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To cite this article: Christopher J Dunn *et al* 2020 *Environ. Res. Lett.* **15** 025001

View the article online for updates and enhancements.

Environmental Research Letters

LETTER

Wildfire risk science facilitates adaptation of fire-prone social-ecological systems to the new fire reality

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Abstract

Large and severe wildfires are an observable consequence of an increasingly arid American West. There is increasing consensus that human communities, land managers, and fire managers need to adapt and learn to live with wildfires. However, a myriad of human and ecological factors constrain adaptation, and existing science-based management strategies are not sufficient to address fire as both a problem and solution. To that end, we present a novel risk-science approach that aligns wildfire response decisions, mitigation opportunities, and land management objectives by consciously integrating social, ecological and fire management system needs. We use fire-prone landscapes of the US Pacific Northwest as our study area, and report on and describe how three complementary risk-based analytic tools—quantitative wildfire risk assessment, mapping of suppression difficulty, and atlases of potential control locations—can form the foundation for adaptive governance in fire management. Together, these tools integrate wildfire risk with fire management difficulties and opportunities, providing a more complete picture of the wildfire risk management challenge. Leveraging recent and ongoing experience integrating local experiential knowledge with these tools, we provide examples and discuss how these geospatial datasets create a risk-based planning structure that spans multiple spatial scales and uses. These uses include pre-planning strategic wildfire response, implementing safe wildfire response balancing risk with likelihood of success, and alignment of non-wildfire mitigation opportunities to support wildfire risk management more directly. We explicitly focus on multi-jurisdictional landscapes to demonstrate how these tools highlight the shared responsibility of wildfire risk mitigation. By integrating quantitative risk science, expert judgement and adaptive co-management, this process provides a much-needed pathway to transform fire-prone social ecological systems to be more responsive and adaptable to change and live with fire in an increasingly arid American West.

Introduction

Fire-prone landscapes of the American West are social-ecological systems (SES) where feedbacks among anthropogenic and ecological factors drive the timing, quantity, and quality of services derived from the natural environment (Liu *et al* 2007, Ostrom 2009,

Spies *et al* 2014). Wildland fire, or the lack thereof, is a critical agent of change mediated by interactions of human and ecological systems (Steelman 2016). Indigenous peoples embraced fire as a tool to provide a range of ecosystem services. This relationship changed following European colonization of North America, and fire exclusion was increasingly viewed as necessary

to enhance extraction of timber and other resources (Greeley 1920, Taylor *et al* 2016, Pausas and Keeley 2019). The relatively cool, wet climate during much of the 20th Century was favorable to fire exclusion (Littell *et al* 2009), and federal and state fire management policies and societal expectations aligned around the assumption that fire exclusion was both desirable and sustainable (Dombeck *et al* 2004, Hudson 2011). More recently, increased fuel loadings and tree densities, lengthening fire seasons, increasing summer temperatures, and declining summer precipitation are making fires larger and more severe while increasing total annual area burned (Steel *et al* 2015, Jolly *et al* 2015, Kitzberger *et al* 2017, Holden *et al* 2018). These climate-fire trends are expected to continue in the coming decades (Westerling *et al* 2011, Abatzoglou and Williams, 2016), further challenging the sustainability of the exclusion paradigm.

Today, there is increasing consensus that human communities, land management agencies, and fire managers need to adapt and learn to live with fire (Moritz *et al* 2014, North *et al* 2015, Thompson *et al* 2015a, Schoennagel *et al* 2017). The US federal government, which typically leads wildfire management in Western US landscapes, recognizes this need via the 2014 National Cohesive Wildland Fire Management Strategy (https://forestsandrangelands.gov/strategy/thestrategy.shtml). However, the prevailing system of fire governance remains focused on integrating multiple governmental agencies to coordinate suppression activities across scales (Davis 2001, Fleming *et al* 2015). Short-term benefits to landowners, management agencies and elected officials incentivize fire exclusion, with personal risk avoidance being a key factor working against reintroducing or managing fires for resource benefit because they are perceived to carry longer-run risks and management dilemmas. These incentives are structured into the fire management system and key performance indicators (Thompson *et al* 2018a), reinforcing fire exclusion in spite of scientific and policymaker recognition that fire contributes positively to ecosystems and long-term risk reduction (Calkin *et al* 2015, Abrams *et al* 2015, Fischer *et al* 2016).

By successfully suppressing ∼98% of ignitions under a range of weather conditions, federal fire managers are preferentially selecting for more damaging fires that burn under more extreme conditions (North *et al* 2015). These fires interact with forest and fuel conditions conducive to high-severity fire in dry forests across the American West (Reilly *et al* 2017, Johnston *et al* 2018, Zald and Dunn, 2018). Consequently, large patches of high-severity fire occur on landscapes (Reilly *et al* 2017, Stevens *et al* 2017), adversely impacting ecosystem resilience (Lindenmayer and Sato, 2018, Stevens-Rumann *et al* (2018), water quality (Bladon 2018), timber resources, community exposure to smoke (Schweizer *et al* 2019) and responder exposure

to hazards (Dunn *et al* 2019). Additionally, the expanding wildland urban interface continues to put homes and life at risk (Haas *et al* 2013, Radeloff *et al* 2018). These adverse wildfire consequences reinforce the exclusion paradigm by confirming deep-seated cultural and cognitive biases towards suppression (Fischer *et al* 2016, Thompson *et al* 2018c), and generate significant external and internal sociopolitical pressures on agencies to suppress all fire (Canton-Thompson *et al* 2008, Donovan *et al* 2011, Steelman and McCaffrey 2011, Collins *et al* 2013, Schultz *et al* 2019).

Counterproductive wildfire management decisions not only exacerbate the adverse consequences of wildfires, but also forgo wildfire benefits. Relative to high-severity fire, low-severity fire typically has benign or positive effects on ecosystem resilience, water quality, community smoke exposure and responder exposure to *in situ* and post-fire hazards (Rodriguez y Silva *et al* 2014, Bladon 2018, Dunn *et al* 2019, Schweizer *et al* 2019). Low-severity fires also inhibit fire occurrence (Parks *et al* 2016), spread (Collins *et al* 2009, Parks *et al* 2015) and severity (Parks *et al* 2014, Larson *et al* 2013), while enhancing containment opportunities (Thompson *et al* 2016b; Beverly 2017). A shift from maladaptive to adaptive feedbacks that minimize adverse fire consequences while maximizing fire benefits remains an elusive practice at scales commensurate with need.

Adaptive governance offers a theoretical framework for facilitating change and building resilience in fire-prone SES (Folke *et al* 2005, Chaffin *et al* 2014). According to Abrams *et al* (2015), a shift to adaptive governance of wildfire would entail resolving pathologies in institutional design of the prevailing wildfire governance, including scalar mismatches, factors that impede creating cross-scale and within-scale linkages, and increasing the adaptability of institutions themselves. Science-based analytical tools for wildfire planning and response are not, by themselves, capable of realizing these kinds of changes. However, they may contribute to solutions by providing a scalable common basis of knowledge, identifying landscapes where fires can be managed for resource benefit with relatively low risk, and by strategically aligning non-wildfire mitigation activities to support suppression where needed and a modified response where possible (Borchers 2005, Meyer *et al* 2015). These science-based analytics also aid cross-boundary planning, recognizing that risks and risk management are interdependent across adjacent jurisdictions and response partners (Hamilton *et al* 2019).

Of key importance in adaptively co-managing wildfire risk is understanding who the partners are in risk mitigation, what type of mitigation activities are appropriate, where mitigation opportunities exist, when to implement mitigation activities, and why specific actions should be taken. The objective of this

manuscript is to provide a basis for answering these questions by: (1) describing production of spatially explicit decision support tools that assess wildfire risk and place that risk within the context of fire management, and (2) describing how the combined interpretation of these tools aligns fire and land management planning across scales in multi-jurisdictional landscapes. We focus more on the latter, leveraging our experience in delivering these tools for real-time decision support on dozens of large fires during the 2017–2019 fire seasons. Furthermore, these same analytics have been or are being integrated into cross-boundary fire response and mitigation planning on dozens of landscapes across the American West. We draw on recent work in the Pacific Northwest, USA (PNW), which the authors were directly involved with, to illustrate key concepts and benefits of integrating these products.

Spatially explicit risk-science tools

### Wildfire risk to valued resources and assets

Quantitative wildfire risk assessments (risk assessments) provide an integrated picture of fire likelihood and consequences, including comparison of both market and non-market valued resources and assets on the basis of net value change (Scott *et al* 2013). Risk assessments integrate four key components: burn probability, fire intensity, susceptibility of resources/assets, and the relative importance of resources/assets. Methodologically, the main components include geospatial analysis, fire simulation, expert judgement elicitation, and multi-criteria decision analysis (Thompson *et al* 2013, Thompson *et al* 2015b). The primary outputs of interest are raster layers of conditional net value change (cNVC), quantifying potential losses and benefits if fire were to occur, and expected net value change (eNVC), quantifying those same potential losses and benefits weighted by burn probability. A summary of this methodology is provided in table 1.

The PNW risk assessment was completed in spring of 2018 and explicitly evaluated wildfire risk across all ownerships and land cover types, recognizing that wildfires impact most wildlands and routinely spread across jurisdictional boundaries with diverse land management objectives (https://oregonexplorer.info/content/pacific-northwest-quantitative-wildfire-risk-assessment). The multi-jurisdictional, regional perspective is a distinguishing feature of the PNW risk assessment relative to earlier risk assessments that were largely focused on federal ownerships. Results from the PNW risk assessment offer an unprecedented opportunity to address wildfire risk strategically across jurisdictions, but requires additional analytics to translate this information into actionable science.

Quantifying operational wildfire management challenges and opportunities

Mapping wildfire management challenges and opportunities supports pre-planning efforts and risk-based decision making, in addition to facilitating collaborative learning among partners and stakeholders (e.g. federal, state, local, and tribal governments; conservation, recreation, and community-based NGOs; forest and livestock industry representatives; homeowners; scientists; user groups; and members of the interested public). Table 2 summarizes the methodology used for two analytical tools depicting important considerations in fire management. The first analytical product quantifies relative responder exposure to fire. Previous exposure analyses relied solely on fire intensity thresholds (e.g. Mitropoulos *et al* 2017), disregarding responder accessibility and mobility. To address this, Suppression Difficulty Index (SDI) weighs fire behavior against road and trail access/egress, including topographic impediments to mobility, in an expert weighted system, to map a relative measure of responder exposure to wildfire (Rodriguez y Silva *et al* (2014), O'Connor *et al* 2016). For the PNW, we focused on fire-prone landscapes regardless of jurisdiction or ownership, at 90th percentile fire weather conditions (moderate to high) and topographically modified wind speed (Finney (2006), Forthofer *et al* 2014). Suppression difficulty index does not address all aspects of risk to responders (e.g. safety features, snag hazards, heat exposure), many of which are being actively pursued in other research efforts (e.g. Butler, 2014 , Campbell *et al* 2015, Dunn *et al* 2019, Penney *et al* 2019).

The second analytical tool depicting aspects of the wildfire management environment is the atlas of potential control locations (PCLs), which identifies areas with the highest likelihood of containment success. Here, we build from methodologies using boosted regression trees (Elith *et al* 2008), a machine learning algorithm, to quantify the relationship between final containment lines for large fires (>200 ha) and nine predictor variables (see supplemental table 1 is available online at stacks.iop.org/ERL/15/025001/mmedia for definitions) indicative of the complex factors evaluated by fire managers during large fire containment (O'Connor *et al* 2017). We developed predictive models of potential control locations across 16 modeling zones covering fire prone landscapes of the PNW (supplemental figure 1). We made adjustments for overfitting in boosted regression tree analysis (supplemental figure 2) and mosaicked predictive maps from all modeling zones into a continuous dataset. We provide a more comprehensive description of our methodology and results as online supplemental material, including an assessment of the relative influence of each predictor (supplemental figure 3) and their response curve (supplemental figure 4). The potential control location atlas complements the suppression difficulty map to
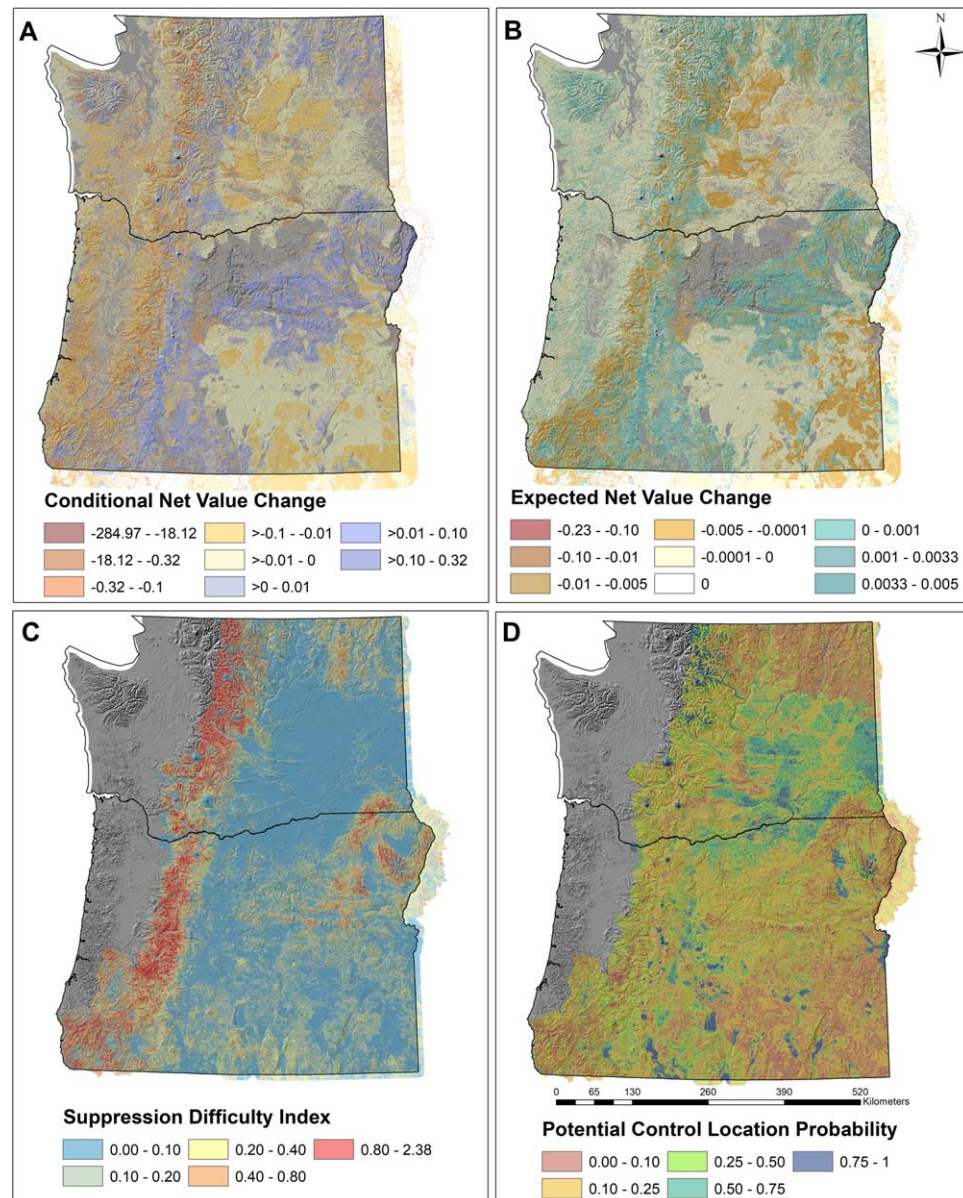
Figure 1. A depiction of the spatial datasets supporting alignment of fire management and mitigation opportunities to protect values at risk in fire prone forests of the Pacific Northwest (PNW), USA. (A) Conditional net value change (cNVC) from the quantitative wildfire risk assessment depicting the positive and negative consequences when a large fire occurs. (B) Expected net value change (eNVC) from the quantitative wildfire risk assessment, integrating both the probability of fire occurrence and cNVC. (C) Suppression difficulty index (suppression difficulty) for fire-prone forested landscapes of the PNW. (D) Potential control location atlas depicting the probability of a feature being a good large fire containment line, across fire-prone forested landscapes of the PNW. Gray areas currently lack data in this region.

identify areas where fire management efforts are likely to be safer and more effective (Dunn *et al* 2017, Wei *et al* 2019).

Integrating wildfire risks and the operational environment

Integrating landscape risk assessments with operational fire management considerations offers important perspectives regarding values at risk and fire managers' ability to minimize near-term losses while maximizing long-term risk reduction benefits. Figure 1 depicts results from the risk assessment, suppression difficulty and potential control location analyses. Several important observations relevant to

fire and land management decisions are evident at this scale. For example, expected net value change maps highlight landscapes with high values and exposure, such as the southwestern interior mountains of the PNW where there are high timber values and critical northern spotted owl (*Strix occidentalis caurina*) habitat. In contrast, the risk assessment maps also depict areas where fire would likely have positive benefits, such as eastern Oregon and Washington where dry forests historically experienced frequent fire (Johnston *et al* 2018). Fire and land managers could manage fires for resource benefit in these landscapes, reducing their potential to transmit fire to adjacent jurisdictions or areas with higher assessed risk. The risk assessment
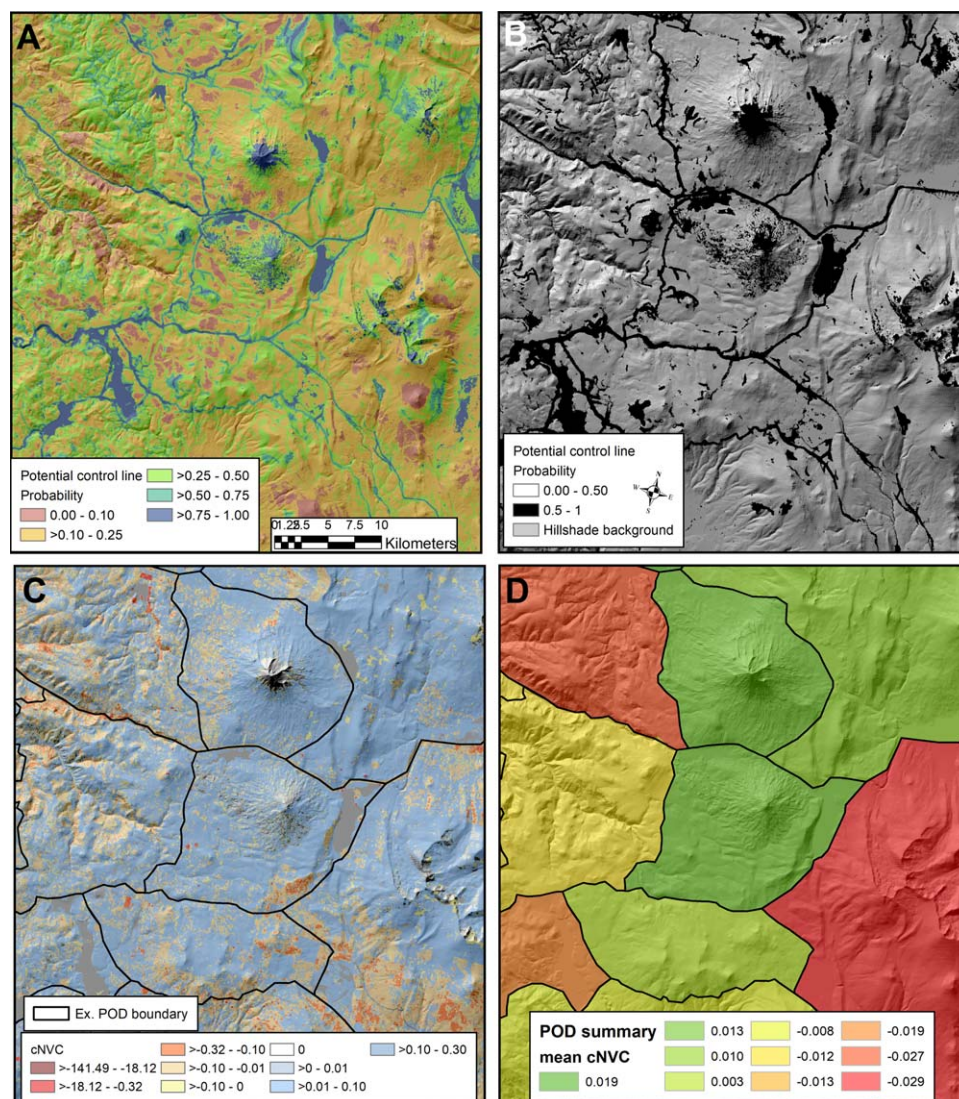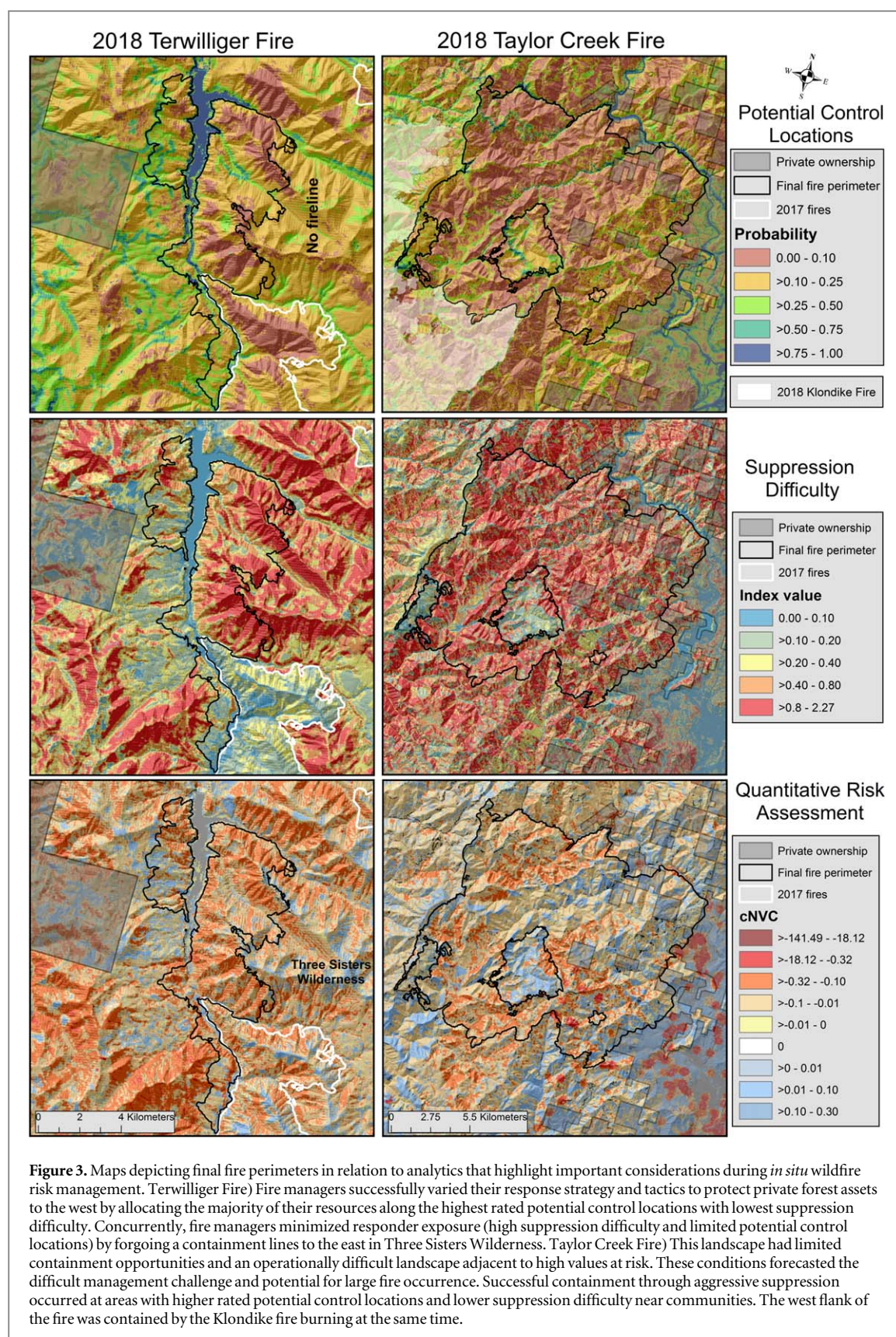
Figure 2. Maps depicting the process of summarizing risk into potential wildfire operational delineations (PODs) to identify strategic wildfire response zones (SRZ). SRZs establish broad response objectives to aid decisions regarding wildfire response in advance of an ignition, based on values at risk summarized as conditional net value change (cNVC) from a quantitative wildfire risk assessment. (A) Potential control line atlas. (B) Potential control lines with greater than 0.50 probability of being a containment feature. (C) Conditional net value change estimated in the quantitative risk assessment. (D) Mean cNVC across the example POD boundaries demonstrating variation across the landscape and potential for establishing variable response strategies ahead of fire occurrence. In practice, this process integrates analytics with partner and fire manager engagement to define values at risk and POD boundaries along effective control locations.

supports efficient allocation of limited financial and operational resources by distinguishing among mapped values based on their exposure to fire, and help identify appropriate mitigation activities (i.e. aggressive suppression, managing fires for resource benefits, hazardous fuels reduction) that meet land management goals.

Mapping wildfire operational challenges and opportunities enriches wildfire risk perspectives, and when integrated with risk assessments provide a more comprehensive perspective on wildfire risk management. Importantly, suppression difficulty and potential control locations are not synonymous but help provide context to the wildfire environment. For example, the southeastern portion of maps in figure 1

is the Northern Great Basin sage-steppe that has low suppression difficulty but limited containment locations, reflective of relatively gentle terrain but rapid wildfire rates of spread through grass and shrub fuels that typically limit containment locations to road corridors. Alternatively, the southwestern portion of maps in figure 1 (i.e. Klamath Mountains) has high suppression difficulty and low potential control locations, representing the most operationally challenging fire management environment. This reality has been reflected in recent fire history, including but not limited to the 1987 Silver (∼39 132 ha), 2002 Biscuit (∼202 321 ha), 2017 Chetco Bar (∼77 346 ha), 2018 Klondike (∼70 924 ha) and 2018 Taylor Creek (∼21 383 ha) fires. These maps enhance risk

Figure 3. Maps depicting final fire perimeters in relation to analytics that highlight important considerations during *in situ* wildfire risk management. Terwilliger Fire) Fire managers successfully varied their response strategy and tactics to protect private forest assets to the west by allocating the majority of their resources along the highest rated potential control locations with lowest suppression difficulty. Concurrently, fire managers minimized responder exposure (high suppression difficulty and limited potential control locations) by forgoing a containment lines to the east in Three Sisters Wilderness. Taylor Creek Fire) This landscape had limited containment opportunities and an operationally difficult landscape adjacent to high values at risk. These conditions forecasted the difficult management challenge and potential for large fire occurrence. Successful containment through aggressive suppression occurred at areas with higher rated potential control locations and lower suppression difficulty near communities. The west flank of the fire was contained by the Klondike fire burning at the same time.

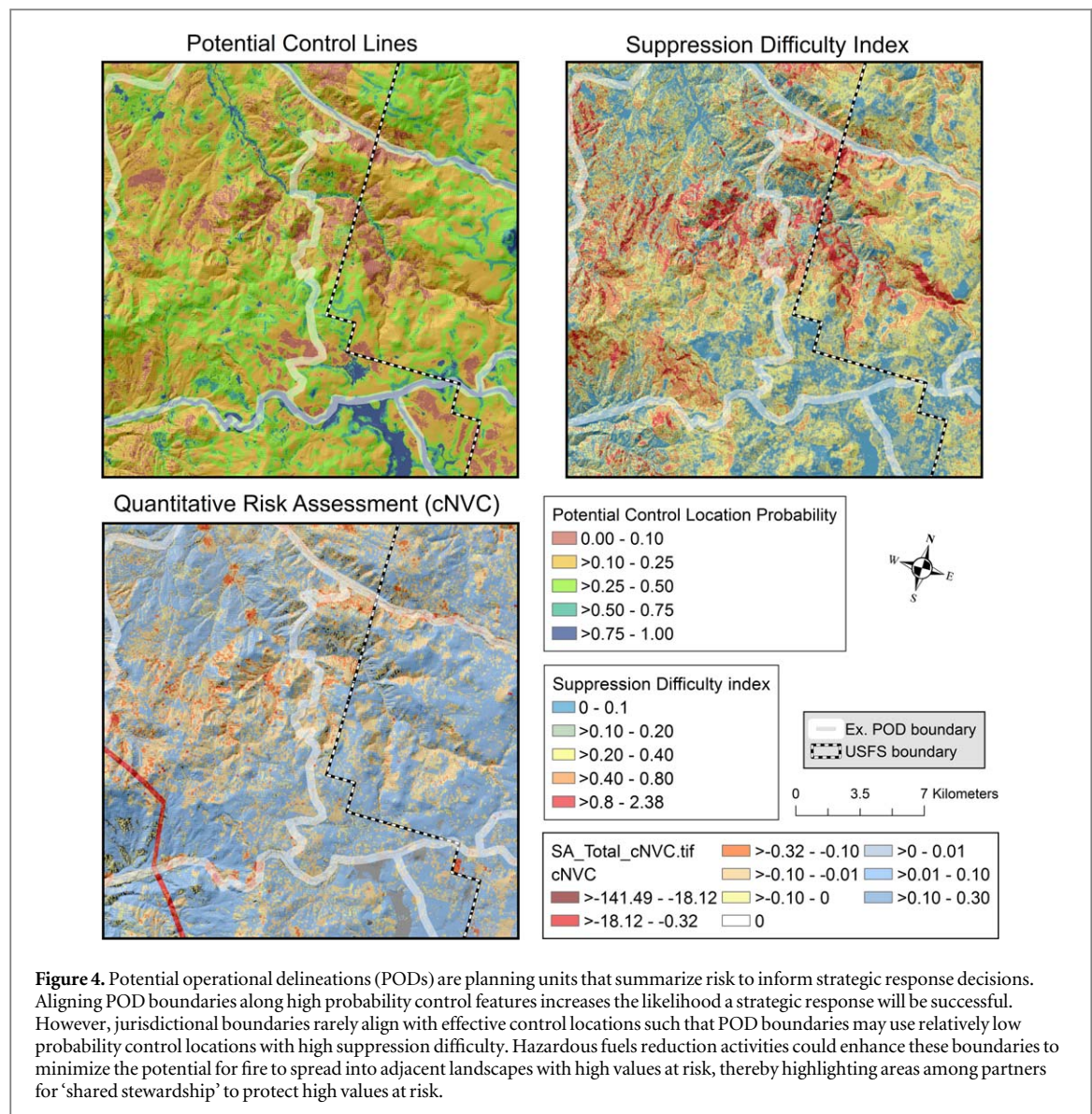assessments to support broad-scale allocation of limited resources and mitigation planning, and benefit from their scalability to project-level implementation in both fire response and mitigation activities as described in the following sections.

Wildfire risk management in action

Engaging fires before they start
All of the aforementioned spatial analytics can be integrated, distilled, and summarized to provide a

Figure 4. Potential operational delineations (PODs) are planning units that summarize risk to inform strategic response decisions. Aligning POD boundaries along high probability control features increases the likelihood a strategic response will be successful. However, jurisdictional boundaries rarely align with effective control locations such that POD boundaries may use relatively low probability control locations with high suppression difficulty. Hazardous fuels reduction activities could enhance these boundaries to minimize the potential for fire to spread into adjacent landscapes with high values at risk, thereby highlighting areas among partners for 'shared stewardship' to protect high values at risk.

common basis on which fire managers, partners and other stakeholders can collectively produce interpretable and actionable plans. One key innovation in this regard is the development of potential wildfire operational delineations (PODs) whose boundaries are relevant to fire operations (e.g. roads, natural barriers, fuel transitions) within which risks and opportunities can be summarized (Thompson *et al* 2016a, Dunn *et al* 2017, Thompson *et al* 2018b). By aligning POD boundaries with high probability potential control locations (figures 2(a), (b)), our intent is to increase the likelihood managers can effectively manage fire in accordance with values at risk. Figure 2 outlines the process of summarizing risk to identify strategic wildfire response zones (SRZs) that aid response decisions in advance of an ignition. Summarizing wildfire risk at this operationally relevant scale frames fire management objectives and response around likely positive or negative consequences. PODs form a logical basis for

efficient spatial response strategies (Wei *et al* 2018, Wei *et al* 2019), have been successfully used to guide real-world response operations (O'Connor and Calkin 2019), and are currently supporting planning efforts on landscapes throughout the American West (Thompson *et al* 2019).

POD delineation occurs at facilitated workshops that directly engage with fire responders and stakeholders at local management units, infusing local knowledge with analytics to minimize biases and errors. Our pre-season planning workshops often include federal and state fire and land managers, Tribal governments, county and local governments, and informed citizens to integrate local knowledge and generate broader learning and ownership of the planning outcome. Researchers subsequently summarize wildfire risk within PODs at a scale that matches current wildfire dynamics (figures 2(c) and (d)), and then fire managers, partners and stakeholders attribute

them with an appropriate fire management strategy. The resulting strategic response zones typically fall into one of three categories: (1) maintain, where wildfires are expected to provide positive benefits such that default strategies should be to manage fires for resource benefit, (2) restore, where wildfires may provide positive benefits under the right fire weather conditions, and (3) protect, where wildfires will result in negative outcomes such that aggressive suppression should be pursued when and where it is safe and effective.

Maps of strategic response objectives become a spatial representation of forest management priorities and direction, serving as a communication tool and a means of tracking progress toward more fire-adapted landscapes. In today's wildfire environment, strategic fire management decisions are land management decisions that should be reflective of social values. By engaging partners and stakeholders in identifying and ranking values at risk and appropriate fire response, our process provides a bridge between communities, fire managers, and agency administrators regarding expectations of fire and land management. By sharing information with diverse governmental and non-governmental stakeholders and allowing them to explore multiple alternative scenarios, this tool may help build the legitimacy needed to engage in adaptive management (Cosens 2013) while sharing the organizational risk that may allow for constructively addressing environmental risks (Borchers 2005). Without pre-determining decisions, pre-planning based on partner input and analytical data is foundational to aligning the broader fire-prone SES around a common purpose and intent.

Engaging fires after they start

The analytical tools described herein scale to tactical wildfire response decisions by providing an objective approach to determining a safe (suppression difficulty) and effective (potential control location atlas) response commensurate with values at risk (risk assessment). Figure 3 depicts tools in relation to the 2018 Terwilliger fire in the western Cascades on the Willamette National Forest and 2018 Taylor Creek fire in the Rogue Basin within the Klamath Mountain Ecoregion of southwestern Oregon (supplemental figure 1). Several of the authors provided these spatial datasets to fire and forest managers for these incidents through the USDA Forest Service's Risk Management Assistance Team (Risk Management Assistance Teams (2019)). On the Terwilliger fire, responders aggressively protected private timber resources to the west by leveraging the best available potential control locations on public lands. Concurrently, the fire burned 'freely' to the east because of limited containment opportunities and high suppression difficulty, despite significant northern

spotted owl habitat at risk. This demonstrates how the operational environment may hinder fire manager's ability to protect valued resources safely and effectively through suppression.

The 2018 Taylor Creek fire example (right panel of figure 3) depicts a burned area with limited connectivity of potential control locations, high suppression difficulty, and significant human and ecological values at risk. The operational environment impeded suppression success until the fire reached more substantial control lines, often closer to valleys where communities reside. Additionally, these maps depict jurisdictions at increased risk to fire because of the challenging operational environment, which can be determined prior to large fire occurrence. Using these analytical tools in pre-planning and carrying them through operational use facilitates greater learning by fire responders while offering feedback to analysts for improvements. They also provide communication tools to partners and stakeholders about fire management decisions and objectives before and during an incident.

Aligning non-wildfire mitigation to support fire engagement

Non-wildfire mitigation actions are an important component of effectively managing wildfire risk, and typically include forest restoration or hazardous fuels reduction (Fernandes and Botelho 2003, Agee and Skinner 2005, Raymond and Peterson 2005). These treatments can reduce burn probability when their spatial allocation is optimized or exceeds ~40% of a landscape (Ager *et al* 2013). However, research suggests these treatments rarely burn in wildfires (Barnett *et al* 2016), that treatment opportunities are limited across many landscapes (North *et al* 2012, North *et al* 2014), and that implementation rates are currently too slow to mitigate fire effects across large, fire-prone landscapes (Barros *et al* 2019). Therefore, developing treatment strategies that directly align with wildfire operations is both efficient and necessary.

The analytical tools offer an opportunity to allocate non-wildfire mitigation actions strategically, from landscape to project-level prioritization, for the explicit purpose of managing the near-term threat and long-term wildfire risk reduction. As noted previously, PODs can be landscape-scale planning units that help direct the allocation of limited financial and operational resources. Once decision makers, intergovernmental coalitions, or multi-stakeholder processes determine priority landscapes, the risk assessment, potential control locations and suppression difficulty maps help downscale resource allocations to specific project areas. For example, treatments can target specific values at high risk, such as private inholdings or critical infrastructure, to

directly reduce their risk so wildfires can be used to increase the scale of those treatment effects. Treatments can also reinforce POD boundaries as fuel break networks to improve the likelihood that pre-planned strategic response is successful, regardless if the strategy is aggressive suppression or managing fires for resource benefit (Ager *et al* 2013, Oliveira *et al* 2016). The need for fuel break network improvement is often realized during the pre-planning POD delineation process, especially near jurisdictional boundaries where there are often limited opportunities to contain a fire within a single jurisdiction (figure 4).

Fire-prone landscapes of the American West often consist of federal, state, county, city or private owners that can transmit fire to adjacent jurisdictions (Palaiologou *et al* 2019), demonstrating a shared responsibility in risk mitigation (Fischer *et al* 2019, Lidskog *et al* 2011). Maps of suppression difficulty, potential control locations and wildfire risk can highlight areas across jurisdictional boundaries where wildfire containment is unlikely, despite the need to protect highly valued resources such as communities (figure 5(a)). In fact, communities may be imbedded in multi-jurisdictional landscapes where multiple federal jurisdictions intermix with a majority privately-owned landscape that has limited containment opportunities and an operationally difficult environment (figure 5(b)). By highlighting these complex fire management landscapes, all jurisdictions and owners can simultaneously assess their exposure to wildfire and their contribution to the exposure of communities. This informs 'shared stewardship' among all jurisdictions and ownerships, especially since private forests can burn with greater severity than public lands (Zald and Dunn 2018). Furthermore, these analytics can inform state, county and local land use planning and zoning regulations intended to prevent urban growth into high risk areas without appropriate mitigation activities (Calkin *et al* 2014, Radeloff *et al* 2018), further promoting adaptive co-management of wildfire risk across scales and purpose.
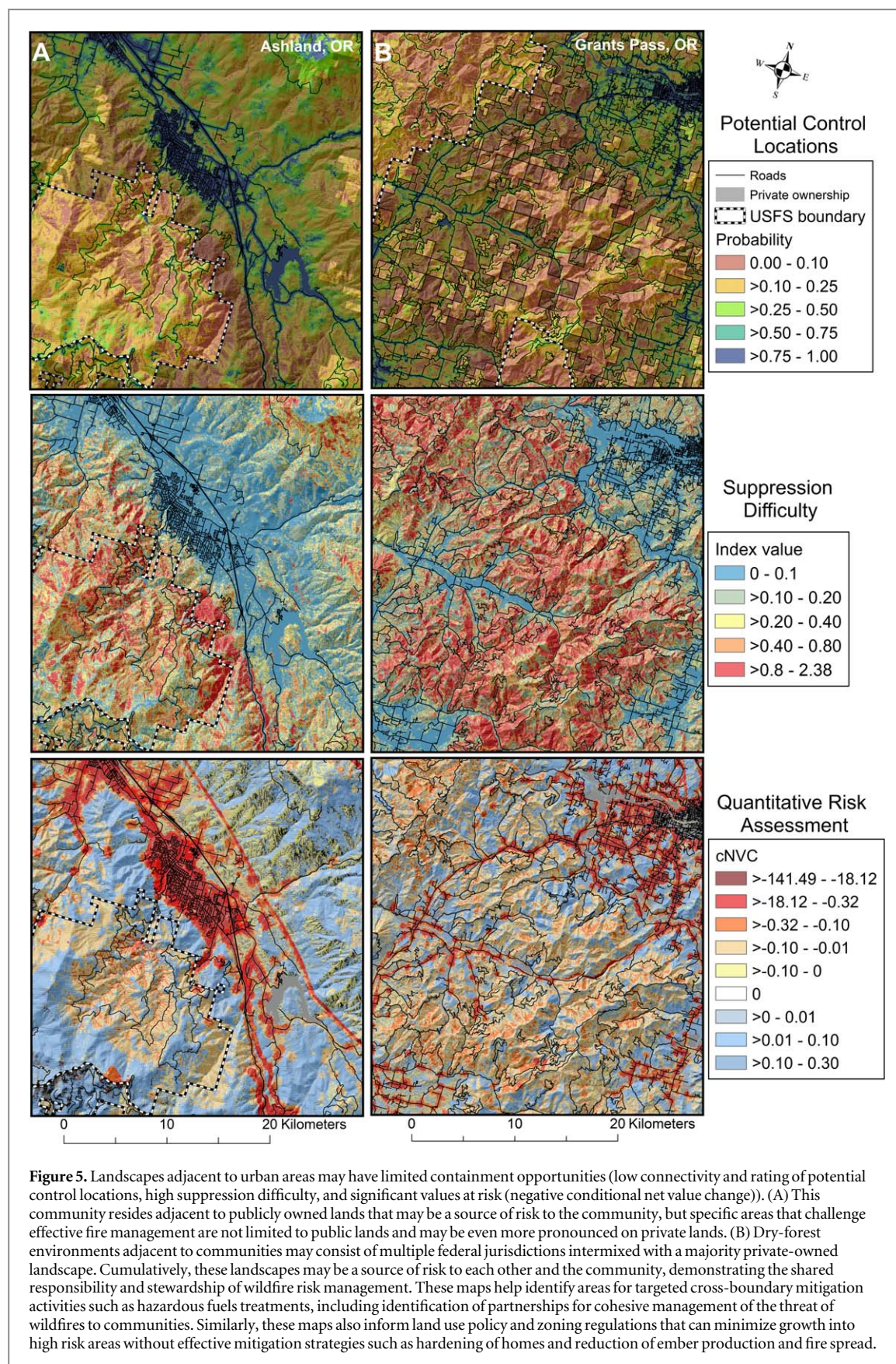
Facilitating adaptive co-management

Adaptive management is a fundamental principle of resilience in SES (Walker *et al* 2004), but remains elusive in fire-prone ecosystems for the multitude of reasons previously described. Breaking out of the 'rigidity trap' is a central challenge for contemporary fire managers (Butler and Goldstein 2010) that will require institutional change both internal and external to federal fire and land management agencies (Moritz *et al* 2014, North *et al* 2015, Thompson *et al* 2015a). We contend that adaptive co-management of wildfire risk—entailing shared discovery, risk-

taking, and learning among the various agencies and actors involved in wildfire governance—is the necessary process for facilitating change (Nowell *et al* 2018, Steelman and Nowell, 2019). By engaging diverse stakeholders, partners, and agencies in defining the problem, and by providing credible data and tools to inform civic science processes, there exists the possibility to generate greater support for the kinds of organizational risk-taking needed to promote alternatives to the fire exclusion paradigm.

Although new technologies will not solve the wildfire problem alone, the analytical tools presented here can be the foundation for adaptive co-management of wildfires because they directly address wildfire management, rather than focusing primarily of forest management (Spies *et al* 2014). These tools provide resources to assess the wildfire management landscape and identify who shares the responsibility to mitigate risk, what opportunities exist, where the need and opportunities are, when to allocate limited resources strategically and efficiently, and why mitigation actions are proposed or taken. By allowing for site-specific examination of alternatives to full suppression, they may help networks of land management agencies and non-agency stakeholders consider barriers and opportunities posed by prevailing governance arrangements and identify key leverage points for change (Abson *et al* 2017).

Undertaking this work before large fires occur fosters discussions among partners, stakeholders, land and fire managers who may otherwise be focused on responding to an existing wildfire threat. Having a common understanding of values at risk within the context of the wildfire operational environment will daylight the services provided by fire management, especially in multi-jurisdictional landscapes, that have historically lacked transparency between and among agencies and the public. Bridging these existing gaps could help address controversies around both aggressive suppression and managing fires for resource benefits, especially given the potential for good decisions to have bad outcomes. Collaborative forest management continues to expand across the American West, typically emphasizing forest management actions to promote ecosystem resilience in fire-prone SES (Spies *et al* 2014, Johnston *et al* 2018). Here we described a process of collaborative wildfire risk management that aligns fire suppression, management of wildfires for resource benefit, and non-wildfire mitigation activities to create synergy of expectations between society, land, and fire managers, so behaviors shift towards adaptive feedbacks that improve resilience of fire-prone SES in a rapidly changing fire environment.

Figure 5. Landscapes adjacent to urban areas may have limited containment opportunities (low connectivity and rating of potential control locations, high suppression difficulty, and significant values at risk (negative conditional net value change)). (A) This community resides adjacent to publicly owned lands that may be a source of risk to the community, but specific areas that challenge effective fire management are not limited to public lands and may be even more pronounced on private lands. (B) Dry-forest environments adjacent to communities may consist of multiple federal jurisdictions intermixed with a majority private-owned landscape. Cumulatively, these landscapes may be a source of risk to each other and the community, demonstrating the shared responsibility and stewardship of wildfire risk management. These maps help identify areas for targeted cross-boundary mitigation activities such as hazardous fuels treatments, including identification of partnerships for cohesive management of the threat of wildfires to communities. Similarly, these maps also inform land use policy and zoning regulations that can minimize growth into high risk areas without effective mitigation strategies such as hardening of homes and reduction of ember production and fire spread.

Acknowledgments

Conflict of Interest

The authors declare no conflicts of interest.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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