atlas covering the entire western US. This will be done using zero-inflated beta regression models that will result in the mean estimate of each burn severity metric as well as the uncertainty for each metric (e.g., the 5th and 95th percentile estimate). Processing workflows will follow established protocols for Landsat-derived burn severity maps in Google Earth Engine [113] and other workflows (e.g., FORCE, the Framework for Operational Radiometric Correction for Environmental monitoring) that allows the integration of other satellites such as Sentinel-2 [114].

Second, we will coordinate outreach to the fire-remote sensing community who have collected field data in 0-5 years post-fire plots to assess the availability of burn severity measures beyond the PNW and Northern Rockies where we have these data in hand. This will include post-fire field data in burned plots such as CBI, basal area loss / remaining, canopy cover loss / remaining, crown vs severe surface fire (scorch v torch), charring / deep charring, soil burn severity, and potentially others as identified or collected by the community. Conversations with the fire remote sensing community and the forest fire management community will provide an opportunity to identify additional relevant metrics that could be added to the atlas. Once these data are acquired and cleaned, we will extend statistical models of burn severity metrics at a pixel level following the approach in the PNW but for the entire western US. These analyses will identify locations where additional field data are needed to fill gaps along gradients or dimensions of important factors (e.g., forest zone, latitude, topography, reburns, etc.) where there is greater uncertainty. Field sampling targeted to these locations will be conducted in summers of 2025 and 2026.

Data inputs for this component are primarily publicly available GIS / remote sensing products (e.g., USGS Landsat archive, USGS digital elevation models, Landfire vegetation and forest structure data), as well as existing field data on burn severity and forest structure from >600 field plots in the Pacific Northwest and Rocky Mountains. Additional data to be integrated into models for the western US will be from publicly available field data from other field sampling efforts [115,116] and newly collected field data in 2025 and 2026. All existing plot and remotely sensed data have a 30-m spatial resolution, and finer resolution data (e.g., ASTER and Sentinel 2 at sub 30-m resolution) and corresponding field measures will be integrated into workflows in future work. Field data collection will be coordinated with objective 2 where field plots will be co-located across objectives to measure burn severity and post-fire vegetation response. Plots will be oriented in a 30-m diameter circle and follow established protocols for burn severity [75–77,79,117] and post-fire vegetation response [77,79,117].

In years 1-3, we will produce a regional burn severity atlas in the PNW for all measures of burn severity and a western US wide atlas for high-priority variables (e.g., tree basal area mortality, canopy cover change). We will also build a curated repository for all existing field data on burn severity and collect additional field data in the western US to fill gaps in quantifying burn severity in forests along key gradients of geography and forest conditions. We will publish peer-reviewed papers that describe the concept of functional burn severity maps, present the models and severity atlas data, and test for trends in patterns and drivers of burn severity among metrics across ecoregions in the western US since the 1980s. Collectively, these datasets and analyses will catalyze new insights into how the broader science, management, and policy community defines and tracks burn severity, and will support decision-making in how to direct and respond to these trends.

Over 5-10 years, we would develop and curate the first-ever western US-wide atlas of multiple quantitative measures of burn severity, and using these data, we could test how individual measures of burn severity are changing over time (from the mid-1980s to the 2030s) and over space (among ecoregions and forest zones). This dataset will help managers and policy makers track trends in ecologically beneficial vs catastrophic fire, and where and when management and policy changes have shifted these trends, a key knowledge gap identified by our stakeholders in objective 1.

3.3.2 Sub-objective 2: What are the trends and drivers of functional landscape patterns of burn severity over time and space across forests of the western US?

As broad-scale aggregate changes to forest fire regimes are unfolding (e.g., increasing total area burned, average burn severity), changes that occur at the focal (e.g., pixel) scale can produce surprising and ecologically important emergent spatial patterns across forest landscapes [112]. Quantifying and understanding how landscape patterns of burn severity are changing, and how these patterns are linked to functional aspects of fire effects and post-fire recovery is key to understanding how changing fire regimes will affect forest resilience. We will use the models developed in sub-objective 1 to extend insights spatially and to quantify how functional measures of burn severity are changing in forests and woodlands of the western US over the last four decades.

As burned forest area has increased since the mid-1980s, so have average levels of burn severity across many US ecoregions [2]. Yet, how or why landscape patterns of key functional aspects of burn severity are changing concomitantly is less understood. For example, landscape mosaics of burn severity govern the spatial template for key ecological processes such as tree seed dispersal from surviving nearby trees [118] and subsequent post-fire carbon sequestration from post-fire tree regeneration [119]. After a fire, the capacity for seed dispersal into severely burned areas varies as a function of the size and configuration of stand-replacing patches [111,120] as well as the pre-fire patterns of forest structure (e.g., the abundance and configuration of mature trees) [112,121]. While some spatial metrics of functional burn severity mosaics (e.g., stand-replacing patch size and shape) consistently scale with fire size [111,116] or respond to drivers such as climate, fuels, and topography in some regions [116,117], a broader understanding of how different functional mosaics of burn severity are changing across the western US is both lacking and needed. We will use the burn severity atlas of on-the-ground fire effects across forests and woodlands of the western US from sub-objective 1 to generate landscape maps of functional burn severity from 1984 through 2024 for all fires greater than 100 ha, characterize trends in functional burn severity mosaics over space and time, and test relationships between trends and key drivers.

We will intersect pre-fire structural data layers from sub-objective 4 (described below) with maps of quantitative measures of burn severity to generate functional outcomes of each burned landscape for multiple response variables. Post-fire live forest stand structure within fire perimeters will be quantified by subtracting basal area killed by fire from the pre-fire live basal area. Additional structural variables such as post-fire relative proportion of basal area by species, stem diameter distributions by species, QMD by species, downed wood, charring, and woody C pools will be quantified depending on available resolution of field and remotely sensed forest structure data. Post-fire crown structure and post-fire seed source will be quantified in situ for each focal pixel and spatially as a function of distance to live remaining seed source from post-fire stand structure attributes above, creating maps of post-fire seed availability that are specific to local tree species [122]. Surviving legacy trees and post-fire seed availability will support quantification of likely post-fire recovery and successional trajectories such as early post-fire tree regeneration or areas where greater duration of complex early-seral structural conditions (e.g., snag abundance, "pre-forest" vegetation) or persistent conversion to non-forest is likely. Finally, we will quantify shifting functional mosaics with delayed mortality 1-5 years post-fire by tracking post-fire NBR trajectories thereby capturing how delayed tree mortality alters the above functional mosaics [123].

We will then test how functional burn severity (with response variables representing key outputs from the above measures) is changing over time (from the mid-1980s to the mid-2020s) and space (within and among ecoregions) across the western US. We will also test relationships between response variables (e.g., cumulative distance to live seed source) and key drivers (pre-fire vegetation/fuels, weather/climate, topography) following our established methods [117]. Of particular interest is examining how the relative importance of drivers of functional burn severity mosaics changes over time and among ecoregions.

Data inputs are from the intersection of publicly available GIS / remote sensing products and the burn severity atlas produced in sub-objective 1. Pre-fire structural data will come from biomass maps in sub-objective 5 (described below), Landfire existing vegetation type [124] and from the most recent prefire TreeMap [125] tree list. TreeMap is a USFS-led initiative which imputes FIA data to Landsat pixel values across the US to produce wall-to-wall forest structure and composition estimates. Burn severity data for each relevant metric of burn severity from sub-objective 1 will then be overlaid spatially on pre-fire vegetation structure to produce each of the post-fire functional burn severity mosaics. Predictor variables are from publicly available data on pre-fire vegetation structure (Landfire), topographic context (USGS DEMs), and weather at the time of fire [126]. Data outputs will inform initializing simulation model runs and benchmarking model outputs for objective 4. Maps of functional burn severity mosaics will also be key inputs to ecosystem service data layers for objective 5.

In years 1-3, we will produce a western US-wide dataset of functional burn severity mosaics for the highest priority variables (e.g., delayed tree mortality, remaining canopy seed source, and distance to seed source). We will publish peer-reviewed scientific papers that ask: *How stationary in space and time are scaling relationships between fire size and functional burn severity mosaics (e.g., distance to seed source) across the western US? What are the patterns and drivers of post-fire seed availability across the western US? What are synergies and tradeoffs among management decisions in post-fire landscapes (especially high-severity fire)?*

Over 5-10 years, we would extend the products from sub-objective 1 in a spatially explicit framework to develop the first western US-wide atlas of functional burn severity mosaics, developed algorithms to update this atlas annually, and test how landscape patterns of functional burn severity measures are changing over time (from the mid-1980s to the 2030s) and over space (among ecoregions and forest zones). This dataset and accompanying analyses would uncover critical insights into the spatial dimensions of fire regime change that are unfolding as patterns scale from pixels to landscapes to regions, and support pre-fire, operations (during fire), and post-fire management and policy decisions that can direct the landscape patterns of fires and their effects. Building on these insights, we would examine mechanistic links between these patterns and drivers (e.g., weather, topography, fuels/vegetation).

3.3.3 Sub-objective 3: How are key fire behavior metrics (e.g., fire intensity, rate of spread) changing over the last 20 years in the western US?

Fire behavior is changing, with documented increases in burned area and intensity across the western U.S. in just the last 20-40 years [2,5,127]. Yet, we still lack understanding of key fire behavior metrics that influence functional severity and long-term ecosystem response, as well as result in devastating property damage and loss of life. We need an integrated understanding of how different aspects, drivers, and impacts of fire behavior are changing across the thousands of fires that have burned across the western U.S.

A suite of satellite records, government databases, and upcoming sensors offer an unprecedented opportunity to understand fire, from drivers, to behavior, to risk and response. Here, we will explore fire regime change across western U.S. forests by determining which spatial, temporal, and energetic metrics of fire behavior have changed over the last 20 years. We will create a harmonized database of ~20,000 fire events that links pre-fire weather, vegetation, topography, fire behavior, and post-fire functional severity metrics. Pre-fire vegetation structure and composition will be composed of structural data from sub-objective 5 below and the most recent prefire TreeMap [125] tree list. In addition, we will use the community-weighted mean fire resistance score (FRS), which integrates six key fire-adapted traits with existing forest stand structure and composition to produce a ranking of fire resistance and associated likelihood of tree survival across forests of the western US [32]. Further, we will explore the metrics that are arguably the most important for ecosystem response, risk mitigation, and operational responses: fire intensity and fire speed. These metrics are also some of the hardest to grasp from remote sensing data and therefore require more advanced approaches to extract and validate this type of information.

We will primarily use MODIS, given the longer temporal record (2001-today) but will supplement with VIIRS and GOES fire detections where appropriate and for more in-depth case studies. Further, we will leverage VIIRS as a proxy for higher spatial and temporal resolution satellite sensors that we expect will provide better detections in the coming decade (e.g., FireSat and C-FIRES, which are under mission development and funding acquisition stages). We will use the existing FIRED, Fire Events Delineation database, which provides events based on the spatial and temporal aggregation of burned area pixels [128]. This product provides daily growth rates for over 80,000 fire events in the MODIS burned area product. We will use Fire Radiative Power (FRP), a measure of heat flux as a proxy for fire intensity and we will use fire growth rate as a proxy for fire speed. Fire behavior metrics included in the data suite could include: daily FRP, aerial growth rate, total event duration, and size. Novel fire behavior metrics could include FRP duration, integrated FRP across sensors, and daily linear rate of spread.

In years 1-3, we will develop an aggregated FRP metric at the daily scale that provides an integrated measure across the daily spread of a fire event, exploring characteristics such as FRP duration. We will prototype a linear rate of growth model that better approximates fireline speed based on geometric growth calculations from burned area daily polygons, with supplemental information from integration across the available active fire detection products. We will leverage existing work at the national scale on rate of spread, to provide a more refined analysis on daily growth rate patterns and trends at the western US ecoregion scale. New fire behavior metrics will be added to the existing FIRED database, which also links to the ICS-209-PLUS dataset, which provides incident command reports [129], and others to explore drivers and impacts. Key insights will be derived from linking fire behavior metrics with ecosystem and societal impacts to advance understanding of how management scenarios can promote lower intensity, slower moving, and lower severity wildfires in a changing climate. This will help us identify key metrics to differentiate between beneficial and catastrophic fire, a knowledge gap identified by stakeholders (see objective 1).

Over 5-10 years, we would provide an integrated set of fire behavior metrics for the western U.S., linked to individual fire events and based on best-available remote sensing imagery that are harmonized with the burn severity atlas and products in other objectives. This could provide an invaluable dataset to explore linkages between fire behavior and consequent tree mortality and recovery processes, over space and time. We would conduct a multivariate exploration of which spatial, temporal, and energetic metrics of fire behavior have changed over the last 20 years, using signals from areas that have already experienced significant temperature increase as harbingers of future decadal change. Connecting across other data products on human-settlement patterns and ecosystem services, we would also be able to explore consequences for ecosystems and society. The management and policy implications of this work are that we would be able to offer insights into why fire regimes are changing and provide targeted recommendations on forest recovery and resilience management actions, such as postfire planting and assisted migration, addressing multiple key knowledge gaps identified in objective 1. This work could also provide an on-ramp to leverage future remote sensing platforms that are designed to capture higher temporal and spatial resolution imagery of active wildfires and post-fire response, such as FireSat. Future remote sensing capabilities could offer fire managers, emergency responders, and land use planners and managers finer resolution information to help suppression decisions and post-fire recovery efforts. But, new sensors like FireSat will only be useful if the scientific community is ready to use them.

3.3.4 Sub-objective 4: When, where, and why is there spatial congruence or divergence between fire behavior and functional measures of burn severity in the western US?

Fire behavior (e.g., fire intensity, rate of spread) and burn severity (e.g., fire-caused vegetation mortality) underpin myriad ecological, management, and policy concerns. These two key attributes of fire regimes are mechanistically linked to some degree [130], as extreme fire behavior is variably associated with greater burn severity [131–133] and slower post-fire recovery [134]. Understanding the degree to which they co-vary over broad extents of space and time is critical to anticipating feedbacks and trajectories of future fire in the western US, as well as how management can affect trajectories to meet target objectives. We will use outputs and data products from sub-objectives 1-3 to provide the first western US - wide empirical test of how fire behavior and severity are related over space and time, with particular focus on understanding congruence and divergence between these two dimensions of fire regimes.

Burn severity is a combined outcome of pre-fire vegetation structure and associated resistance (or conversely susceptibility) to damage or mortality from fire interacting with the behavior of fire (resulting from fuels, weather, and topography) [130,135]. For example, given a landscape of homogenous forest structure and composition, spatial variability in heat intensity or duration from a fire would drive variability in burn severity. Conversely, spatially homogeneous heat intensity from a fire would drive variability in burn severity across a landscape that was spatially variable in fire-resistance traits of trees. As such, management actions that can reduce burn severity via pre-fire forest and fuels management or real-time operational fire management depend on understanding the correspondence between patterns and drivers of fire behavior and burn severity. Here, we propose to characterize the spatial congruence and divergence between fire behavior and burn severity across the western US in the 21st century, and test for mechanisms underpinning the observed patterns.

Using the integrated fire behavior-fire severity database described in sub-objective 3, we will quantify relationships between key fire behavior metrics (e.g., FRP and fire speed) and burn severity attributes (e.g., tree basal area killed by fire and distance to live seed source for years 1-5 post-fire). Data will be used for each fire at three spatial resolutions: 1-km pixels at the finest scale (determined by the spatial resolution of one pixel for MODIS/VIIRS data resolution); daily perimeter (all 1-km MODIS/VIIRS pixels with each day's fire spread), and total fire event (all 1-km MODIS/VIIRS pixels within each fire perimeter). For each 1-km pixel (native resolution of MODIS), pre-fire vegetation structure (30-m pixels), FRS scores (250m pixels), and burn severity attributes (30-m pixels) will be averaged to the 1-km fire-behavior pixel. For spatial scales of daily perimeters and total fire perimeters, data from each source will be averaged among pixels within that spatial extent and assigned to the daily and event perimeter, respectively.

We will then test hypotheses regarding the relationships between fire behavior and severity in the 21st century, as moderated by pre-fire forest structure and composition (e.g., fire-related traits). For example, we will compare the relative effect sizes of pre-fire vegetation structure, FRS scores, live fuel moisture content (LFMC), FRP, and fire speed for predicting functional metrics of burn severity. We anticipate that over a range of fire intensity there will be a strong effect of pre-fire vegetation structure and FRS, but there may be a threshold in FRP beyond which pre-fire vegetation structure has no effect [133]. Next, we will quantify the coupling of fire behavior and fire severity over space since 2001, and whether the relationship between fire behavior and severity is weakening or strengthening over time. We expect a weakening of the relationship between fire behavior and severity metrics as additional stressors (e.g., drought, insect outbreaks) result in less fire intensity required to produce the same level of fire severity [136], and this trend will depend on declining stand-level FRS scores over time. We will also test whether areas with prior disturbances or management actions that shift pre-fire forest structure toward greater FRS scores (e.g., low-severity wildfires, thinning and prescribed burning) exhibit more consistently positive relationships between fire behavior and severity metrics. We will also identify locations where fire-behavior and burn severity metrics individually have changed the most over the last 20 years, as well as where the relationship between them has changed the most. Finally, we will link outputs here to modeled and observed data on combustion and smoke (objectives 4 and 5). Data inputs for this component are from earlier sub-objectives with the exception of the FRS score dataset [32], which is publicly available [137]. Outputs from analyses from this sub-objective will be important for calibrating model simulations in objective 4 and comparing to future projections of convergence/divergence of fire behavior and severity.

Given this sub-objective builds on the previous sub-objectives, progress would only occur later in the project. Over 5-10 years, we would produce the first western US wide set of analyses that document spatial and temporal patterns, as well as the underlying mechanisms, of relationships between forest structure, fire behavior, and burn severity. This is critical for developing metrics to evaluate beneficial vs catastrophic fire, a key knowledge gap defined by our stakeholders (see objective 1). We would publish several peer-reviewed scientific papers that describe these trends, their drivers, and their implications. These findings will directly support management and policy decisions aimed at directing / stewarding changes in fire regimes currently being explored and implemented by management and agency partners. We could lay a critical foundation for a framework that can inform similar analyses of fire behavior and severity using data coming online with much finer spatial and temporal resolution (e.g., FireSat, NASA, FireSense). These insights would build key understanding of fire regime change across multiple dimensions of fire events and effects, and directly support management efforts to reduce fire severity via management pre-, during, and post-fire.

3.3.5 Sub-objective 5: How are forest structure, function, and cover changing in response to fire and proactive forest management?

Recent increases in forest area burned [1] and forest area burned at high severity [2] are likely to have profound and long-lasting impacts on forests in the western US. Additionally, forest management actions such as thinning and prescribed fire are likely to become more widespread in future years, modifying trends in fire activity. To evaluate the impacts of fire as well as the efficacy of forest management decisions, we must be able to accurately estimate their effect on forest cover, structure, and function. We will build on previous work to improve and extend estimates of forest biomass, structural characteristics, and live fuel moisture and use our estimates to examine how forests are changing in response to fire and forest management activities over time.

To estimate forest biomass, we will leverage an existing annual aboveground biomass (AGB) product for the Landsat record (1984-2020) [138,139]. In this work, the authors compiled a series of lidar flights across the western US, derived lidar metrics of canopy height and density, and estimated AGB across lidar landscapes by relating field-based AGB estimates to lidar metrics. They used a subset of lidar-derived AGB estimates to train a random forest model based on Landsat time series indices, climate variables, and topographic characteristics to predict AGB across the western US. We will extend this dataset to include live, dead, and declining aboveground forest AGB pools using the same field datasets and lidar-derived metrics. Employing established methods [140] in addition to spectral mixture analysis, we will estimate each forest AGB pool annually across the Landsat record through the end of the project. Forest AGB pools estimated in this sub-objective will be used to force and calibrate simulation models for the historical period (objective 4) and can be updated annually as new information becomes available. To examine changes to forest AGB and structural characteristics in response to fire, we will focus on previously burned areas. Using statistical models, we will test the influence of initial fire severity (sub-objectives 1 and 2), fire behavior characteristics (sub-objective 3), and, where applicable, the type of management action, on the recovery trajectories of forest carbon pools as well as fuels characteristics over time.

We also will use Landsat time series to assess long-term post-fire recovery trajectories and characterize functional ecological variation in recovery and successional dynamics. Focusing on pixels with Landsat imagery after wildfire or management activities, we will evaluate post-fire structural and compositional changes, first using existing datasets of forest structure and composition (TreeMap [125], BigMap [141]), then using an experimental approach to classify post-fire recovery trajectories. Big Map is a similar product to TreeMap also produced by the USFS. While TreeMap and Big Map are extremely powerful datasets, both have limited temporal resolution (TreeMap: 2014, 2016, BigMap: 2014-2018) produced with a 3- to 5-year lag, we will use space-for-time substitutions to elucidate post-fire forest recovery rates and successional dynamics. We will also employ an experimental approach attempting to categorize long-term post-fire recovery trajectories. Using Landsat pixels that burned after 1984, we will calculate an ensemble of vegetation indices and use a time series segmentation algorithm (LandTrendR or Continuous Change Detection and Classification) to derive temporal recovery metrics from Landsat bands and indices (e.g. means and slopes for each time segment related to disturbance and recovery period, duration of the time segment, magnitude of change over the time segment) [142,143]. We will perform a semi-supervised clustering [144] on derived segment spectral and temporal characteristics to characterize variability in post-fire recovery trajectories. We will then compare clusters to high resolution orthoimagery (e.g. National Agriculture Imagery Program, WorldView), the datasets of forest biomass, structure and composition described above, lidar data, and other sources where available to convert the resulting clusters into ecologically relevant recovery trajectory classifications. If this approach is successful, we will test new methods to hindcast annual recovery trajectory classifications back through the Landsat record, updating annually as new Landsat imagery becomes available. To determine indicators of regeneration success, we will compare estimates of recovery trajectories with those of burn severity (sub-objectives 1 and 2), fire behavior (sub-objective 3), management treatment type, and post-fire climate. This work will catalyze capacity for decision-makers and managers to plan proactive forest management actions and guide post-fire regeneration pathways.

We will characterize live fuel moisture content (LFMC) as a key aspect of forest function. LFMC represents the ecosystem's ability to take up water and to protect against increasing atmospheric drying forces (e.g. evaporative demand via vapor pressure deficit) under increasingly hot temperatures. It influences the risks of drought-driven tree mortality and future fire. It is also an indicator of how well buffered an ecosystem is to hydrometeorological conditions more generally [145,146]. Since the influence of precipitation and temperature on forest function depends on a range of interacting biotic (e.g. plant hydraulics, root-soil hydraulic interactions, leaf area) and abiotic (soil type, typography) factors whose individual roles would be too difficult to disentangle at scale, LFMC acts as an overall indicator of the degree to which an ecosystem is buffered to drought stress (beyond its direct impact on fire behavior) [147] . Several algorithms exist for large-scale mapping of LFMC from optical sensors (e.g. MODIS, Sentinel-2), but these have not been implemented at scale and are not available for analysis. Additionally, these sensors are limited by cloud cover and are sensitive to only the top of the canopy. Co-PI Konings's group has previously developed a publicly available wall-to-wall dataset of LFMC using synthetic aperture radar data that penetrates deeper into the canopy and is insensitive to clouds. However, this dataset is only available for six years because of sensor limitations. We will use machine learning models to combine both data sources (as well as other inputs) to extend the microwave record backwards, and build a multidecadal record of LFMC across the western US since 2002 at 250 m resolution. This record can then be used for the LFMC-related analyses in sub-objectives 3 and 4 above, and will also be used to help with model calibration in objective 4. We will then use this dataset to determine how prior fire and management activities affect forest moisture buffering to drought, and how the influence of previous fire and proactive forest management compares in magnitude to the influence of climate and forest structure trends. Data inputs for analysis of forest carbon, structural characteristics, ecological recovery trajectories, and management activities come from publicly available geospatial and remote sensing datasets as well as contributed field plot characteristics.

In the next 1-3 years, we will derive the methodology for and build a new long-term record of annual biomass pools, post-fire recovery metrics, and a catalog of LFMC. Over 5-10 years, we could use these datasets to examine how changes to LFMC-hydroclimate sensitivity, post-fire recovery, and forest biomass and structural characteristics respond to different fire characteristics and management actions (e.g. prescribed burning, thinning). These assessments could enable us to track how forests are changing in near real-time, essential insights for assessing the resilience of pre-fire forests and evaluating the social and ecological impacts of fire, both key knowledge gaps identified by stakeholders (see objective 1).

3.4 Objective 4: **Quantify the drivers of observed trends in forest fire, project how forests and fire regimes may continue to change in the future, and determine how current and future stewardship actions may shape future outcomes.** Building off management strategies developed with stakeholders, we will use an ensemble of process-based simulation models to ask:

3.4.1 Sub-objective 1: How have human-caused climate change and natural variability combined to contribute to western US forest-fire trends over the last several decades?

Forest fires of the western US have increased in size and severity at astonishing rates over the last four decades. Annual burned forest area grew more than 1,000 percent since the early 1980s [1], and the areas burned in 2020 and 2021 dwarfed previous records [6,7]. We will use forest-ecosystem and fire modeling to provide the most comprehensive assessment yet of the causes that underpin observed trends in western US forest-fire activity in recent decades. Previous work by our group and others has unequivocally demonstrated that human-caused climate change underpins much of these recent increases in forest-fire activity [3,8]. However, past studies have not allowed for spatially-explicit investigation of how climate-change effects vary across the tremendously diverse geography of western US forests. Past studies have also not quantified the relative impacts of human and natural ignition patterns and past and current fire-suppression efforts that have left a legacy of increased fuel loads in some but not all western US forests. Further, prior studies have largely focused on area burned because it is well measured and strongly correlated with climate data. However, other fire metrics such as fire intensity and severity are also critically important. We are poised to gain unprecedented understanding of how human-caused climate change, natural climate variability, human population, and fuel characteristics have contributed to recent changes across the multiple dimensions of forest-fire regimes, including fire intensity and severity. To do so, we are developing a coupled modeling framework that simulates forest ecosystem processes like fire-induced damage and mortality of trees, biomass combustion, postfire tree regeneration, and successional trajectories of forest cover, structure, and functions, as well as key fire characteristics (occurrence, sizes, intensity, severity, and shapes).

Forest ecosystems will be simulated by the DYNAmic Temperate and Boreal Fire and FORest-EcosySTem simulator (DYNAFFOREST) model that we published in 2022 [148], developed by PI Hansen. DYNAFFOREST is similar to iLand (described in objective 2) because it was designed to explore how forests respond to disturbance in a spatially explicit manner. However, the representation of forests in DYNAFFOREST is simplified compared to iLand such that the model is computationally tractable to be run at a relatively fine spatial resolution (1-km) across all western US forests (> 800,000 km^2), making it ideal for modeling forests and fire across all of the western US. DYNAFFOREST represents 12 forest types, simulates forest dynamics on annual time steps, and captures critically important and complex ecosystem processes that are not included in earth-system models. For example, in DYNAFFOREST, forests that have reached reproductive maturity disperse seeds within and across grid cells according to PFT-specific dispersal kernels following mortality events. Thus, the seeds available for potential forest regeneration represent nearby forest types. The forest type that establishes is dictated by climate in the years of the regeneration window. The team (co-PI Trugman and PI Hansen) has already published a paper where they used DYNAFFOREST to understand how proposed vegetation management interventions in the Sierra Nevada impact forest carbon loss and burn severity [149].

The forest-fire model is statistical and operates monthly at a 12-km spatial resolution. It simulates the probability, occurrence, and sizes of forest fires as functions of fuel characteristics, human population, and climate. Development of the forest-fire model is led by co-PI Park Williams. The initial version of the model is completed and will be published in 2024. Based on rigorous cross-validation of the forest-fire model, we know that it reproduces the past several decades of observed western US forest-fire activity with high fidelity. DYNAFFOREST passes fuels information to the fire model. DYNAFFOREST then uses outputs from the fire model to grow realistic fire shapes and to estimate biomass combustion, crown damage, and tree mortality. We have already developed the computing infrastructure to run the DYNAFFOREST and forest-fire models in a dynamically coupled manner.

Co-PI Trugman has also developed a computationally efficient plant hydraulics model that requires inputs of soil moisture, atmospheric CO_2, temperature, and VPD. This model is able to run efficiently at scales comparable to the continental US and produces prognostic vegetation water status given local climate [150], which is useful both for anticipating drought driven mortality [150] that increases downed woody fuel loads and for estimating LFMC, both of which contribute to wildfire risk. Co-PIs Trugman and Konings are currently working with regional-scale plant water status outputs to validate plant model predictions of LFMC using several LFMC products derived from satellite-based microwave backscatter and optical reflectance as described in objective 3 [71]. We will include the vegetation hydraulics module in DYNAFFOREST to improve simulations of fuel moisture and drought- and fire-induced mortality and will use remotely sensed LFMC developed in objective 3 by co-PI Konings to improve the statistical fire model.

To assess the role of human-caused climate change on recent forest-fire activity, we have developed an alternate historical (1951–present) record of high-resolution (4-km) daily climate data for the western US *from which human-caused climate trends in temperature, precipitation, humidity, wind speed, and solar radiation have been removed*. We estimate human-caused climate change to be the median trends among 27 CMIP6 climate models, and these human-caused trends include changes in the variability of climate, not just changes in the means. Forcing our coupled simulations with this alternate historical climate dataset and comparing the outputs to our primary simulations forced by observed climate will allow us to quantitatively assess, in a spatially explicit manner, to what extent human-caused climate change has affected forest fire and forest ecosystems over the last seven decades and how the nature of these relationships varies across space.

Over the next 1-3 years, we will publish a technical description of the fire model in a peer-reviewed journal (in 2024), and we will then publish a high-impact article presenting our initial assessment of the spatially-explicit drivers of changes in forest-fire frequency, size, and biomass combustion from 1951–present.

Over 5-10 years, we would be able to improve the DYNAFFOREST and forest-fire models, leading to better constrained and more comprehensive re-assessments of historical changes in the western US wildfire regime. For example, DYNAFFOREST could be improved based on experimental results from objective 2 to include understory fuels and grasses and effects of enhanced CO_2 on tree seedling establishment. Data produced in objective 3 would allow us to rigorously compare simulated forest cover, structure, and functions, as well as fire severity and biomass combustion to observational records, leading to improvements in our simulations of these processes and how the fire model represents effects of prior burning on subsequent fire occurrence and spread. Objective 3 would also provide new observational datasets of forest biomass, allowing for improved calibration of DYNAFFOREST and a parameterization of the fire model that uses observed fuel characteristics rather than simulation outputs for the observed period. Additionally, we could re-implement several of the components of DYNAFFOREST within a differentiable parameter learning framework [151] to enable the combination of the process knowledge embedded in the model with the power of machine learning and several of the remotely sensed datasets from objective 3 to develop alternative schemes for improved spatial parametrization. We could also improve the DYNAFFOREST spin-up process to better reflect pre-Euro American fire regimes by forcing it with tree-ring informed paleo climate data, and advance the fire model to explicitly simulate human- vs lightning-ignited fires and to better simulate the spread and shapes of fires.

Improved simulations of historical trends in fire activity and their underlying causes would provide valuable context for decision makers regarding the current state of forest ecosystems and fire, providing actionable information into how the relative importance of climate change vs fuel densification vs human impacts (suppression and ignitions) varies across the spatially heterogeneous western US. This is critical for developing reliable metrics that can differentiate between beneficial and catastrophic fire, as well as for identifying the underlying causes, a key knowledge gap identified by stakeholders (see objective 1).

3.4.2 Sub-objective 2: How will western US forest-fire regimes change between now and 2100 based on projections from 27 climate models and various emissions scenarios?

It is widely expected that annual forest area burned, and likely the area burned by severe fires, will continue to increase in the western US over the next several decades [2,59]. Yet, current models that project future burning do not consider how forests will change and feedback to alter subsequent fire frequency, size, behavior, or effects, which we know is extremely unrealistic. We will use our coupled model framework to simulate, **for the first time**, the dynamic interplay between forest fire and forest fuels across the western US in response to projected changes in climate and human population between now and 2100. The expectation that forest-fire activity will continue to increase is guided by observations of a strong and exponential effect of heat and aridity on burning in the western US [1] and projections of continued warming and fire-season aridification. However, static extrapolation of the historical relationships between fire and climate into the future is problematic as it leads to impossibly large predictions of forest-fire area by the end of the century that actually exceeds the available forest area to burn, and in many areas, implies fire return intervals that are too short for forests to reestablish from the last fire [152]. Previous work has tried to produce more realistic forest-fire projections by attempting to impose a self-regulating feedback from fire (fire reduces subsequent fire by reducing fuels) based on simplistic assumptions regarding whether and for how long a burned area cannot reburn [59,153]. This is a great first step. However, in reality, the strength and duration of any self-regulating feedback between forests and fire is going to be wildly variable in space and time, dependent on many factors, such as the severity of the previous burn, the postfire vegetation type that establishes, the climate during the period of establishment, and the climate/meteorology leading up to and during subsequent potential fires. Our ability to perform coupled forest-fire simulations through the remainder of the 21st century is necessary to account for these factors. It will thus mark a major advance, not only in our understanding of future forest-fire trends but also in our ability to identify a suite of effective management scenarios (e.g., prescribed burning, fuel reduction treatments, thinning) that can help to avoid undesired social-ecological outcomes, as described in sub-objective 4.

To perform simulations of future forests and fire, co-PI Williams has developed high-resolution (4-km) statistically downscaled daily climate projections of western US temperature, precipitation, humidity, wind velocity, and solar radiation for 27 CMIP6 climate models for the historical (1850–2014) period as well as a future (2015–2100) scenario that assumes a middle-of-road human emissions trajectory (SSP2-

4.5). This was a major computational effort, resulting in a large database (>10 Tb). With the code and computer infrastructure in place, however, we can now easily repeat this effort for additional future emissions scenarios, including a low-end (SSP1-2.6) and high-end (SSP3-7.0) scenario. We will obtain maps of future projected population density across the western US (see objective 5 for additional details), which is an important predictor in our forest-fire model.

In the next 1–3 years, we will industrialize our computing approach to accommodate the massive number of coupled simulations that are necessary when we force the model with a wide range of future climate projections. We will develop our coupled modeling infrastructure on the NSF and National Center for Atmospheric Research (NCAR) supercomputer, Derecho. We plan to publish two high-impact papers presenting fire and forest-ecosystem projections forced by climate projections from the 27 CMIP6 climate models under two or three emissions scenarios. Projections will focus on three forecast horizons meant to support different decision-maker needs. We will make projections for every year between now and 2100, allowing for inference on near-term (5 to 10 years), mid-term (mid-21st century), and long-term (2100) forecasting horizons. Results will also be summarized at different spatial scales to support decision makers, including at the grid-cell (1-km) level, as well as for western US watersheds, level III ecoregions, western US counties, states, and all of the western US. The papers will provide the most rigorous and comprehensive projections to date of how western US forest-fire activity and forest ecosystems are likely to change between now and the end of this century and the relative importance of greenhouse-gas emissions scenarios, climate, and fuels.

Over 5-10 years, we could produce an ensemble of future projections of western US forest-fire and forest characteristics forced by a wide range of climate models and emissions scenarios. Additionally, we expect the next generation of climate projections from CMIP7 to become available around 2026. At that time, we could update our downscaled climate-projection database and coupled simulations so that we can publish the first CMIP7-based projections of western US forests and fire and assess changes from CMIP6. Future projections will directly address several knowledge gaps identified by stakeholders (see objective 1). Specifically, future simulations will support decision making by providing practitioners and policy makers with very clear information on where, when, how they might expect changes in near-term fire activity, with critical insights into the drivers of change, including the relative importance of overly abundant fuels vs climate change. This should help decision makers with myriad strategies including planning fuel treatments (sub-objective 4), evaluating how to manage a dwindling water supply (objective 5), and developing zoning policies for homes in the WUI (objective 5).

3.4.3 Sub-objective 3: Where, when, how, and why will forests change fundamentally in response to unprecedented climate extremes including drought and fire across a range of spatial scales, from landscapes to the entire western US? When, where, and at what spatial scales do self-regulating vegetation-fire feedbacks emerge and how strong are they?

Changes in forest structure and cover with increased fire activity will determine where and when fuels feedbacks emerge that can constrain subsequent burning [28,59,154]. Thus, accurately modeling vegetation is important for projecting future fire regimes [25,155]. No single model is appropriate for all questions and scales. Thus, to provide the most rigorous process-based simulations of western US forest dynamics to date, we will develop an ensemble of projections with several forest models that operate at individual tree to western-US wide scales. We will use the models to determine how forest cover, structure, and functions may change with increasing fire and ongoing climate change. The model ensemble will include iLand-SVD (Scaling Vegetation Dynamics) and regional to western-US wide simulations from DYNAFFOREST [82,148,156].

Combining insights from multiple models can provide powerful insights because they each have their strengths and weaknesses. For example, iLand (described in depth in objective 2) is complementary to DYNAFFOREST in its design and purpose. However, it is far more complex and much finer resolution in its representation of processes. The benefit is that iLand provides a very detailed representation of forest dynamics. The downside is that the model is only computationally tractable for up to ~ 60,000 ha, but a new meta-model, SVD, has been designed specifically for use with iLand to develop regional- to continental-scale forest and disturbance projections. Deep neural networks are trained on output from many landscape simulations (iLand and other models) across climate scenarios to learn under what sets of climate, disturbance, forest succession, and management conditions transitions occur among 10s to 100s of thousands of different states in forest cover, composition, structure, and functions. Transition probabilities are then used to force a state and transition model at continental scales. SVD can also be dynamically coupled with fire projections produced in sub-objectives 1 and 2.

We will choose locations for iLand landscapes based on the following criteria: 1. to cover the range of climate space and forest compositions found in the western US; 2. locations where we do not already have a strong parametrization for iLand (California, middle Rockies, SW); 3. co-located with our field sites (field plots described in objective 2) and Moore Foundation SPARK locations as appropriate and warranted. We will run iLand in each simulated landscape, forced with fire projections and climate products produced in sub-objectives 1 and 2 for the years 1951-2100. The iLand catalog could then be used to train SVD, and SVD projections will be run for the same time period and under the same climate/fire projections for all of the western US. The ultimate goal will be to dynamically couple SVD with the statistical fire model produced in sub-objective 1. We will then conduct inter-model comparisons among iLand, SVD, and DYNAFFOREST projections, to determine where, when, and why forest models agree and diverge in their projections. To conduct multi-model vegetation projections and intercomparisons, we will further downscale the catalog of daily climate projections produced in sub-objective 1 and 2 to a 100 m resolution for our iLand landscapes (27 CMIP6 climate models for the historical and future periods). We will also make use of the statistical fire projections produced for those sub-objectives.

In the next 1–3 years, we will produce peer reviewed papers that describe parameterizations and test for the bounds of forest functional resilience in individual landscapes. We will also produce an ensemble of historical and 21st century iLand simulations paired with the statistical fire model.

Over 5-10 years, we would develop the most rigorous multi-model approach available for process-based simulation of disturbance prone forests that considers critical processes from the individual tree to the continent. We would use this novel multi-model approach to produce a large catalog of vegetation-fire simulations under different scenarios of future climate and emissions trajectories. The multi-model approach could ensure that we can address a large range of stakeholder questions at all relevant scales from the stand to the whole western US with the appropriate level of represented processes, addressing key knowledge gaps identified by stakeholders including the need for frameworks to scale ecological information up and down and to translate across geographies (see objective 1). Such an integrated tool is essential for supporting effective decision making during a time of profound and complex change. For example, we will be able to determine where climate and disturbance scenarios agree and diverge, to identify hotspots where change is more likely and areas where uncertainty is highest. Results would be summarized in a series of high-impact papers that describe how, where, when, and why forests may change and feedback to affect subsequent fire at stand, landscape, and entire western-US scales.

3.4.4 Sub-objective 4: Where and how might management and policy strategies, designed with decision makers, affect changes in forests and fire regimes and at what spatial and temporal scales do interventions have impact?

With unprecedented federal investment in the Infrastructure Investment and Jobs Act and the Inflation Reduction Act, widespread forest and fire management actions are now being implemented across the western US. These strategies could alter how fire frequency, size, and severity changes over coming decades [60]. However, the western US domain is vast. Thus, treatments must be strategically planned for maximum impact. But, forests and fire regimes evolve slowly. Evaluating the efficacy of contemporary management on the reduction of catastrophic fire and maintenance of resilient forests will require monitoring over decades and across the vast domain of western US forests. Performing experiments with process-based simulations can inform and support strategic decisions because we can test the impacts of current strategies without waiting decades for outcomes to play out. We can also compare current approaches with other plausible strategies without the significant investment of capital that actual implementation would require [83]. This allows for bold experimentation.

We are developing a suite of co-developed forest and fire management scenarios to test with our modeling framework, based on proposed solutions in the literature [157] and many conversations with stakeholders. Scenarios are designed to systematically vary across three axes (Fig. 3). Along the first axis, we vary the approach used to reduce fuels. Options include wildland fire use, prescribed burning, and two techniques for mechanical thinning, implemented separately and together. The second axis varies the range of spatial domains in which treatments are implemented, including treating forests only within the WUI, spreading treatments across all publicly-managed forests, and following an approach used by the US Forest Service where intensity of treatment varies with proximity to human structures and endangered species habitats (Potential Operational Delineations; PODs). Along the third axis, we vary the amount of acres treated per year across the spectrum of feasibility, from currently tractable with current investments, to idealistically bold. Treatment frequency (not shown in Fig. 3) will vary relative to area treated. We will apply re-treatments within the model every 10, 25, or 50 years after the completion of the previous set of treatments.

This suite of scenarios explores much of the parameter space of possible management strategies, approaches, and extent of management on the landscape, in order to determine how to best reduce and prevent catastrophic forest fires in coming decades. Each management scenario (e.g., unique combinations from each of the three axes plus treatment frequency) also has a different goal or set of goals that stakeholders identify as important. The goals currently include fewer fires across the western US, fewer fires in the WUI, fewer fires specifically in and around Lower Income and Disadvantaged Communities (LIDAC) and other vulnerable communities in the WUI, less severe fires, and more resilient forests. New goals can be added over the course of the project in continued consultation with stakeholders.

It is critical to understand how management can affect subsequent fire and forest resilience at stand to entire western US scales, because many small-scale treatments will add up to broader scale outcomes. Unfortunately, no model can address these uncertainties across all necessary scales. Thus, we will test each management scenario in both DYNAFFOREST and iLand-SVD, which will provide a comprehensive understanding of treatment efficacy across all spatial domains of interest. We will run each scenario multiple times, varying the spatial configuration of treatments each time. We will run each scenario, including a baseline no-management scenario, forced with both historical and future climate projections (GCMs and SSPs specified in sub-objective 2 above). We will compare the results within each scenario to the no-management scenario, using the goal of the management strategy as the quantitative metric of impact (e.g., number of fires within the WUI). We will compare the efficacy of management scenarios across future climate projections, allowing us to determine how the utility of strategies changes with current and future climate. The western US contains several ecological regions that vary widely in climate conditions, forest dynamics, and historical fire-regime characteristics. It is almost certain that the success of management strategies will vary with this complex geography. We will

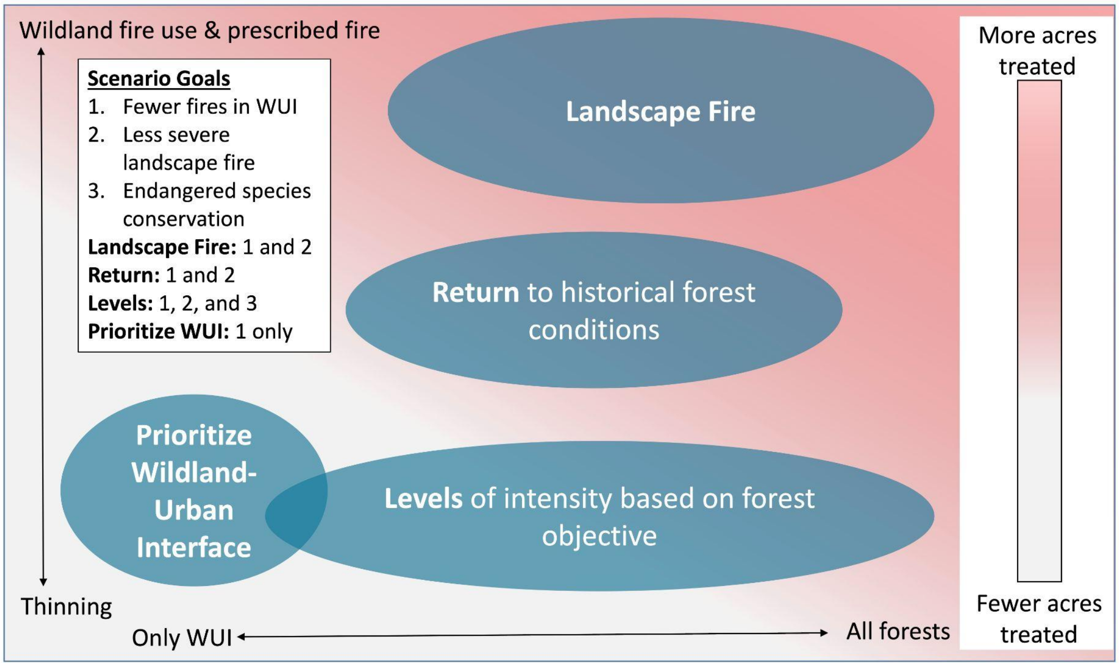

Figure 3. Four possible management scenarios (blue circles) and how they vary across three axes. The first axis (Y axis) is the type of treatment, with thinning only strategies on the bottom, the combined thinning and wildland fire use and prescribed burning strategy in the middle, and the wildland fire use and prescribed fire only strategy on the top. The second axis (X axis) is the spatial domain over which treatments are implemented, from only the wildland-urban interface (WUI) on the left to all forests on the right. The third axis, which is diagonal, displays variation in the annual number of acres treated, from what is currently feasible today in the bottom left to an idealistically bold ideal number in the top right. Each possible management strategy addresses between one and three goals, listed in the inset box.

compare variables of interest from the different management scenarios within and across regions (e.g., watershed, ecoregion, counties, states, all of the western US). We will compare how well each management scenario performs versus the no-management baseline, over future climate scenarios, and across different ecological regions within the western US. This will allow us to provide concrete recommendations to practitioners about what strategies are most effective at promoting beneficial fire and fostering forest resilience, where, and how that efficacy changes over time.

The fire models, forest models, and downscaled future climate forcing data and scenarios (27 GCMs under 2-3 emission scenarios for the period 1951-2100), as well as the benchmarking of the forest and fire models, described in sub-objectives 1 and 2 are required to run management experiments with DYNAFFOREST. The setup and benchmarking of 20 landscapes across the western US are required to run management experiments with iLand-SVD. We have already developed a thinning module for DYNAFFOREST led by co-PI Trugman's lab and successfully implemented thinning treatments within DYNAFFOREST for the Sierra Nevada Mountains of California[149] (Fig. 4).

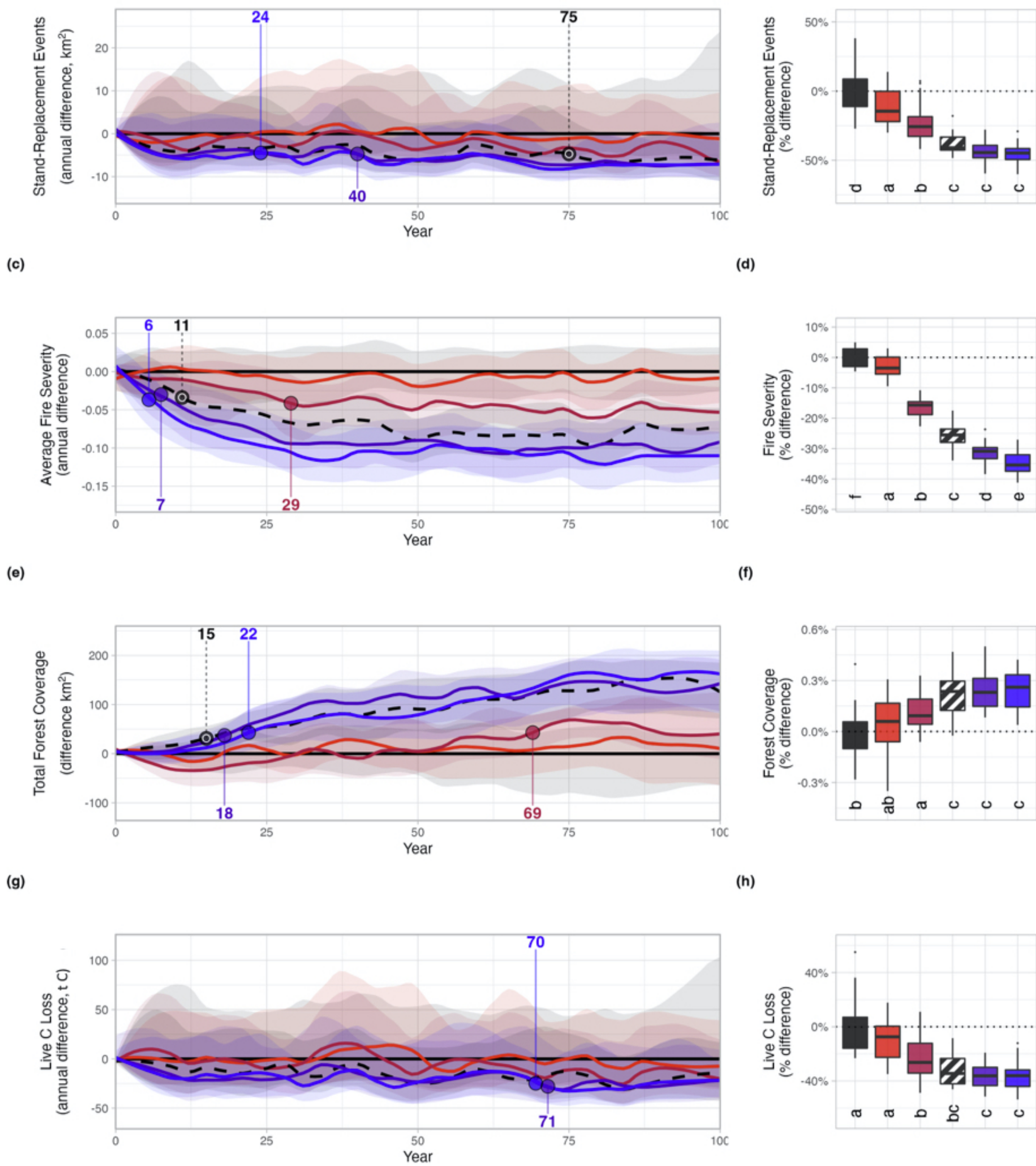

Figure 4. Increased annual fuels treatment extent decreases pyrogenic stand-replacement rates, wildfire severity, forest conversion to grassland, and live carbon loss rates, and results in an earlier time of emergence (ToE) for treatment effects in 100 year simulations of the Sierra Nevada Mountain Range in CA using the forest model DYNFFOREST. All values are plotted relative to the annual ensemble median value of the no-treatment control scenario. (a) Time series of relative areal differences in pyrogenic stand-replacement events (km2) and (b) percent difference in ensemble mean values for pyrogenic stand-replacement events relative to the control scenario over years 75-100. Negative values correspond to a reduction in stand mortality events. (c) Time series of relative differences in annual mean fire severity for

cells 33 affected by fire and (d) percent difference ensemble mean values for fire severity relative to the control scenario over years 75-100. Negative values correspond to a reduction in fire severity. (e) Time series of relative differences in overall forest coverage and (f) percent difference in ensemble mean values for overall forest coverage relative to the control scenario over years 75-100. Positive values correspond to an increase in forest coverage. (g) Time series of relative difference in live carbon (metric tons C) lost to wildfire and (h) percent difference in ensemble mean values for live carbon loss relative to the control scenario over years 75-100. Negative values correspond to a decrease in live C loss. For time series plots, the solid line is the ensemble median (50th percentile) relative to the control ensemble median, and ribboning indicates the IQR (25th -75th percentile range). From Daum et al. (2024).

In the next 1-3 years, we will build a prescribed-fire module within DYNAFFOREST. We will also run a pilot version of the full management experiment, implementing scenarios that use thinning as the only fuel reduction strategy. For the management strategies that specifically target the WUI, we will integrate the current and projected future extent of the WUI from objective 5. We will then use the results of the pilot experiment to make recommendations for the spatial optimization and timing of management actions. While these recommendations will only be preliminary, they will provide immediate guidance to managers with limited time and resources.

Over 5-10 years, we would run the full management experiment, with all 27 GCMs and 2-3 emissions scenarios. We could compare how well each management strategy performs to make specific recommendations for management actions, including spatial location, extent, and timescale of treatments, across all of the western US. The multi-model framework would allow us to test management strategies that might decouple climate and fire at stand to continental scales, tailoring insights to the many scales that stakeholders with diverse needs work at. We would additionally create a spatial and temporal optimization framework to maximally reduce catastrophic fire while accounting for limited resources in implementing management [158].

3.5 Objective 5: **Quantify current and future consequences for people, biodiversity, and ecosystem services essential to human wellbeing and economies.** This includes human smoke exposure, fire risk in the WUI, species and functional diversity, carbon storage, and the provision of water. Living more sustainably with fire and the secure provision of ecosystem services during a time of profound change will only occur with improved ecological understanding. We will interrogate model output from objective 4 and a variety of geospatial datasets to ask:

3.5.1 Sub-objective 1: How have human smoke exposure, WUI dynamics, biodiversity, water quantity, and forest carbon storage changed in response to fire and other drivers in recent decades?

Smoke: Smoke exposure is worsening in communities across the western US with increased burning [159,160]. Management activities, particularly prescribed burning, will likely play a major role in efforts to mitigate catastrophic forest-fire risk [60,161,162]. However, prescribed burns also produce smoke. It remains poorly resolved whether and how the human health consequences of exposure to smoke differ between prescribed fires and wildfires, and how fuel treatments may impact future wildfire emissions and smoke exposure. As increased federal and state funding is allocated to fuel treatments, a pressing need exists to quantify public health impacts, tradeoffs, and potential co-benefits. This is particularly true among communities who may be more vulnerable to smoke exposure impacts, low income, unhoused, and Black, Indigenous, and communities of color (BIPOC). Such groups already experience disproportionately high exposures to anthropogenic sources of air pollution and have decreased access to smoke exposure reduction strategies, making them extremely vulnerable. In addition to experiencing disproportionate exposure from spending a lot of time outside, agricultural workers are also vulnerable to smoke effects due to the physically demanding nature of their jobs, which lead to high respiration rates. Finally, individuals with preexisting conditions, particularly respiratory conditions such as asthma and chronic obstructive pulmonary disorder, pregnant people, elderly, and young children may also be more susceptible to health impacts associated with smoke exposure. We know that historical smoke exposures have not been experienced equitably across these groups, and it is possible that future exposure burdens from wildfire and prescribed burning will impact these groups differently, highlighting the need to consider environmental justice implications of past and future smoke exposures and health impacts.

We will establish a baseline of historical smoke exposure impacts by connecting existing daily smoke exposure estimates for wildfires, prescribed burns, and agricultural burns generated using the GEOS-Chem atmospheric chemical transport model (0.25° x 0.3125° degree, western US, 2014-2020) to demographic information and health outcomes and assess the existing exposure burdens across vulnerable human subpopulations. In preparation for the availability of simulation outputs from objective 4, we will also use existing historical fire-forest model output (back to 1951) to translate changes in burned area to fire emissions estimates needed for use in an air pollution dispersion model. We will compare emissions estimates derived from historical model runs to existing satellite-derived fire emissions inventories, such as Fire INventory from NCAR (FINN), Global Fire Emissions Database (GFED), Global Fire Assimilation System (GFAS), etc., which are mostly available since 2000 due to satellite coverage [163,164,165]. Leveraging these emissions estimates, we will use GEOS-Chem to model smoke concentrations for recent decades. Most smoke exposure datasets only go back to the mid-2000s. Thus, availability of longer-term emissions estimates will allow us to establish a better understanding of trends in historical exposure burdens. Depending on computation constraints, this may be carried out as a spatial subset or using time slices.

WUI: Wildfires pose the biggest threat to people and their homes in the WUI. The WUI has grown rapidly in recent decades (Fig. 5), both in area and density of homes within the WUI [166, 42, 43], and is likely to continue to grow. However, assessment of long-term WUI trends are lacking. Mapping the WUI requires data on both houses and wildland vegetation, in order to map 'intermix WUI', or, the area where houses and wildland vegetation intermingle, and 'interface WUI', where developed areas abut up to wildland areas [167,168]. To establish historical observational baselines of WUI change, United States Census data provide decadal information on housing patterns for census units (e.g., 'census blocks') since 1990, and our team has developed algorithms based on census estimates of the age of houses to 'backcast' past housing density as far back as 1940 [169,170]. Comparably detailed data on past wildland vegetation patterns is lacking, but a first approximation of past WUI change based on housing data alone shows that most WUI in the western US emerged after the 1970s (unpublished data). In addition to the lack of historical vegetation data, another shortcoming of our current approach is that census units in rural areas can be very large (thousands of hectares), making the resulting WUI maps coarse. We will fine tune these observational historical baselines of WUI for every decade since 1940 for the western US, by (a) developing new algorithms to integrate the information on past housing patterns from our census-based backcasts with spatially detailed information on housing location from the maps of building footprints provided by Microsoft, which we have used to map current WUI based on building locations [171, 172], and (b) integrating data on past vegetation patterns as modeled in DYNAFFOREST for objective 4.

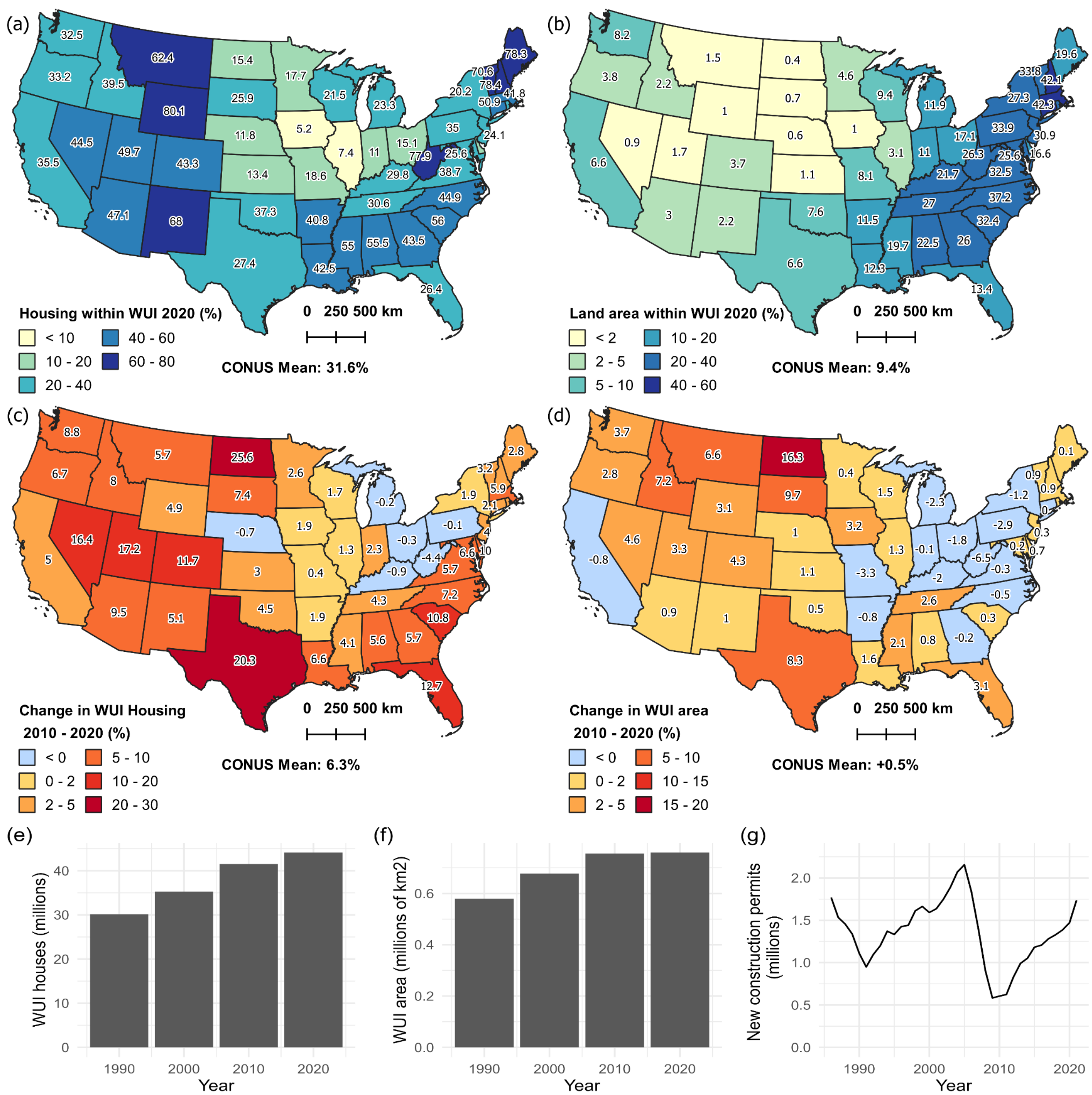

Figure 5. (A) Proportion of houses within the WUI. (B) Proportion of the land area that is WUI. (C and D) Percentage growth of WUI houses (C) and WUI area from 2010 to 2020 (D). (E) Total numbers of WUI houses in 1990, 2000, 2010, and 2020. (F) WUI area in 1990, 2000, 2010, and 2020. (G) Number of new construction permits from 1990 to 2021. In many states, especially in the interior West and the Southeast, more than 40% of all houses are in the WUI. In the East, WUI also covers large proportions of most states. Growth in the number of WUI houses was highest in Texas and South Dakota and overall greater than growth in the amount of WUI area. WUI growth slowed after 2010, as indicated by the smaller increases in both WUI houses and WUI area from 2010 to 2020 than in prior decades. New construction permits peaked before the 2008 recession at about 2 million per year in 2004 to 2006, dropped to about 600,000 per year in 2009 and 2010, and recovered to 1.7 million in 2021. CONUS, conterminous US. From Volker et al. (2023)

Biodiversity: Fire has played a key role in the evolution of biodiversity [173,174], and many western US species are adapted to forest fires [175]. However, larger and more severe fires threaten forest ecosystems and the plant and vertebrate species they contain [174,176]. Yet, species are likely to respond in complex and individual ways, making it difficult to predict the implications for biodiversity. Further, synthetic and open access regional biodiversity assessments for the western US are currently lacking. We have established a detailed and rigorous baseline for bird diversity by assessing the current richness of functional guilds in the western US, using Breeding Bird Survey data to map both the guild richness [177], and distributions of individual bird species, at spatial resolutions suitable for management. We will extend this work by applying models to predict how recent fires have already affected bird richness and distributions. In our models, vegetation cover is a key predictor variable, and we will run experiments in which we rerun predictions assuming that recent wildfires did not change vegetation patterns and assess how much biodiversity differs from the real-world outcomes, allowing us to isolate the impact of wildfires. We have additionally used Global Biodiversity Information Facility (GBIF) [178] occurrence data to assess the current richness of pollinator species across the western US for four families of common pollinators: *Apidae* (bees), *Megachilidae* (bees), *Papilionidae* (butterflies), and *Pieridae* (butterflies). We will reanalyze these data with an included vegetation predictor variable to quantify the relationship between vegetation characteristics at any given site and pollinator richness. We will also extend this work to assess understory plant diversity by leveraging GBIF plant occurrence data. Using the relationships found between (1) bird richness, (2) pollinator richness, and (3) understory plant richness versus vegetation characteristics, climate, fire, and other predictors, we will set up a workflow to use forest-fire model output along with downscaled climate products from objective 4 to determine bird and plant richness.

Increased functional diversity of specific plant traits is correlated with greater post-fire recovery of forest ecosystems [179]. Knowing the locations of these high and low functional diversity areas is crucial for post-fire management planning because areas of high functional diversity could be left to regenerate naturally post-fire, whereas areas of low functional diversity could be targeted for post-fire restoration efforts. We will assess functional diversity of fire-adaptation, regeneration, and hydraulic traits across the western US. We will create a database of these traits connected to tree and shrub species, informed by both existing databases (e.g. TRY Plant Trait database [180], Xylem Functional Traits Database [181]) and the field surveys outlined in objectives 2 and 3. We will use our compiled traits database along with FIA data on approximate species locations [182] to create maps of functional richness for fire-adaptation [137], regeneration, and hydraulic traits [183]. In order to project functional richness into the future under climate and management scenarios, using the forest-fire model outputs from objective 4, we will take the average of our mapped functional richness for each of the 12 PFTs in DYNAFFOREST and calculate functional richness for all individual species in iLand-SVD simulations [183].

Carbon storage: Forests play a key role in the global carbon cycle, providing a net carbon sequestration of nearly 20% of 20th-century anthropogenic emissions [48]. Assessments of current and future carbon storage are desperately needed to inform decision making about whether, where, and how forests might be managed as natural climate solutions. In order to accurately predict changes to future carbon storage, we first established a baseline of current aboveground and belowground live and dead carbon distributions across all forested EPA level III ecoregions in the western US [53], using FIA data [182]. We have also determined trends of live and dead carbon stocks across the western US over the last two decades. Live carbon has declined, causing an increase in dead carbon, across most of the western US (excluding the wet Pacific Northwest, where live carbon increased). We determined how climate, fire, anthropogenic disturbances, and topography have shaped patterns of live and dead carbon storage. The relative importance of drivers varied by ecoregion, but climate and fire were almost always important (Fig. 6). To ensure that we can create accurate future projections of live and dead carbon storage in objective 4, we will benchmark the outputs of our forest models with the observed carbon baseline derived from FIA data.

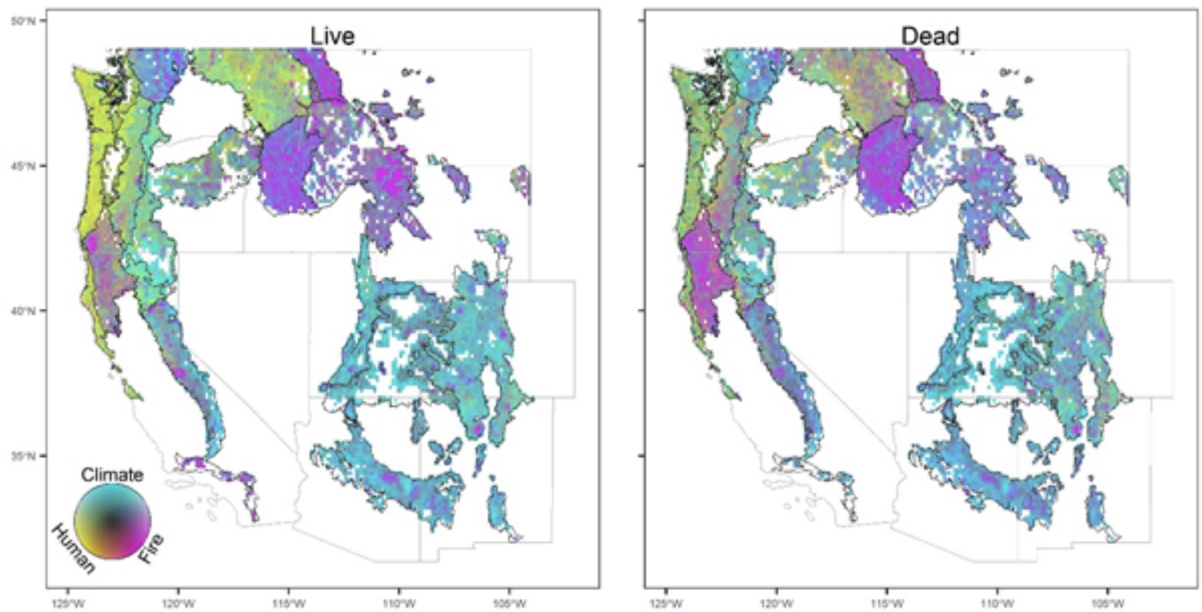

Figure 6. Relative importance of driver categories in predicting western US live and dead forest carbon densities between 2005 and 2019. Grid cells have been resampled from the original 4-km resolution to 12-km to facilitate visualization. Adapted from Hall et al. (In Revision).

Water: Projected increases in forest fires [59] presage large impacts on water supply in the arid western US [184], where streamflow, reservoir levels, and groundwater are already in decline. Fire tends to temporarily increase streamflow, but the effect varies with climate conditions and changes with postfire successional trajectories [185, 186]. To determine how predicted increases in fire will impact water supply, western US-wide analyses of both current and future trends in streamflow are needed. We have already established an observational baseline of annual streamflow response to fire for the period 1984-2019 [5]. We assessed the strength and duration of post-fire streamflow changes relative to forest cover area burned across more than 70 forested basins in the western US and found that, on average, fires that burned 20% or more of a watershed's forested area led to significantly higher streamflows over at least the next 6 years.

To build on this work, we will create an expanded annual database of post-fire streamflow changes for each watershed that has been burned since 1984 with available data. The database will include streamflow metrics relevant to water supply and flood risk as well as an array of geophysical watershed characteristics, initial fire characteristics, and forest conditions not included in the original database. We will gather streamflow data, catchment areas, and static watershed characteristics from USGS hydrological (National Water Information System, 3D Hydrography Program) and geological (Gridded Soil Survey) databases. We will calculate seasonal streamflow extremes (high and low flow quantiles) as well as annual climate indices [187], forest cover [188], and dominant vegetation type. To characterize initial fire characteristics and changes to post-fire forest conditions, we will analyze Landsat satellite images to derive annual and seasonal vegetation indices (e.g. NDVI, EVI, NBR, CBI, LAI) across catchment areas [189,190]. Future iterations of the database will incorporate the functional burn severity atlas developed in objective 3. In anticipation of integrating with forest and fire projections from objective 4, we will use this expanded watershed database to build a predictive model of post-fire streamflow response, with machine learning regression methods, which can take as its input either simulated projections or dynamically updated remote sensing indices. To ensure that we can predict future changes in water supply using simulations, we will predict streamflow at the watershed scale using simulation outputs for the historical record (1984-present) and benchmark model predictions against observations.

Because establishing historical benchmarks is a critical first step, all goals for this sub objective will be met in the next 1-3 years. We will establish a baseline understanding of human smoke exposure further into the past than has ever been produced. We will develop a flexible workflow that allows us to link the forest and fire modeling framework described in objective 4 to air pollution models. We will create, publish, and widely share, maps of historical WUI patterns at fine spatial resolution across the western US, and develop the algorithms for dynamically coupling WUI models with the forest and fire modeling framework in objective 4. We will fine tune models of bird [177] and pollinator [191] biodiversity across the western US to ensure that they closely link with forest and fire simulation products. We will use this framework to build understory plant species models and link them with model outputs from objective 4. We will benchmark current live and dead carbon storage as simulated in objective 4. Finally, we will create a spatial and tabular database of observed post-fire watershed and streamflow dynamics at an annual scale. Using this database, we will derive empirical relationships between post-fire watershed and streamflow dynamics, preparing us to build predictive models of streamflow with simulations. These data will provide essential baselines for addressing key knowledge gaps identified by stakeholders (see objective 1).

3.5.2 Sub-objective 2: How will human smoke exposure, WUI dynamics, biodiversity, provision of water and forest carbon storage change over the next century?

To quantify effects of climate change and increased burning on people, biodiversity, and ecosystem services, we will draw heavily from the forest and fire simulation ensembles produced in objective 4. Specifically, we will select model runs from a subset of the 27 GCMs and 3 SSPs used in objective 4 that bookend the range of climate futures we may experience. We will also select 2-3 of the management scenarios in objective 4 that are representative of currently realistic forest management approaches.

Smoke: We will leverage the workflow established in sub-objective 1, which links our forest-fire modeling framework developed in objective 4 with fire emissions estimates and smoke exposure modeling, to quantify emissions and smoke exposure tradeoffs from projections of future burning and forest management strategies under different climate scenarios. We will generate emissions estimates for the full western US. These fire emissions estimates will be used as an input into the GEOS-Chem atmospheric model to estimate projected wildfire and prescribed fire smoke exposure in several select urban and rural/agricultural centers and across the western US. To leverage the full range of management and climate scenarios evaluated under objective 4, we may implement complimentary source-receptor modeling approaches, which are less computationally expensive and will allow us to assess sensitivities of population exposure levels to changes in fire emissions under each scenario for key locations, including urban centers and highly exposed rural regions (e.g., agricultural regions) where exposure among vulnerable communities is of particular concern.

WUI: Past WUI changes provide excellent information to predict future WUI because housing growth is most likely near areas that recently grew [170]. Another critical driver is demand for more houses, which depends on future human population and household size. Both of these factors are affected by a host of demographic drivers such as migration, population age structure, and reproductive rates. Population predictions based on demographic models are readily available [192]. We will downscale these drivers based on our existing algorithms [170]. Please note that we are not proposing to predict changes in housing patterns in response to future fires because empirical evidence of both rebuilding rates and new development after recent wildfires shows that fires do not result in a reduction in development, at least currently [193,194]. However, dominant vegetation type is important, and we will use projections of future forest cover and dominant tree-species composition from the ensemble produced in objective 4 to map scenarios of future WUI. The integration between future WUI dynamics and the fire-forest modeling in objective 4 will be dynamic, such that our predictions of future housing patterns will inform simulated ignition patterns for the fire model, and forest simulations will serve as an input to WUI predictions. We will quantify wildfire risk in the WUI by calculating the area burned, intensity, and severity of fires that burn with current and forecasted areas of development.

Biodiversity: Leveraging the models built in sub-objective 1 and forest-fire model output from objective 4 at 1 km resolution, we will produce decadal projections of species and guild richness for birds, pollinators, and understory plants for all forested EPA level III ecoregions in the western US and for all forested areas within western US counties and states. We will use these projections of biodiversity to determine spatial patterns of high and low richness under different future climate scenarios and over time. We will additionally project biodiversity responses to forest and fire management scenarios. We will compare projections of species and functional guild richness to the observational baselines produced sub-objective 1 and across climate and management scenarios in order to identify the scenarios with the least impact on biodiversity over coming decades and the scenarios in which biodiversity is most degraded. We will additionally map (DYNAFFOREST) or calculate (iLand-SVD) projected functional richness (as described in sub-objective 1) in response to future climate and management scenarios, so as to determine how and where functional richness is projected to change.

Carbon: We will use simulations from objective 4 to quantify future aboveground and belowground live and dead carbon storage across the western US. We will summarize these carbon storage projections for all forested EPA level III ecoregions. To ensure the relevance of these predictions for land managers and policy makers, we will also summarize projections for forested areas within western US counties and states. We will project live and dead carbon storage responses to simulated forest and fire management scenarios. We will compare projections of live and dead carbon storage to the observational baseline established in sub-objective 1 and across scenarios. This comparison will allow us to identify scenarios in which carbon storage is either enhanced or least degraded during the 21st century, and the scenarios in which carbon storage is most degraded.

Water: We will predict the magnitude, duration, and temporal dynamics of future post-fire streamflow using forest-fire simulations and our stream flow models from sub-objective 1. We will aggregate annual simulated projections to the watershed scale by calculating forest cover, dominant plant functional type (PFT), fire characteristics (i.e., area burned and carbon combusted), and forest carbon stocks. We will also calculate annual and seasonal climate metrics (precipitation, temperature, vapor pressure deficit) from the climate scenarios used to force forest-fire simulations in objective 4. Across climate and management scenarios, we will predict streamflow changes and compare our projections to the historical observational baseline established in sub-objective 1. We will quantify streamflow changes relative to the historical baseline annually from 2025-2100. We will assess these changes at multiple spatial scales: watersheds, counties, states, and forested EPA level III ecoregions. Finally, we will identify the most and least desirable annual streamflow characteristics (total, average, and <10th or >90th percentiles) and rank climate and management scenarios to discern the scenarios that have the largest impacts on streamflow.

Because we must establish baselines first, all of these activities would occur over the next 5-10 years. Specifically, we could establish an in-depth understanding of community-level smoke exposure tradeoffs under different climate and forest management scenarios. As fuel treatment efforts continue to expand, the analysis of smoke exposure tradeoffs can be used by public health practitioners to coordinate smoke preparedness planning and to protect vulnerable populations. We could support a transition towards a future where WUI communities are fire resilient and the vast majority of fires are beneficial because the wildfire problems in the western US are a social-ecological problem. That transition will require changes to both how and where houses are built and our research could provide the scientific information to foster such changes. We would predict bird, pollinator, and plant biodiversity in response to future climate, fire regimes, and management scenarios. Ideally, additional guilds, such as mammals, would be added to our assessment. This work could result in assessments of future biodiversity of western US forests for managers and decision makers. We could produce spatial projections of how climate and management scenarios will interactively affect future live and dead carbon storage across the western US through 2100. These projections would allow us to make recommendations for prioritizing areas where protection will be most effective for maintaining or even enhancing carbon storage [195, 196]. We could produce annual projections of watershed streamflow totals, extremes, and flashiness through 2100 across intensifying fire regimes and management scenarios. Using these projections, we could make recommendations for effective management of streamflow, and therefore water supply.

3.5.3 Sub-objective 3: Where are the current and future areas of robust ecosystem services and areas of degraded services? Where and when do inflection points emerge during the 21st-century in which ecosystem services rapidly degrade or disservices accelerate?

Healthy forests provide numerous ecosystem services people rely on, such as carbon storage, water supply, and biodiversity [197]. However, they can also provision disservices like smoke or poor water quality that negatively impact people. Effectively managing forests to ensure secure and robust provision of ecosystem services requires knowing how ecosystem service quality varies across space and time, including identifying areas where ecosystem services have been particularly degraded [198, 199]. Further, future burning and management efforts to address fire could mediate ecosystem service provision across space and time. With projected increases in fire driven by climate change, forests may reach inflection points at which they shift to fundamentally different ecosystem states, with the potential for concurrent collapse of critical ecosystem services and/or acceleration of disservices [200, 201]. Knowing when these inflection points might occur could help managers and decision-makers prevent ecosystems from reaching them.

We will overlay the distributions of individual ecosystem services (carbon storage, water supply, biodiversity) and disservices (smoke, wildfire risk within the WUI) produced in sub-objective 1, to determine areas of robust ecosystem service provision, and areas of degraded services or disservices. We will produce this spatial overlay of services and disservices for both the current and projected future period. Using the projections of future individual ecosystem services and disservices, we will quantify the relationship between (1) number of fires, (2) fire size, and (3) fire severity and areas of ecosystem services and disservices to determine how the suite of forest carbon storage, water supply, biodiversity metrics (i.e., species or functional richness), smoke, and fire risk within the WUI jointly vary with projected changes to fire in the western US and across management scenarios.

Potential exists for non-linear changes over time in individual ecosystem services or disservices, creating an inflection point at which services collapse and/or disservices accelerate[200, 201]. We will identify these inflection points through the 21st century. We will also quantify relationships between inflection points and future fire regime characteristics. We will compare the relationship between fire and inflection points in ecosystem services and disservices across climate change and management scenarios, with the goal of (1) synthetically quantifying how changing fire regimes drive nonlinear changes in ecosystem-service provision and (2) identifying whether some climate change or management scenarios prevent ecosystem service collapse.

Activities in sub-objective 3 would require completing sub-objective 1 and 2, and thus, this work would begin later in the project. Over 5-10 years, we would produce analyses of (1) the spatial distribution of current and future ecosystem services and disservices, including the impact of climate and management scenarios, (2) the impact of changing fire regimes on future ecosystem services and disservices, (3) inflection points at which future ecosystem services crash or ecosystem disservices accelerate, and (4) the relationship between number, size, and severity of future fire and ecosystem service and disservice inflection points. These analyses will form the basis of concrete recommendations to decision-makers, including spatial tools, if requested by stakeholders.

3.5.4 Sub-objective 4: What are the synergies and trade-offs among ecosystem services and disservices now and in the future? What are the direct and indirect drivers of these synergies and trade-offs?

Ecosystem services and disservices are almost never provisioned independently from one another, and often, synergies and tradeoffs exist within baskets of ecosystem services. In other words, ecosystems that provision one service robustly may not provision another ecosystem service (tradeoff) or ecosystems that robustly provision a service may also provision another (synergies). Because stakeholders often have differing needs from ecosystems, and thus, different goals for the management of ecosystems [202, 203], understanding synergies and tradeoffs among multiple ecosystem services and disservices is essential [204].

Using the stacked ecosystem services and disservices map produced for sub-objective 3, we will quantify synergies and trade-offs among ecosystem services and disservices in the empirical, historical record as a baseline. To determine synergies among ecosystem services, we will quantify spatial correlations among sets of ecosystem services and disservices (e.g. linear correlations of areas with higher landscape live carbon storage and higher biodiversity or non-linear correlations of areas with higher landscape live carbon storage and streamflow [205]). Similarly, we will determine ecosystem service trade-offs by quantifying linear and non-linear correlations among robust services and degraded services (e.g., areas of WUI are likely areas with lower landscape live carbon storage).

We will then apply the synergies and trade-offs framework to the future projections of individual ecosystem services produced in sub-objective 2. We will also identify if any ecosystem services change from synergistic to trade-off type relationships during the 21st century with various management scenarios. We will determine which climate change and future management scenarios maximize synergies among ecosystem services [204]. We will expand the spatial optimization framework developed in objective 4 to a multi-objective analysis that identifies the spatial and temporal implementation of management scenarios that maximally reduces catastrophic fire and maintains/enhances critical suites of ecosystem services (smoke reduction, reducing wildfire risk to WUI houses, and carbon storage, water supply, and biodiversity maximization) [158]. We will determine underpinning drivers of synergies and trade-offs [206, 207], using the climate, topographic, and burn history factors identified as drivers of individual ecosystem services or disservices in sub-objective 1.

Activities in sub-objective 4 require completing sub-objectives 1, 2, and 3, and thus, this work would begin later in the project. Over 5-10 years we could produce analyses of synergies and trade-offs among current and future ecosystem services and disservices. Comparisons between current and future synergies and trade-offs could help decision-makers form sustainable expectations for ecosystem services and disservices with increased fire, (e.g., more long-term smoke exposure with more frequent low-intensity fires or across-the-board reductions in ecosystem services). We will also produce analyses of (1) direct and indirect drivers of current and future ecosystem services and disservices and (2) spatial optimization of multiple ecosystem services through implementation of management strategies on the landscape. Like in sub-objective 2, these analyses could form the basis of concrete recommendations to decision-makers, including spatial tools, if requested.

4. Structure of the Collaborative

4.1 Science structure

WFFRC is organized to foster horizontal culture and hierarchical structure such that it engenders a collaborative, engaged, and creative community, while maintaining mechanisms for decision making, conflict mediation, and effective governance.

WFFRC is internally organized across multiple levels. It is composed of ~10 science teams, each led by a PI at an academic or non-profit institution. The lead science team is based at Cary Institute of

Ecosystem Studies. The PI of each team is responsible for leading their team and ensuring their deliverables, as specified in each team's statement of work (SOWs) are produced on time. Teams participate in one or more science working groups organized around collaborative themes (Fig. 7). Each working group is led by a project co-PI or senior personnel, and participants include other co-PIs, senior personnel, postdocs, and students. Working group leads serve two-year terms and can serve multiple terms. WG leads are appointed by the executive committee. The executive committee oversees all WFFRC governance. It is led by the Director and includes the Deputy Director of Policy and Management and four WFFRC co-PIs. Each executive committee member serves a 2- or 3-year term. Members can serve multiple terms. The executive committee appoints new members. The external advisory committee advises the executive committee.

4.2 Science culture

WFFRC will only succeed with fostering a robust collaborative culture. This will be accomplished in a variety of ways. First, WFFRC will prioritize leadership opportunities (authorship, proposals, etc.) for early career members. Ideas of all, particularly students and postdocs, will be heard and encouraged. Interactions, idea sharing, and collaboration among WFFRC teams will be fostered through both formal

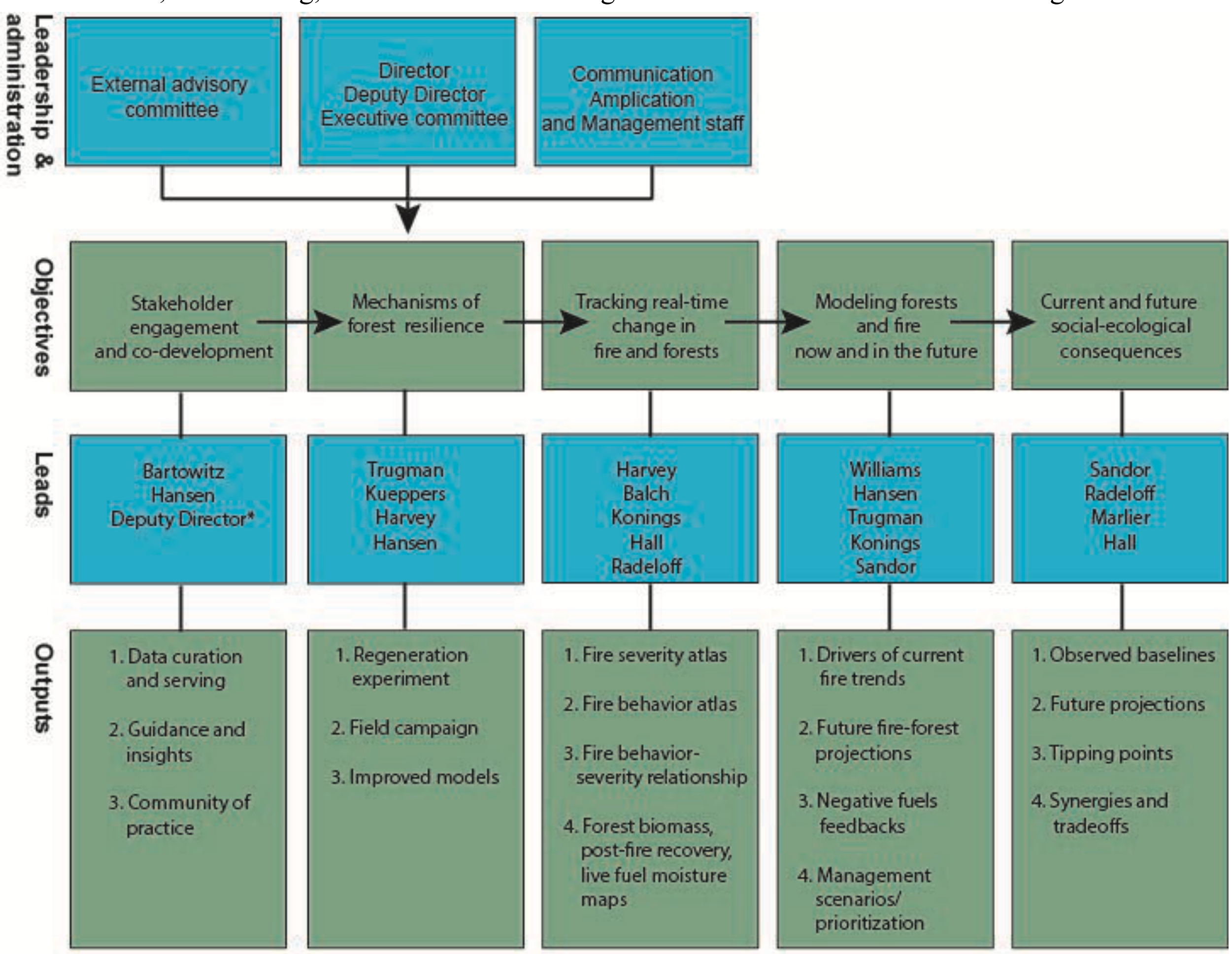

Figure 7. Organization of WFFRC. Blue fill represents personnel in leadership, administration and science roles. Green represents objectives and outputs. Note that the Deputy Director will lead stakeholder engagement and co-development when hired.

and informal avenues. WG leads will be expected to hold monthly zoom meetings. These meetings are meant to foster collaboration among teams toward specific integrative milestones. Additionally, the Communications, Amplification and Management (CAM) staff will coordinate monthly all-scientist plenary zoom meetings. These meetings are meant to encourage interaction and engagement across working groups. The executive committee will meet quarterly to discuss governance issues. Three of these meetings will be online and one will be in person the day before the American Geophysical Union Fall Meeting. Once per year, the external advisory committee will join the executive committee. Finally, the CAM staff will organize an annual two-day in-person WFFRC science meeting. The location of the meeting will rotate to reduce travel and cost burden. Meetings will include opportunities for early-career scientists to share their work and to network with others. Finally, we will establish and maintain a WFFRC slack that includes channels for each working group.

4.3 Communications, Amplification and Management (CAM) staff structure and roles

Director – the Director will provide scientific leadership and coordinate the shared vision of WFFRC. The Director's responsibilities include:

- Ensuring the work conducted by each research team contributes to synthetic scientific advancement that can support management and policy.
- Communicating WFFRC's progress and findings to a wide variety of scientific, governmental, and public audiences.
- Be the front-line fundraiser for WFFRC with governmental, foundation and private donors.
- Lead WFFRC science meetings and related activities and ensure meetings are targeted, efficient, and productive.
- Oversee the CAM staff in coordination and amplification activities to ensure strong communication between and among the science teams and CAM group and to ensure the science teams are sufficiently supported and accessible to management and policy communities.

Deputy Director of Policy and Management – The Deputy Director of Policy and Management will report to the Director and is responsible for advancing the research into tangible solutions. They will be the key point of contact with policy makers, managers, and communities. They will ensure that WFFRC science is responsive to practitioner needs and that the science is available in real time to be incorporated into decision making. This will include building a network of stakeholders and nurturing the network throughout the project. The Deputy Director will organize annual idea exchanges with scientists and stakeholders, interface with the science teams to ensure their science is actionable, produce briefs of scientific results targeted at management and policy communities, coordinate responses to policy and manager requests for scientific information about fire, organize webinars, and partner with boundary spanning organizations, such as the Joint Fire Science Program's Fire Exchange Network and the Climate and Wildfire Institute.

Program Manager – The Program Manager's responsibility will be the day-to-day management of WFFRC including internal coordination, reporting, budgeting, meeting planning and external communication. In coordination with the Director and Deputy Director, the Program Manager will ensure science teams are well supported and have the resources needed to meet their respective goals.

5. Data Management Plan (DMP)

This project has many collaborative teams with science objectives that will only be accomplished by dense and continuous data coordination and sharing. Further, a fundamental goal of the project is to produce science insights and products that support decision making. This requires that data streams are accessible to a wide range of audiences. Thus, high-quality data management is of the utmost importance for ensuring project success. All WFFRC data will be: (a) archived in a Findable, Accessible, Interoperable, and Re-Usable (FAIR) data repository with metadata; (b) shared among WFFRC investigators during active research; and (c) promptly made available to decision makers and other researchers. Below, we lay out the roles and responsibilities of data management personnel, the standards and expectations for data management across all WFFRC investigators, and the training plans and procedures for ensuring standards are met.

5.1 Personnel roles and responsibilities

Key roles are as follows:

Environmental Data Science Innovation and Inclusion Lab (ESIIL) science team-The ESIIL science team will provide intellectual leadership, training, and advice to WFFRC teams on data management. This will ensure all investigators are provided the necessary resources to meet open science best practices. The team will interface annually with the WFFRC executive committee to review the DMP and compliance. The DMP will be revised as needed based on these assessments.

WFFRC Program Manager- The WFFRC Program Manager will be responsible for oversight and management of the cloud storage space for active dataset sharing and for long-term archiving of WFFRC datasets at the Cary Institute of Ecosystem Studies Institutional data repository run by Figshare. The Program Manager will report to the WFFRC executive committee annually on compliance.

Team data lead- Each science team will identify a data lead (a postdoc, if possible, to provide leadership training opportunities), who are responsible for ensuring that data management best practices are followed within their group, including organization and sharing of active datasets and long-time archiving of data once published. They will coordinate with the WFFRC Program Manager.

Executive committee- The executive committee will be responsible for ensuring that data management activities robustly support the scientific objectives and decision support goals of WFFRC. The committee will oversee the Program Manager in their data management responsibilities, and will coordinate with the ESIIL science team to determine whether the DMP requires revision to meet open science best practices. Finally, the executive committee is ultimately responsible for ensuring compliance as described below in the compliance section.

5.2 Code documentation and version control

Science teams in WFFRC will be expected to thoroughly annotate all analytical code used to develop products and scientific insights. The expectation is that any WFFRC investigator could take another team's code and replicate analytical pipelines from raw data to the final product. WFFRC will encourage all teams to use a notebook format for code (e.g., R notebook or Jupiter notebook) to encourage thorough annotation and documentation. All science teams will also be expected to use cloud-based version control in a centralized WFFRC GitHub repository to ensure all workflows are documented and available for subsequent research. For field-based data, teams will be expected to use consistent and standard variable names defined by WFFRC. All field researchers will maintain Open Science Network field/lab notebooks updated regularly with descriptions of field activities, data collection, and challenges encountered.

5.3 Data types and standards

Due to the diverse nature of data that will be collected and used by WFFRC teams and the need for extensive data sharing across teams, it is essential that all investigators adhere to consistent data format standards. WFFRC teams will store all spatial data as netCDF files, all field tabular data will be stored as

CSVs, and non-spatial simulation output will be stored in SQLITE databases. NetCDF files must include thorough embedded meta data including projection, date range, spatial resolution, short variable names, units, and long variable descriptions. The WFFRC standard geographic projection will be NAD 1983 USGS Contiguous USA Albers (ESRI: 102039). When possible, netCDFs should be compressed to level 5 or greater. CSV tabular field data must be formatted in long orientation, include column headers, and must include a first page with variable names, units, and descriptions. SQLITE databases should include variable names, units, and descriptions.

5.4 In-progress data storage, back up, and sharing

When data products are in development or as analyses are conducted, WFFRC teams must produce workflows such that master data sets remain un-manipulated. Data sets in active use must be stored in multiple locations including one offsite cloud-based storage solution (e.g., google drive, network accessed storage server, etc.). WFFRC scientists are encouraged to make use of backup solutions that snapshot work environments on weekly or more frequent intervals. Active datasets and products should be available to other WFFRC teams and shared promptly and in an organized well-documented manner. WFFRC scientists are required to maintain a pre-staged data storage and delivery environment in a WFFRC cloud storage environment, likely Cyverse. Team data leads will be responsible for their team's data, and they will coordinate with the program manager to ensure that they are meeting expectations.

5.5 Long-term data archiving, intellectual property and data licensing

WFFRC teams are encouraged to archive data sets upon submission of preprints and/or peer-reviewed papers. Archiving of all data is required at the time of publication or three years after data collection. Data referenced in publications will be appropriately cited via digital object identifiers. All WFFRC data must be archived at Cary Institute of Ecosystem Studies online repository. Ecological metadata language (EML) will be the standard for metadata documentation. EML documentation is required for all products including netCDFs that include embedded metadata. The WFFRC program manager will review all archive submissions to ensure standards are met. Investigators must plan accordingly to ensure ample time for review. Investigators will be required to explicitly license data products with an appropriate Creative Commons license such as CC-0 or CC-BY that define policies for data re-use, re-distribution, and attribution. Licensing will be included in metadata.

5.6 Training

Data management training specific to the WFFRC DMP and general open-science best practices will be offered at least annually either online or in a hybrid format including at the WFFRC annual science meeting. Training will be led by the ESIIL science team and other WFFRC investigators as appropriate. Training will be available to all WFFRC students, postdocs, and interested PIs. Students and postdocs will be required to attend at least one training. Training will focus on conveying open-science best practices, specifically designed around WFFRC data management policies and procedures.

5.7 Procedures to ensure compliance

If WFFRC teams do not comply with data management policies, the executive committee will work with the team PI to improve data management practices. If teams continue to not comply, the executive committee may choose to withhold the next funding increment until the team is in compliance. Teams may also be permanently removed from WFFRC if they continue to not follow data-management policies.

6. Intellectual Credit and Authorship Guidelines

By accepting funds, all project personnel agree to the following guidelines for assigning intellectual credit and authorship. Guidelines are meant to ensure all participants' contributions are appropriately acknowledged and to address previous inequities in opportunities for success. The foundation of our philosophy is to elevate junior colleagues including graduate students, postdoctoral associates, and early-career faculty. This is important given that success and recognition at early career stages is essential for career progression, and one of our long-term goals is to train and place the next generation of fire and forest ecologists into positions where they will be able to support effective decision making for decades to come. We will use the CRediT (Contributor Role Taxonomy) framework as a guide for assigning credit for WFFRC products. [208] The framework defines 14 ways in which personnel can contribute to a project, ranging from conceptualization to funding acquisition. We will assign authorship to those who contribute to two or more of the following categories; conceptualization, methodology development, software/coding, validation of results, formal analysis of data, writing (original or revision of manuscripts), data visualization, and funding acquisition. In addition, we will set the following expectations for authorship:

1. Early-career scientists will be prioritized as first authors to ensure opportunities for success during a critical stage of career development.
2. We will err on the side of inclusivity with deciding authorship, but we will avoid ghost authorship where people are added honorarily or to boost the impact of papers.

We will mediate any potential conflicts with intellectual credit and authorship in the following manner. Incidents will be submitted to the Program Manager, who will set up a meeting of the executive committee. The executive committee will discuss the issue and facilitate a resolution that is agreeable to all parties involved. If an agreement is not reached or if an incident includes members of the executive committee, we will engage the external advisory committee as outside mediators.

7. Collaborator Agreement

The success of WFFRC will depend on all of us being generous, engaged, and responsive collaborators. We have agreed that one of the biggest opportunities for scientific breakthroughs will be at the edges of our respective disciplines. Such trans-disciplinary work will require fostering an environment in which collaborative team-based science can thrive. To ensure we build such a community, all team members are asked to agree to the following set of guidelines focused on internal collaboration, publication and presentations, stakeholder engagement, and open-science best practices.

Internal collaboration:

1. Co-PIs must track their budgets closely and spend out allocations before the end of the period of performance. No-cost extensions will not be granted (use it or lose it).
2. Promptly respond to requests for information for a) annual reporting efforts led by the CAM staff at Cary, and b) proposals to secure the next round of funding from Moore Foundation or other sources of funding Cary/CAM staff pursue to meet co-funding expectations.
3. Promptly reply to requests for availability (online polls) to schedule meetings.
4. Try to attend all monthly plenary meetings and monthly meetings for your working group(s). We endeavor to keep the regular meeting load low. But continued conversation is the driver of collaboration and innovation, recognizing that conflicts arise.
5. Each co-PI must budget from their award to attend the annual WFFRC science meeting and is requested to try to bring at least one postdoc or student. We will rotate the locations of annual meetings (e.g., LA, SF, Boulder, Seattle, Cary) to reduce travel burden and costs. CAM staff will organize meetings to reduce hosting burden.

6. Try to be responsive to requests and engagement from other WFFRC teams. Concretely, the breakthroughs we all think are possible will likely emerge from sharing insights, data, and products across groups. This will require being prompt and willing to answer questions.

7. Co-PIs and senior personnel should consider serving on the Executive Committee and/or as working group leads at some point during the project.

Publication and presentations:

8. Please note and follow authorship guidelines for what constitutes sufficient contribution to be included on WFFRC papers and products.

9. In accordance with Moore Foundation policies, all papers must be published open access. Please budget accordingly in your award.

10. In manuscripts, acknowledge funding from the Gordon and Betty Moore Foundation and WFFRC with the following text. "We acknowledge funding from the Gordon and Betty Moore Foundation under grant # 11974. This paper is a contribution of the Western Fire and Forest Resilience Collaborative." As funding sources evolve, this text may change for everyone or particular teams, please proactively ask Winslow and/or the CAM staff at Cary what the most updated language should be.

11. In talks, when appropriate, acknowledge funding from the Gordon and Betty Moore Foundation and include the Western Fire and Forest Resilience Collaborative branding/logo.

Stakeholder engagement:

12. Contribute to stakeholder engagement efforts when asked. This may include working with CAM staff at Cary to produce a short summary of your research, attending stakeholder listening sessions, presenting in a webinar, etc. Again, we will endeavor to keep the burden low.

13. Consider leading stakeholder engagement efforts and promoting WFFRC. This could include writing op-eds, hosting field trips, etc.

14. Submit pdfs of all accepted papers supported with WFFRC funding to the project database using the online form we will setup so they can be made available for stakeholders. This will include submitting a short plain language summary (~ 1 paragraph) to accompany the paper.

Open science best practices

15. Submit all datasets to the project data repository upon publication of papers.

16. Adhere to good data hygiene in your lab including robust systems for code documentation and version control, robust, cloud-based data backup, and writing proper meta-data using the Ecological Metadata Language (EML). See data management plan.

17. Encourage your lab to participate in data-science training opportunities provided through ESIIL and other data-science training organizations.

8. Postdoctoral Mentoring Plan (PMP)

Most Ph.D. graduates in biological and environmental sciences are employed outside academia. Thus, a central focus to our postdoctoral mentorship plan is to provide postdoctoral research associates (PDs) with opportunities to engage formally and informally with nonacademic partners. Given the transdisciplinary nature of the research required, and the strong emphasis on knowledge co-production, WFFRC is well poised to provide robust experiences that launch PD careers in a wide range of professional settings. From the very beginning, PDs will be engaged as collaborators and peers by the entire Collaborative, actively participating in monthly all investigator meetings, stakeholder engagement sessions, and data management training. PIs will be encouraged to budget for professional development opportunities, ranging from courses focused on reducing barriers for people from historically excluded groups (e.g., National Center for Faculty Development and Diversity) to courses on software engineering, statistics, and Earth-system modeling. All PIs will be asked to follow best-practices as outlined by the National Postdoctoral Association and the National Academy of Science. The ultimate goal is to train the next cohort of leaders in the research and science-based management of forests and fire regimes.

Defining the role of PDs in projects: WFFRC PDs will contribute to all aspects of research including developing methods, collecting, analyzing, and modeling data, writing manuscripts and grant proposals, and mentoring students. PDs will serve as glue that helps bind teams together. They will be encouraged to pursue integrative projects that require incorporating data from across WFFRC's teams. Supported by their PIs and WFFRC program manager, PDs will serve as data team leads, responsible for ensuring that data management best practices are followed, including organization and sharing of active datasets and long-time archiving of data once published. They will be encouraged to engage in outreach activities and to present at professional conferences and workshops.

Career Development Plan: All WFFRC PDs will be expected to follow a 7-step career development plan: 1) Individual Development Plan (IDP): Each PD will develop an IDP and set SMART goals (Specific, Measurable, Achievable, Relevant, and Time-bound) with their PI. An IDP template will be provided to each team. Monthly all investigator meetings will help ensure PDs are meeting their research and professional development goals. 2) Career counseling: PIs will mentor PDs in developing hard and soft skills needed to be successful in a variety of career paths, help craft competitive application materials, and prepare for interviews. 3) Establish Group PD Policies: PIs and PDs will develop a collaborative policy that clearly outlines PD responsibilities (project and data management; leadership on publications and proposals; teaching and mentoring activities; participation in conferences and workshops).4) Publications: PDs will have priority as first authors on project papers and co-authorship assigned using the CRediT framework (see authorship guidelines). 5) Organizing sessions and presenting at conferences: PIs will be expected to mentor PDs in organizing special sessions and presenting at academic conferences and at the annual WFFRC meeting. 6) Grant proposal writing: PIs will mentor PDs in proposal writing by providing constructive feedback on research plans, questions/hypotheses, and communication of preliminary results.7) Guidance in teaching, mentoring: PDs will directly mentor student researchers, organize and lead the graduate seminar series and participate in science communication workshops.

REFERENCES

1. Juang, C. S. *et al.* Rapid growth of large forest fires drives the exponential response of annual forest-fire area to aridity in the western United States. *Geophysical Research Letters* **49**, e2021GL097131 (2022).
2. Parks, S. A. & Abatzoglou, J. T. Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophysical Research Letters* **47**, e2020GL089858 (2020).
3. Abatzoglou, J. T. & Williams, A. P. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* **113**, 11770–11775 (2016).
4. Westerling, A. L. Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, 20150178 (2016).
5. Williams, A. P. *et al.* Growing impact of wildfire on western US water supply. *Proceedings of the National Academy of Sciences* **119**, e2114069119 (2022).
6. Higuera, P. E. & Abatzoglou, J. T. Record-setting climate enabled the extraordinary 2020 fire season in the western United States. *Global Change Biology* **27**, 1–2 (2020).
7. Reilly, M. J. *et al.* Cascadia burning: The historic, but not historically unprecedented, 2020 wildfires in the Pacific Northwest, USA. *Ecosphere* **13**, e4070 (2022).
8. Williams, A. P. *et al.* Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future* **7**, 892–910 (2019).
9. Turco, M. *et al.* Anthropogenic climate change impacts exacerbate summer forest fires in California. *Proceedings of the National Academy of Sciences* **120**, e2213815120 (2023).
10. Zhang, F. *et al.* Five decades of observed daily precipitation reveal longer and more variable drought events across much of the western United States. *Geophysical Research Letters* **48**, e2020GL092293 (2021).
11. Overpeck, J. T. & Udall, B. Climate change and the aridification of North America. *Proceedings of the National Academy of Sciences* **117**, 11856–11858 (2020).
12. Overpeck, J. & Udall, B. Dry times ahead. *Science* **328**, 1642–1643 (2010).
13. Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M. & Stahle, D. W. Long-term aridity changes in the western United States. *Science* **306**, 1015–1018 (2004).
14. Seager, R. & Vecchi, G. A. Greenhouse warming and the 21st century hydroclimate of southwestern North America. *Proceedings of the National Academy of Sciences* **107**, 21277–21282 (2010).
15. Williams, A. P. *et al.* Large contribution from anthropogenic warming to an emerging North American megadrought. *Science* **368**, 314–318 (2020).
16. Williams, A. P., Cook, B. I. & Smerdon, J. E. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change* 1–3 (2022) doi:10.1038/s41558-022-01290-z.
17. Steel, Z. L., Safford, H. D. & Viers, J. H. The fire frequency-severity relationship and the legacy of fire suppression in California forests. *Ecosphere* **6**, art8 (2015).
18. Parks, S. A. *et al.* Contemporary wildfires are more severe compared to the historical reference period in western US dry conifer forests. *Forest Ecology and Management* **544**, 121232 (2023).
19. Stephens, S. L. *et al.* Forest restoration and fuels reduction work: Different pathways for achieving success in the Sierra Nevada. *Ecological Applications,* e2932 (2024).
20. Roos, C. I. *et al.* Indigenous fire management and cross-scale fire-climate relationships in the Southwest United States from 1500 to 1900 CE. *Science Advances* **8**, eabq3221 (2022).
21. Knight, C. A. *et al.* Land management explains major trends in forest structure and composition over the last millennium in California's Klamath Mountains. *Proceedings of the National Academy of Sciences* **119**, e2116264119 (2022).
22. Hagmann, R. K. *et al.* Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications* **31**, e02431 (2021).

23. Shuman, J. K. *et al.* Reimagine fire science for the Anthropocene. *PNAS Nexus* **1**, pgac115 (2022).
24. Higuera, P. E., Shuman, B. N. & Wolf, K. D. Rocky Mountain subalpine forests now burning more than any time in recent millennia. *Proceedings of the National Academy of Sciences* **118**, (2021).
25. Seidl, R. & Turner, M. G. Post-disturbance reorganization of forest ecosystems in a changing world. *Proceedings of the National Academy of Sciences* **119**, e2202190119 (2022).
26. Davis, K. T. *et al.* Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences* **116**, 6193–6198 (2019).
27. Davis, K. T. *et al.* Reduced fire severity offers near-term buffer to climate-driven declines in conifer resilience across the western United States. *Proceedings of the National Academy of Sciences* **120**, e2208120120 (2023).
28. Coop, J. D. *et al.* Wildfire-driven forest conversion in western North American landscapes. *BioScience* **70**, 659–673 (2020).
29. Ratajczak, Z. *et al.* Abrupt change in ecological systems: Inference and diagnosis. *Trends in Ecology and Evolution* **33**, 513–526 (2018).
30. He, T., Belcher, C. M., Lamont, B. B. & Lim, S. L. A 350-million-year legacy of fire adaptation among conifers. *Journal of Ecology* **104**, 352–363 (2016).
31. Falcon-Lang, H. J., Mages, V. & Collinson, M. The oldest Pinus and its preservation by fire. *Geology* **44**, 303–306 (2016).
32. Stevens, J. T., Kling, M. M., Schwilk, D. W., Varner, J. M. & Kane, J. M. Biogeography of fire regimes in western U.S. conifer forests: A trait-based approach. *Global Ecology and Biogeography* **29**, 944–955 (2020).
33. Johnstone, J. F. *et al.* Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment* **14**, 369–378 (2016).
34. Liang, S. & Hurteau, M. D. Novel climate–fire–vegetation interactions and their influence on forest ecosystems in the western USA. *Functional Ecology* **37**, 2126–2142 (2023).
35. Hansen, W. D. & Turner, M. G. Origins of abrupt change? Postfire subalpine conifer regeneration declines nonlinearly with warming and drying. *Ecological Monographs* **89**, e01340 (2019).
36. Kashian, D. M., Turner, M. G., Romme, W. H. & Lorimer, C. G. Variability and convergence in stand structural development on a fire-dominated subalpine landscape. *Ecology* **86**, 643–654 (2005).
37. Turner, M. G., Romme, W. H., Gardner, R. H. & Hargrove, W. W. Effects of fire size and pattern on early succession in Yellowstone National Park. *Ecological Monographs* **67**, 411–433 (1997).
38. Turner, M. G., Whitby, T. G., Tinker, D. B. & Romme, W. H. Twenty-four years after the Yellowstone Fires: Are postfire lodgepole pine stands converging in structure and function? *Ecology* **97**, 1260–1273 (2016).
39. Hill, A. P., Nolan, C. J., Hemes, K. S., Cambron, T. W. & Field, C. B. Low-elevation conifers in California's Sierra Nevada are out of equilibrium with climate. *PNAS Nexus* **2**, pgad004 (2023).
40. Shive, K. L. *et al.* Ancient trees and modern wildfires: Declining resilience to wildfire in the highly fire-adapted giant sequoia. *Forest Ecology and Management* **511**, 120110 (2022).
41. Soderberg, D. N. *et al.* Assessing giant sequoia mortality and regeneration following high-severity wildfire. *Ecosphere* **15**, e4789 (2024).
42. Radeloff, V. C. *et al.* Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences* 201718850–201718850 (2018) doi:10.1073/pnas.1718850115.
43. Radeloff, V. C. *et al.* Rising wildfire risk to houses in the United States, especially in grasslands and shrublands. *Science* **382**, 702–707 (2023).
44. Syphard, A. D. *et al.* Human influence on California fire regimes. *Ecological Applications* **17**, 1388–1402 (2007).
45. Syphard, A. D., Radeloff, V. C., Hawbaker, T. J. & Stewart, S. I. Conservation threats due to human-caused increases in fire frequency in Mediterranean-climate ecosystems. *Conservation Biology* **23**, 758–769 (2009).

46. Federal Firefighting Costs (Suppression Only). *National Interagency Fire Center* https://www.nifc.gov/fire-information/statistics/suppression-costs.
47. Blood, M. R. California insurance market rattled by withdrawal of major companies. *AP News* (2023).
48. Harris, N. L. *et al.* Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change* **11**, 234–240 (2021).
49. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2021).
50. Case, M. J., Johnson, B. G., Bartowitz, K. J. & Hudiburg, T. W. Forests of the future: Climate change impacts and implications for carbon storage in the Pacific Northwest, USA. *Forest Ecology and Management* **482**, 118886 (2021).
51. Hudiburg, T. *et al.* Carbon dynamics of Oregon and Northern California forests and potential land-based carbon storage. *Ecological Applications* **19**, 163–180 (2009).
52. Stanke, H., Finley, A. O., Domke, G. M., Weed, A. S. & MacFarlane, D. W. Over half of western United States' most abundant tree species in decline. *Nature Communications* **12**, 451 (2021).
53. Hall, J. *et al.* Forest carbon storage in the Western United States: distribution, drivers, and trends. *Earth's Future* (In Review).
54. Raoelison, O. D. *et al.* Wildfire impacts on surface water quality parameters: Cause of data variability and reporting needs. *Environmental Pollution* **317**, 120713 (2023).
55. Flavelle, C. & Healy, J. Arizona Limits Construction Around Phoenix as Its Water Supply Dwindles. *New York Times* (2023).
56. Aguilera, R., Corringham, T., Gershunov, A. & Benmarhnia, T. Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. *Nature Communications* **12**, 1493 (2021).
57. Gould, C. F. *et al.* Health effects of wildfire smoke exposure. *Annu. Rev. Med.* **75**, annurev-med-052422-020909 (2024).
58. Cook, B. I. *et al.* Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Future* **8**, e2019EF001461 (2020).
59. Abatzoglou, J. T. *et al.* Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth Environment* **2**, 1–8 (2021).
60. Prichard, S. J. *et al.* Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications* **31**, e02433 (2021).
61. Schuurman, G. W. *et al. Resist-Accept-Direct (RAD)-A Framework for the 21st-Century Natural Resource Manager*. *Natural Resource Report* https://pubs.usgs.gov/publication/70217053 (2020) doi:10.36967/nrr-2283597.
62. On Fire: The Report of the Wildland Fire Mitigation and Management Commission, September 2023.
63. Confronting the Wildfire Crisis. https://www.fs.usda.gov/managing-land/wildfire-crisis.
64. NASA FireSense. https://cce.nasa.gov/firesense/index.html.
65. NSF Expands Wildland Fire Research Teams and Capabilities Through FIRE-PLAN Awards. https://www.nsf.gov/news/news_summ.jsp?cntn_id=308222&org=ENG.
66. Heal, A. Alaska firefighters experiment with targeting blazes to save carbon. *Washington Post* (2023).
67. NOAA and Wildfire. https://www.noaa.gov/noaa-wildfire.
68. Forest Health Research Program. https://www.fire.ca.gov/Home/What-We-Do/Grants/Forest-health-research-program.
69. Chapin III, F. S. *et al.* Increasing wildfire in Alaska's boreal forest: pathways to potential solutions of a wicked problem. *BioScience* **58**, 531–540 (2008).

70. Prichard, S. J. *et al.* Next-generation biomass mapping for regional emissions and carbon inventories: Incorporating uncertainty in wildland fuel characterization. *Journal of Geophysical Research: Biogeosciences* **124**, 3699–3716 (2019).
71. Rao, K., Williams, A. P., Flefil, J. F. & Konings, A. G. SAR-enhanced mapping of live fuel moisture content. *Remote Sensing of Environment* **245**, 111797 (2020).
72. Hansen, W. D. *et al.* Global forests are influenced by legacies of past inter-annual temperature variability. *Environmental Research: Ecology* **1**, 011001 (2022).
73. Heilmayr, R., Dudney, J. & Moore, F. C. Drought sensitivity in mesic forests heightens their vulnerability to climate change. *Science* **382**, 1171–1177 (2023).
74. Jump, A. S. *et al.* Structural overshoot of tree growth with climate variability and the global spectrum of drought-induced forest dieback. *Global Change Biology* **23**, 3742–3757 (2017).
75. Harvey, B. J., Andrus, R. A. & Anderson, S. C. Incorporating biophysical gradients and uncertainty into burn severity maps in a temperate fire-prone forested region. *Ecosphere* **10**, e02600 (2019).
76. Saberi, S. J., Agne, M. C. & Harvey, B. J. Do you CBI what I see? The relationship between the Composite Burn Index and quantitative field measures of burn severity varies across gradients of forest structure. *International Journal of Wildland Fire* **31**, 112–123 (2022).
77. Donato, D. C., Harvey, B. J. & Turner, M. G. Regeneration of montane forests 24 years after the 1988 Yellowstone fires: A fire-catalyzed shift in lower treelines? *Ecosphere* **7**, (2016).
78. Harvey, B. J., Donato, D. C. & Turner, M. G. High and dry: post-fire tree seedling establishment in subalpine forests decreases with post-fire drought and large stand-replacing burn patches. *Global Ecology and Biogeography* **25**, 655–669 (2016).
79. Stevens-Rumann, C. S. *et al.* Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters* (2017) doi:10.1111/ele.12889.
80. Kemp, K. B., Higuera, P. E. & Morgan, P. Fire legacies impact conifer regeneration across environmental gradients in the U.S. northern Rockies. *Landscape Ecology* **31**, 619–636 (2016).
81. Stevens-Rumann, C., Morgan, P. & Hoffman, C. Bark beetles and wildfires: How does forest recovery change with repeated disturbances in mixed conifer forests? *Ecosphere* **6**, art100 (2015).
82. Seidl, R., Rammer, W., Scheller, R. M. & Spies, T. A. An individual-based process model to simulate landscape-scale forest ecosystem dynamics. *Ecological Modelling* **231**, 87–100 (2012).
83. Hansen, W. D., Abendroth, D., Rammer, W., Seidl, R. & Turner, M. Can wildland fire management alter 21st-century subalpine fire and forests in Grand Teton National Park, Wyoming, USA? *Ecological Applications* **30**, e02030 (2020).
84. Seidl, R. *et al.* Multi-scale drivers of spatial variation in old-growth forest carbon density disentangled with lidar and an individual-based landscape model. *Ecosystems* **15**, 1321–1335 (2012).
85. Seidl, R., Rammer, W. & Spies, T. A. Disturbance legacies increase the resilience of forest ecosystem structure, composition, and functioning. *Ecological Applications* **24**, 2063–2077 (2014).
86. Hansen, W. D., Braziunas, K. H., Rammer, W., Seidl, R. & Turner, M. G. It takes a few to tango: Changing climate and fire regimes can cause regeneration failure of two subalpine conifers. *Ecology* **99**, 966–977 (2018).
87. Braziunas, K. H., Hansen, W. D., Seidl, R., Rammer, W. & Turner, M. G. Looking beyond the mean: Drivers of variability in postfire stand development of conifers in Greater Yellowstone. *Forest Ecology and Management* **430**, 460–471 (2018).
88. Allen, C. D. & Breshears, D. D. Drought-induced shift of a forest–woodland ecotone: Rapid landscape response to climate variation. *Proceedings of the National Academy of Sciences* **95**, 14839–14842 (1998).
89. Lenoir, J., Gégout, J. C., Marquet, P. A., de Ruffray, P. & Brisse, H. A significant upward shift in plant species optimum elevation during the 20th century. *Science* **320**, 1768–1771 (2008).
90. Esquivel-Muelbert, A. *et al.* Compositional response of Amazon forests to climate change. *Global Change Biology* **25**, 39–56 (2019).

91. Kelly, A. E. & Goulden, M. L. Rapid shifts in plant distribution with recent climate change. *Proceedings of the National Academy of Sciences* **105**, 11823–11826 (2008).
92. Hanbury-Brown, A. Intensifying fire regimes and water limitation drive declines in post-fire conifer regeneration that persist for decades. *Ecosphere*. (In Review).
93. Fusco, E. J., Finn, J. T., Balch, J. K., Nagy, R. C. & Bradley, B. A. Invasive grasses increase fire occurrence and frequency across US ecoregions. *Proceedings of the National Academy of Sciences* **116**, 23594–23599 (2019).
94. Hättenschwiler, S. *et al.* Atmospheric CO2 enrichment of alpine treeline conifers. *New Phytologist* **156**, 363–375 (2002).
95. Smith, A. R. *et al.* Elevated CO2 enrichment induces a differential biomass response in a mixed species temperate forest plantation. *New Phytologist* **198**, 156–168 (2013).
96. Dawes, M. A. *et al.* Species-specific tree growth responses to 9 years of CO2 enrichment at the alpine treeline. *Journal of Ecology* **99**, 383–394 (2011).
97. Walker, A. P. *et al.* Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2. *New Phytologist* **229**, 2413–2445 (2021).
98. Niinemets, Ü., Flexas, J. & Peñuelas, J. Evergreens favored by higher responsiveness to increased CO2. *Trends in Ecology & Evolution* **26**, 136–142 (2011).
99. LaDeau, S. L. & Clark, J. S. Rising CO2 levels and the fecundity of forest trees. *Science* **292**, 95–98 (2001).
100. Koven, C. D. *et al.* Benchmarking and parameter sensitivity of physiological and vegetation dynamics using the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) at Barro Colorado Island, Panama. *Biogeosciences* **17**, 3017–3044 (2020).
101. Buotte, P. C. *et al.* Capturing functional strategies and compositional dynamics in vegetation demographic models. *Biogeosciences* **18**, 4473–4490 (2021).
102. Gao, X. California annual grass phenology and allometry influence ecosystem dynamics and fire regime in a vegetation demography model. *New Phytologist* (In Review).
103. Hanbury-Brown, A. R., Ward, R. E. & Kueppers, L. M. Forest regeneration within Earth system models: current process representations and ways forward. *New Phytologist* **235**, 20–40 (2022).
104. Ellsworth, D. S. *et al.* Elevated CO2 does not increase eucalypt forest productivity on a low-phosphorus soil. *Nature Clim Change* **7**, 279–282 (2017).
105. Hersbach, H. *et al.* The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* **146**, 1999–2049 (2020).
106. Rahimi, S. *et al.* Evaluation of a reanalysis-driven configuration of WRF4 over the western United States from 1980 to 2020. *Journal of Geophysical Research: Atmospheres* **127**, e2021JD035699 (2022).
107. Key, C. H. & Benson, N. C. Landscape assessment: ground measure of severity, the Composite Burn Index. in *D.C. Lutes (ed.), FIREMON: Fire effects monitoring and inventory system* (USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, 2005).
108. French, N. H. F. *et al.* Using Landsat data to assess fire and burn severity in the North American boreal forest region: an overview and summary of results. *International Journal of Wildland Fire* **17**, 443–462 (2008).
109. Parks *et al.* Giving ecological meaning to satellite-derived fire severity metrics across North American forests. *Remote Sensing* **11**, 1735 (2019).
110. Saberi, S. J. & Harvey, B. J. What is the color when black is burned? Quantifying (re)burn severity using field and satellite remote sensing indices. *Fire Ecology* **19**, 24 (2023).
111. Buonanduci, M. S., Donato, D. C., Halofsky, J. S., Kennedy, M. C. & Harvey, B. J. Consistent spatial scaling of high-severity wildfire can inform expected future patterns of burn severity. *Ecology Letters* **10.1111/ele.14282**, (2023).
112. Harvey, B. J., Buonanduci, M. S. & Turner, M. G. Spatial interactions among short-interval fires reshape forest landscapes. *Global Ecology and Biogeography* **32**, 586–602 (2023).

113. Parks, S. A., Holsinger, L. M., Voss, M., Loehman, R. & Robinson, N. Mean composite fire severity metrics computed with Google Earth Engine offer improved accuracy and expanded mapping potential. *Remote Sensing* **10**, 879 (2018).
114. Frantz, D. FORCE—Landsat + Sentinel-2 analysis ready data and beyond. *Remote Sensing* **11**, 1124 (2019).
115. Reiner, A. L., Baker, C., Wahlberg, M., Rau, B. M. & Birch, J. D. Region-specific remote-sensing models for predicting burn severity, basal area change, and canopy cover change following fire in the southwestern United States. *Fire* **5**, 137 (2022).
116. Cansler, C. A. & McKenzie, D. Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. *Ecological Applications* **24**, 1037–1056 (2014).
117. Harvey, B. J., Donato, D. C. & Turner, M. G. Drivers and trends in landscape patterns of stand-replacing fire in forests of the US Northern Rocky Mountains (1984–2010). *Landscape Ecology* **31**, 2367–2383 (2016).
118. Gill, N. S. *et al.* Limitations to propagule dispersal will constrain postfire recovery of plants and fungi in western coniferous forests. *BioScience* biab139 (2022) doi:10.1093/biosci/biab139.
119. Turner, M. G., Tinker, D. B., Romme, W. H., Kashian, D. M. & Litton, C. M. Landscape patterns of sapling density, leaf area, and aboveground net primary production in postfire lodgepole pine forests, Yellowstone National Park (USA). *Ecosystems* **7**, 751–775 (2004).
120. Collins, B. M. *et al.* Alternative characterization of forest fire regimes: incorporating spatial patterns. *Landscape Ecology* **32**, 1543–1552 (2017).
121. Gill, N. S., Hoecker, T. J. & Turner, M. G. The propagule doesn't fall far from the tree, especially after short-interval, high-severity fire. *Ecology* **102**, (2021).
122. Rodman, K. C. *et al.* Refuge-yeah or refuge-nah? Predicting locations of forest resistance and recruitment in a fiery world. *Global Change Biology* **29**, 7029–7050 (2023).
123. Reilly, M. J., Zuspan, A. & Yang, Z. Characterizing post-fire delayed tree mortality with remote sensing: sizing up the elephant in the room. *fire Ecology* **19**, 64 (2023).
124. Rollins, M. G. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire* **18**, 235 (2009).
125. Riley, K. L., Grenfell, I. C., Finney, M. A. & Wiener, J. M. TreeMap, a tree-level model of conterminous US forests circa 2014 produced by imputation of FIA plot data. *Scientific Data* **8**, 11 (2021).
126. Abatzoglou, J. T. Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology* **33**, 121–131 (2013).
127. Balch, J. K. *et al.* Warming weakens the night-time barrier to global fire. *Nature* **602**, 442–448 (2022).
128. Balch, J. K. *et al.* FIRED (Fire Events Delineation): An open, flexible algorithm and database of US fire events derived from the MODIS burned area product (2001–2019). *Remote Sensing* **12**, 3498 (2020).
129. St. Denis, L. A. *et al.* All-hazards dataset mined from the US National Incident Management System 1999–2020. *Scientific Data* **10**, 112 (2023).
130. Keeley, J. E. Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire* **18**, 116 (2009).
131. Heward, H. *et al.* Is burn severity related to fire intensity? Observations from landscape scale remote sensing. *International Journal of Wildland Fire* **22**, 910 (2013).
132. Birch, D. S. *et al.* Vegetation, topography and daily weather influenced burn severity in central Idaho and western Montana forests. *Ecosphere* **6**, art17 (2015).
133. Miquelajauregui, Y., Cumming, S. G. & Gauthier, S. Modelling variable fire severity in boreal forests: Effects of fire intensity and stand structure. *PLOS ONE* **11**, e0150073 (2016).
134. Sparks, A. M. *et al.* Fire intensity impacts on post-fire temperate coniferous forest net primary productivity. *Biogeosciences* **15**, 1173–1183 (2018).

135. Morgan, P. *et al.* Challenges of assessing fire and burn severity using field measures, remote sensing and modelling. *International Journal of Wildland Fire* **23**, 1045 (2014).
136. van Mantgem, P. J. *et al.* Climatic stress increases forest fire severity across the western United States. *Ecology Letters* **16**, 1151–1156 (2013).
137. J. T. Stevens. Fire resistance trait data for 29 western North American conifer species. U.S. Geological Survey data release https://doi.org/10.5066/P97F5P7L (2020).
138. Hudak, A. T. *et al.* A carbon monitoring system for mapping regional, annual aboveground biomass across the northwestern USA. *Environmental Research Letters* **15**, 095003 (2020).
139. Emick, E. *et al.* An approach to estimating forest biomass while quantifying estimate uncertainty and correcting bias in machine learning maps. *Remote Sensing of Environment* **295**, 113678 (2023).
140. Hudak, A. T. *et al.* Towards spatially explicit quantification of pre- and postfire fuels and fuel consumption from traditional and point cloud measurements. *Forest Science* **66**, 428–442 (2020).
141. Wilson, B. T., Knight, J. F. & McRoberts, R. E. Harmonic regression of Landsat time series for modeling attributes from national forest inventory data. *ISPRS Journal of Photogrammetry and Remote Sensing* **137**, 29–46 (2018).
142. Evgeny G. Shvetsov, Kukavskaya, E. A., Buryak, L. V. & Barrett, K. Assessment of post-fire vegetation recovery in Southern Siberia using remote sensing observations. *Environmental Research Letters* **14**, 055001 (2019).
143. Viana-Soto, A., Aguado, I., Salas, J. & García, M. Identifying Post-fire recovery trajectories and driving factors using landsat time series in fire-prone Mediterranean pine forests. *Remote Sensing* **12**, 1499 (2020).
144. Wang, J. A. *et al.* Extensive land cover change across Arctic–Boreal Northwestern North America from disturbance and climate forcing. *Global Change Biology* **26**, 807–822 (2020).
145. Dickman, L. T. *et al.* Integrating plant physiology into simulation of fire behavior and effects. *New Phytologist* **238**, 952–970 (2023).
146. Martinez-Vilalta, J., Anderegg, W. R. L., Sapes, G. & Sala, A. Greater focus on water pools may improve our ability to understand and anticipate drought-induced mortality in plants. *New Phytologist* **223**, 22–32 (2019).
147. Rao, K., Williams, A. P., Diffenbaugh, N. S., Yebra, M. & Konings, A. G. Plant-water sensitivity regulates wildfire vulnerability. *Nature Ecology and Evolution* **6**, 332–339 (2022).
148. Hansen, W. D., Krawchuk, M. A., Trugman, A. T. & Williams, A. P. The Dynamic Temperate and Boreal Fire and Forest-Ecosystem Simulator (DYNAFFOREST): Development and evaluation. *Environmental Modelling & Software* **156**, 105473 (2022).
149. Daum, K. L. *et al.* Do vegetation fuel reduction treatments alter forest fire severity and carbon stability in California forests? *Earth's Future* **12**, e2023EF003763 (2024).
150. Quetin, G. R., Anderegg, L. D. L., Boving, I., Anderegg, W. R. L. & Trugman, A. T. Observed forest trait velocities have not kept pace with hydraulic stress from climate change. *Global Change Biology* **29**, 5415–5428 (2023).
151. Tsai, W.-P. *et al.* From calibration to parameter learning: Harnessing the scaling effects of big data in geoscientific modeling. *Nature Communications* **12**, 5988 (2021).
152. Westerling, A. L., Turner, M. G., Smithwick, E. A. H., Romme, W. H. & Ryan, M. G. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences* **108**, 13165–13170 (2011).
153. Hurteau, M. D., Liang, S., Westerling, A. L. & Wiedinmyer, C. Vegetation-fire feedback reduces projected area burned under climate change. *Scientific Reports* **9**, 2838–2838 (2019).
154. Liang, Y., Duveneck, M. J., Gustafson, E. J., Serra-Diaz, J. M. & Thompson, J. R. How disturbance, competition, and dispersal interact to prevent tree range boundaries from keeping pace with climate change. *Global Change Biology* **24**, e335–e351 (2018).
155. Seidl, R. To model or not to model, that is no longer the question for ecologists. *Ecosystems* **20**, 222–228 (2017).

156. Rammer, W. & Seidl, R. A scalable model of vegetation transitions using deep neural networks. *Methods in Ecology and Evolution* **10**, 879–890 (2019).
157. North, M. P. *et al.* Pyrosilviculture needed for landscape resilience of dry western United States Forests. *Journal of Forestry* **119**, 520–544 (2021).
158. Flecker, A. S. *et al.* Reducing adverse impacts of Amazon hydropower expansion. *Science* **375**, 753–760 (2022).
159. McClure, C. D. & Jaffe, D. A. US particulate matter air quality improves except in wildfire-prone areas. *Proceedings of the National Academy of Sciences* **115**, 7901–7906 (2018).
160. Burke, M. *et al.* The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences* **118**, e2011048118 (2021).
161. Schoennagel, T. *et al.* Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences* **114**, 4582–4590 (2017).
162. Stephens, S. L. *et al.* Fire and climate change: conserving seasonally dry forests is still possible. *Frontiers in Ecology and the Environment* **18**, 354–360 (2020).
163. Kaiser, J. W. *et al.* Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeosciences* **9**, 527–554 (2012).
164. van der Werf, G. R. *et al.* Global fire emissions estimates during 1997–2016. *Earth System Science Data* **9**, 697–720 (2017).
165. Wiedinmyer, C. *et al.* The Fire Inventory from NCAR version 2.5: an updated global fire emissions model for climate and chemistry applications. *Geoscientific Model Development* **16**, 3873–3891 (2023).
166. Hammer, R. B., Radeloff, V. C., Fried, J. S. & Stewart, S. I. Wildland–urban interface housing growth during the 1990s in California, Oregon, and Washington. *International Journal of Wildland Fire* **16**, 255–265 (2007).
167. Radeloff, V. C. *et al.* The wildland–urban interface in the United States. *Ecological Applications* **15**, 799–805 (2005).
168. Kramer, H. A., Mockrin, M. H., Alexandre, P. M. & Radeloff, V. C. High wildfire damage in interface communities in California. *International Journal of Wildland Fire* **28**, 641–650 (2019).
169. Radeloff, V. C., Hammer, R. B. & Stewart, S. I. Rural and suburban sprawl in the U.S. midwest from 1940 to 2000 and Its relation to forest fragmentation. *Conservation Biology* **19**, 793–805 (2005).
170. Radeloff, V. C. *et al.* Housing growth in and near United States protected areas limits their conservation value. *Proceedings of the National Academy of Sciences* **107**, 940–945 (2010).
171. Carlson, A. R., Helmers, D. P., Hawbaker, T. J., Mockrin, M. H. & Radeloff, V. C. The wildland–urban interface in the United States based on 125 million building locations. *Ecological Applications* **32**, e2597 (2022).
172. Carlson, A. R. *et al.* The extent of buildings in wildland vegetation of the conterminous U.S. and the potential for conservation in and near National Forest private inholdings. *Landscape and Urban Planning* **237**, 104810 (2023).
173. He, T., Lamont, B. B. & Pausas, J. G. Fire as a key driver of Earth's biodiversity. *Biological Reviews* **94**, 1983–2010 (2019).
174. Kelly, L. T. *et al.* Fire and biodiversity in the Anthropocene. *Science* **370**, eabb0355 (2020).
175. Keeley, J. E. & Pausas, J. G. Evolutionary ecology of fire. *Annual Review of Ecology, Evolution, and Systematics* **53**, 203–225 (2022).
176. Ayars, J., Kramer, H. A. & Jones, G. M. The 2020 to 2021 California megafires and their impacts on wildlife habitat. *Proceedings of the National Academy of Sciences* **120**, e2312909120 (2023).
177. Carroll, K. A. *et al.* Mapping multiscale breeding bird species distributions across the United States and evaluating their conservation applications. *Ecological Applications* **34**, e2934 (2024).
178. GBIF: The Global Biodiversity Information Facility (2024) What is GBIF? https://www.gbif.org/what-is-gbif.

179. Spasojevic, M. J. *et al.* Scaling up the diversity–resilience relationship with trait databases and remote sensing data: the recovery of productivity after wildfire. *Global Change Biology* **22**, 1421–1432 (2016).
180. Kattge, J. *et al.* TRY – a global database of plant traits. *Global Change Biology* **17**, 2905–2935 (2011).
181. Gleason, S. M. *et al.* Weak tradeoff between xylem safety and xylem-specific hydraulic efficiency across the world's woody plant species. *New Phytologist* **209**, 123–136 (2016).
182. USDA Forest Service. Forest Inventory and Analysis database. Forest Service 904 (2019).
183. Trugman, A. T., Anderegg, L. D. L., Shaw, J. D. & Anderegg, W. R. L. Trait velocities reveal that mortality has driven widespread coordinated shifts in forest hydraulic trait composition. *Proceedings of the National Academy of Sciences* **117**, 8532–8538 (2020).
184. Hallema, D. W. *et al.* Burned forests impact water supplies. *Nature Communications* **9**, 1307 (2018).
185. Buma, B. & Livneh, B. Key landscape and biotic indicators of watersheds sensitivity to forest disturbance identified using remote sensing and historical hydrography data. *Environmental Research Letters* **12**, 074028 (2017).
186. Wine, M. L., Cadol, D. & Makhnin, O. In ecoregions across western USA streamflow increases during post-wildfire recovery. *Environmental Research Letters* **13**, 014010 (2018).
187. Thornton, P. E. *et al.* Gridded daily weather data for North America with comprehensive uncertainty quantification. *Scientific Data* **8**, 190 (2021).
188. Hansen, M. C. *et al.* High-resolution global maps of 21st-century forest cover change. *Science* **342**, 850–853 (2013).
189. Bright, B. C. *et al.* Prediction of forest canopy and surface fuels from lidar and satellite time series data in a bark beetle-affected forest. *Forests* **8**, 322 (2017).
190. Huang, C. *et al.* An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. *Remote Sensing of Environment* **114**, 183–198 (2010).
191. Souther, S. K., Sandor, M. E., Sample, M., Gabrielson, S. & Aslan, C. E. Bee and butterfly records indicate diversity losses in western and southern North America, but extensive knowledge gaps remain. (In Review*)*.
192. Woods & Poole Economics. https://www.woodsandpoole.com/.
193. Alexandre, P. M., Mockrin, M. H., Stewart, S. I., Hammer, R. B. & Radeloff, V. C. Rebuilding and new housing development after wildfire. *International Journal of Wildland Fire* **24**, 138–149 (2014).
194. Kramer, H. A. *et al.* Post-wildfire rebuilding and new development in California indicates minimal adaptation to fire risk. *Land Use Policy* **107**, 105502 (2021).
195. Hudiburg, T. *et al.* Terrestrial carbon dynamics in an era of increasing wildfire. *Nature Climate Change* **13**, 1306–1316 (2023).
196. Buotte, P. C., Law, B. E., Ripple, W. J. & Berner, L. T. Carbon sequestration and biodiversity co-benefits of preserving forests in the western United States. *Ecological Applications* **30**, e02039 (2020).
197. Watson, J. E. M. *et al.* The exceptional value of intact forest ecosystems. *Nature Ecology and Evolution* **2**, 599–610 (2018).
198. Grêt-Regamey, A., Brunner, S. H., Altwegg, J., Christen, M. & Bebi, P. Integrating expert knowledge into mapping ecosystem services trade-offs for sustainable forest management. *Ecology and Society* **18**, (2013).
199. Jung, M. *et al.* Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nature Ecology and Evolution* **5**, 1499–1509 (2021).
200. Watson, S. C. L., Grandfield, F. G. C., Herbert, R. J. H. & Newton, A. C. Detecting ecological thresholds and tipping points in the natural capital assets of a protected coastal ecosystem. *Estuarine, Coastal and Shelf Science* **215**, 112–123 (2018).

201. Watson, S. C. L. *et al.* Does agricultural intensification cause tipping points in ecosystem services? *Landscape Ecology* **36**, 3473–3491 (2021).
202. King, E., Cavender-Bares, J., Balvanera, P., Mwampamba, T. H. & Polasky, S. Trade-offs in ecosystem services and varying stakeholder preferences: evaluating conflicts, obstacles, and opportunities. *Ecology and Society* **20**, (2015).
203. Karimi, A., Yazdandad, H. & Fagerholm, N. Evaluating social perceptions of ecosystem services, biodiversity, and land management: Trade-offs, synergies and implications for landscape planning and management. *Ecosystem Services* **45**, 101188 (2020).
204. Morán-Ordóñez, A. *et al.* Future trade-offs and synergies among ecosystem services in Mediterranean forests under global change scenarios. *Ecosystem Services* **45**, 101174 (2020).
205. Thom, D. *et al.* The climate sensitivity of carbon, timber, and species richness covaries with forest age in boreal–temperate North America. *Global Change Biology* **25**, 2446–2458 (2019).
206. Cord, A. F. *et al.* Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. *Ecosystem Services* **28**, 264–272 (2017).
207. Dade, M. C., Mitchell, M. G. E., McAlpine, C. A. & Rhodes, J. R. Assessing ecosystem service trade-offs and synergies: The need for a more mechanistic approach. *Ambio* **48**, 1116–1128 (2019).
208. Brand, A., Allen, L., Altman, M., Hlava, M. & Scott, J. Beyond authorship: attribution, contribution, collaboration, and credit. *Learned Publishing* **28**, 151–155 (2015).