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Potential operational delineations: new horizons for proactive, risk-informed strategic land and fire management

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Abstract

Background: The PODs (potential operational delineations) concept is an adaptive framework for cross-boundary and collaborative land and fire management planning. Use of PODs is increasingly recognized as a best practice, and PODs are seeing growing interest from federal, state, local, tribal, and non-governmental organizations. Early evidence suggests PODs provide utility for planning, communication, coordination, prioritization, incident response strategy development, and fuels mitigation and forest restoration. Recent legislative action codifies the importance of PODs by devoting substantial financial resources to their expansion. The intent of this paper is to explore new horizons that would help land and fire management organizations better address risks and capitalize on opportunities. Specifically, we focus on how PODs are a natural platform for improvement related to two core elements of risk management: how we leverage preparation and foresight to better prepare for the future; and how we learn from the past to better understand and improve performance and its alignment with strategy.

Results: We organize our exploration of new horizons around three key areas, suggesting that PODs can enable climate-smart forest and fire management and planning, inform more agile and adaptive allocation of suppression resources, and enable risk-informed performance measurement. These efforts can be synergistic and self-reinforcing, and we argue that expanded application of PODs at local levels could enhance the performance of the broader wildland fire system. We provide rationales for each problem area and offer growth opportunities with attendant explanations and illustrations.

Conclusions: With commitment and careful effort, PODs can provide rich opportunities for innovation in both backward-looking evaluative and forward-looking anticipatory frameworks. In addition to continued improvement of core PODs elements, attention must be paid to being more inclusive and participatory in PODs planning, to building sufficient capacity to expand PODs applications in meaningful boundary spanning ways, to ensure their continuity and relevance over time through maintenance and updating, and to deliver necessary information to responders to inform the effective management of wildfires. Lastly, ongoing monitoring and evaluation of PODs and related initiatives is essential to support organizational learning and continual improvement.

Keywords: Planning, Risk, Boundary spanning, Climate change, Performance measurement, Prioritization, Incident response, Modeling, Technology transfer

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Resumen

Antecedentes: El concepto de Delineaciones de Operaciones Potenciales (PODs en idioma Inglés) es un marco conceptual adaptativo tendiente a romper barreras y realizar planificaciones de manejo colaborativo en el manejo de tierras y del fuego. El uso de los PODs está siendo paulatinamente reconocido como una buena práctica y se están viendo con un interés creciente por parte de las organizaciones federales, estatales, locales, tribales, y otras ONGs. Evidencias recientes sugieren que los PODs son de utilidad para el planeamiento, comunicación, coordinación, priorización, el desarrollo estratégico de respuestas a incidentes, y la mitigación de combustibles y restauración de bosques. Acciones recientes de legislación codifican la importancia de los PODs mediante la asignación de cuantiosos recursos para su expansión. El objetivo de este trabajo es explorar nuevos horizontes que podrían ayudar a las organizaciones de manejo de tierras y del fuego para afrontar de mejor manera los riesgos y capitalizar oportunidades. Específicamente, nos enfocamos sobre cómo los PODs sirven como plataformas naturales para el mejoramiento relacionado con dos elementos clave del manejo del riesgo: cómo aprovechamos la preparación y prevemos para alistarnos mejor para el futuro, y cómo aprendemos del pasado para entender mejor y mejorar la performance y su alineación con la estrategia.

Resultados: Organizamos nuestra exploración de nuevos horizontes alrededor de tres áreas claves, sugiriendo que los PODs pueden habilitar un manejo más inteligente y sostenible del bosque teniendo en cuenta el cambio climático y el planeamiento y manejo del fuego, informar de manera más ágil y adaptativa la ubicación de recursos para la supresión, y permitir medir la performance de la información del riesgo. Estos esfuerzos pueden ser sinergísticos y auto reforzantes, y argüimos que la expansión en la aplicación de los PODs a niveles locales puede mejorar la performance del amplio sistema de gestión de incendios. Proveemos los modelos racionales para cada área problemática y ofrecemos oportunidades de crecimiento y asistencia con explicaciones e ilustraciones.

Conclusiones: Con compromiso y cuidadosos esfuerzos, los PODs pueden proveer de ricas oportunidades para la innovación tanto en evaluaciones retrospectivas como en marcos anticipatorios a futuro. De manera adicional al continuo mejoramiento de los elementos centrales de los PODs, la atención debe ser puesta en ser más inclusivos y participativos en el planeamiento de los PODs, para construir suficiente capacidad como para expandir su aplicación en caminos que superen los límites para asegurar su continuidad y relevancia en el tiempo a través de su mantenimiento y actualizaciones, y para enviar la información necesaria a los respondientes para informarlos sobre el manejo efectivo de los incendios forestales. Por último, el monitoreo y evaluación constante de los PODs e iniciativas relacionadas es esencial para apoyar el aprendizaje organizacional y su continuo mejoramiento.

Background

In recent years a planning concept initially developed by the USDA Forest Service known as potential operational delineations, or PODs, has resulted in a more proactive approach to fire planning and management that can support risk-informed decisions (i.e., decision processes infused with insights from risk identification and assessment along with other salient information) and improve outcomes. The Infrastructure Investment and Jobs Act of 2021 codifies the importance of PODs, making available up to $100M for the Secretaries of Interior and Agriculture to conduct preplanning fire workshops that develop PODs and select potential control locations (PCLs) for fire containment (H.R. 3684 §40803(c)(7)). PODs strategically align with advanced fire analytics and risk analyses, integrate with forest and fire operations, provide a platform for a range of decision support applications, and can enhance design of fuels reduction and forest restoration treatments. Work to develop PODs over the next five years will ideally offer a channel for various actors to meaningfully engage and co-produce knowledge and will likely guide cross-boundary wildfire and fuels planning and management for the coming decades. Throughout this paper we will leverage examples of PODs in action in the western United States (US) to highlight key themes and concepts.

In its most basic form, a POD is a polygon or container whose boundaries are defined by features suitable for fire control (e.g., ridgetops and roads), and within which information on ecological conditions, fire risks, management opportunities, and strategic objectives can be summarized. PCLs that form the boundaries of PODs are typically identified in workshop settings by combining the expert knowledge of local fire managers with maps of fire control likelihood built by analyzing historical fire and landscape data. The PODs process is intentionally like the more ad-hoc process of an incident management team designing an operations strategy, by identifying management concerns and locations where management actions may be more effective. Two fundamental ideas to implementing the PODs planning framework are (1) working across physical boundaries by intentionally drawing PCLs according to fire management opportunities afforded by the landscape irrespective of jurisdictional boundaries, and (2) working across social boundaries by intentionally engaging with a broad range of landowners, partners, cooperators, and stakeholders to build shared understanding of fire management goals, challenges, and opportunities.

Groups of PODs are often integrated with quantitative wildfire risk assessments to identify strategic response categories that establish risk-informed objectives and strategic guideposts for fuels management and fire response. Risk assessments begin with identification of a set of highly valued resources and assets, consider how they may be impacted by fire, rate their importance, and then combine this information with models of fire likelihood and intensity (Scott et al. 2013; Thompson et al. 2015). These response category assignments are based on local management and policy context along with risk criteria (Thompson et al. 2016a). Three broad categories are often defined: "Protect" signify areas with potential for loss that management activities would work toward protecting. "Maintain" signify areas that offer the potential for ecological benefits from fire. "Restore" signify a middle ground that could fit into either protect or maintain depending on the characteristics of the incident, and where fuels treatment may be a necessary precursor to reintroducing fire. These strategic response categories are typically assigned to individual PODs, resulting in a mosaic of strategic response categories across a landscape, although in some cases much broader zones of common categories have been established (e.g., the Inyo National Forest Land Management Plan; USDA Forest Service 2019).

By identifying control opportunities and establishing objectives, PODs can accelerate the process of developing risk-informed incident response strategies. Furthermore, because PODs are developed collaboratively, they can improve the communication and coordination of decisions that affect multiple stakeholders. The aim is not to predetermine response decisions, but rather to simplify the decision space while accounting for flexibility in response to changing conditions—the context in which the fire is burning, including weather and resource availability, is incredibly important and should rightly guide local and time-sensitive decisions. Broadly speaking, the aims are to reduce uncertainties and dampen time pressures.

Recent experience on the Tonto National Forest nicely illustrates these planning concepts highlighting three wildfires from 2017 that spanned strategic response categories that the Forest managed for different risk-based strategic objectives: protection on the Highline Fire, restoration on the Pinal Fire, and maintenance on the Brooklyn Fire (Fig. 1). As discussed in Wei et al. (2018), wildfires in PODs identified as suitable for restoring or maintaining ecological conditions with fire may be managed more often with equally weighted protection and resource objectives resulting in less full perimeter control. In such cases response operations may focus more on utilization of existing features, construction of control features in areas of high PCLs, site-specific protection of vulnerable HVRAs, and tactical firing operations to secure these features in areas of low responder hazard. In part due to insights and lessons learned from early adopters like the Tonto National Forest, adoption of PODs has steadily grown to now include more than 60 landscapes encompassing National Forest System lands across the western US, working across boundaries and in coordination with other federal, state, local, and non-governmental organizations.

PODs can conceptually be embedded within an ecosystem of decision support products used for assessment, planning, fuels management, and incident response (Fig. 2). On the upper left – the primary focus of this paper – are assessment and planning tools that support identification of PODs and corresponding risk-informed strategic response categories. On the upper right are incident response tools, including the existing Wildland Fire Decision Support System (WFDSS; Noonan-Wright et al. 2011; Calkin et al. 2011) as well as emerging tools like the POD Atlas, a map-based product which summarizes a host of relevant information for each POD (Thompson et al. 2020) and the Risk Management Assistance program, a multi-year effort to improve the quality of risk analysis and decision making on many of the most complex, challenging, and high visibility fire events (Calkin et al. 2021). On the lower right are fuels management tools, including the existing Interagency Fuel Treatment Decision Support System (IFTDSS; Drury et al. 2016), as well as emerging tools that generate accurate spatial information quantifying delivered costs associated with treatment prescriptions (Hogland et al. 2018) and leverage the PODs framework to assign prescriptions and spatially prioritize treatment locations (Hogland et al. 2021). Future work in PODs may be able to complement and leverage other approaches to analyzing transmission risks and developing landscape treatment strategies such as firesheds (Bahro et al. 2007; Vaillant et al. 2011; Ager et al. 2015).

Scholarship on PODs has ranged from theoretical studies and hypothetical use cases to reviews and feedback from on-the-ground implementation (Table 1). These studies and experiences demonstrate that PODs can support adoption of more formal risk management processes as well as translation of plans into action. They also demonstrate the importance of learning in the development

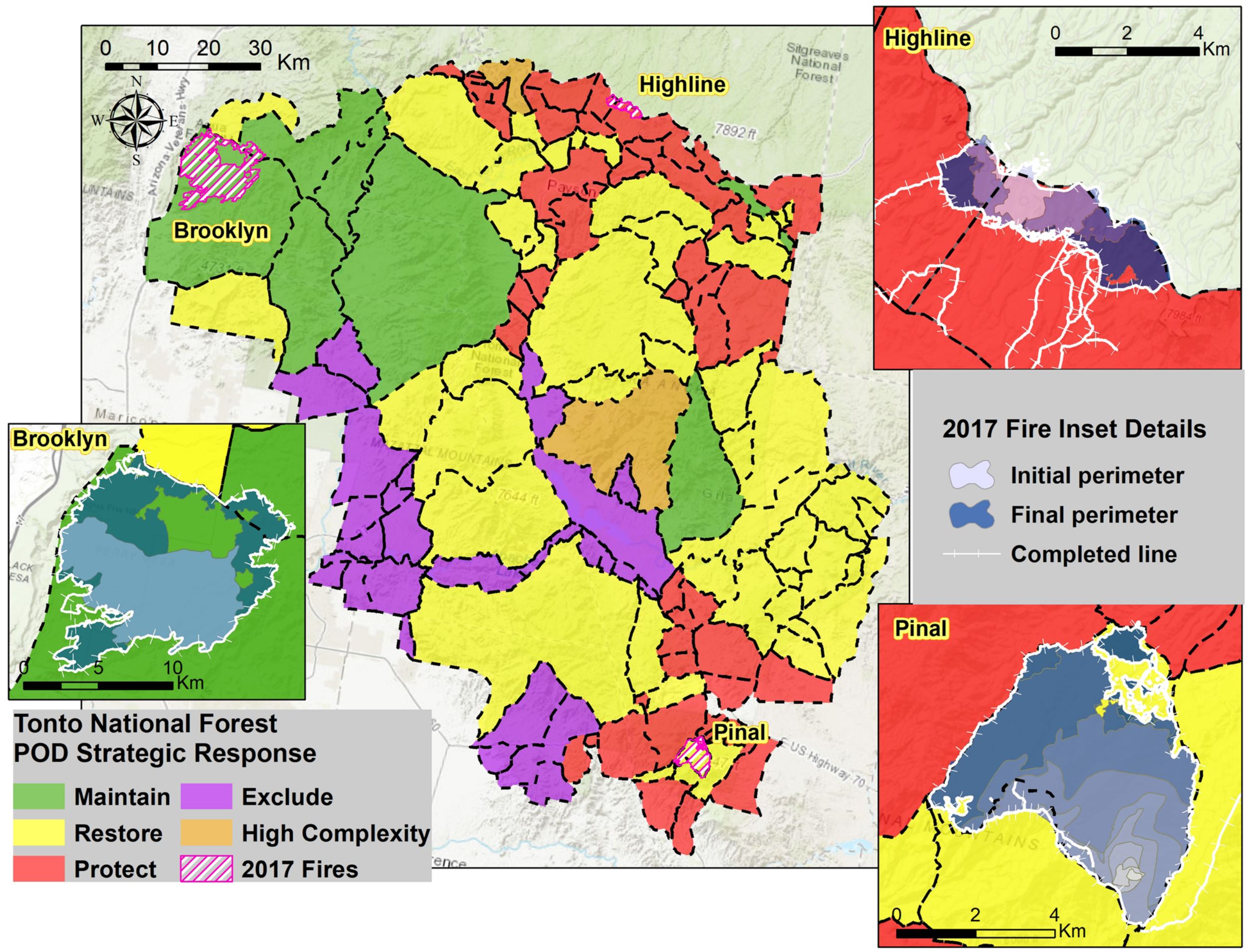

Fig. 1 Potential operational delineations (PODs) and risk-informed strategic response categories on the Tonto National Forest, along with the progression maps of three large wildfires and corresponding completed fire containment lines from 2017. "High Complexity" is a special case of the "Protect" designation reserved for PODs that should transition to "restore" once fuel treatments near susceptible infrastructure are completed. "Exclude" is unique to forests of the American Southwest and represents desert ecosystems not adapted to fire but where fire does not pose significant risk to human life or infrastructure. More information on these incidents is available on the PODs Story Map and in O'Connor and Calkin (2019)

of PODs, both in terms of investing time in inquiry and sharing lessons as well as exploring new avenues such as optimization and prioritization. Furthermore, PODs share a common set of objectives and analytics with the Forest Service's aforementioned Risk Management Assistance program, which brings people with the knowledge and skills to generate, distribute, and help end users interpret a variety of decision support products (Schultz et al. 2021, Calkin et al. 2021). The co-evolution and growth of PODs and Risk Management Assistance is ideally leading to increased understanding of their use by fuels and fire managers in the field.

Since its inception, the term "PODs" has evolved and expanded to become shorthand for a broader, adaptive framework of strategic fire management planning that is cross-boundary, collaborative, and designed to improve alignment between fire management and land management decisions. The physical PODs network of fire control polygons provides the operational context for a strategic risk-based approach to land management and incident management objectives informed by a collaboratively produced risk assessment. The conceptual framework enables mapping of pre-planned strategic incident response at landscape scales that reflect the challenges and opportunities for leveraging fire benefits where and when possible and guarding against fire damages where and when necessary. As an incident-level operational decision support tool, strategic fire management planning pre-positions a nearly complete catalog of highly valued resources and assets, including their

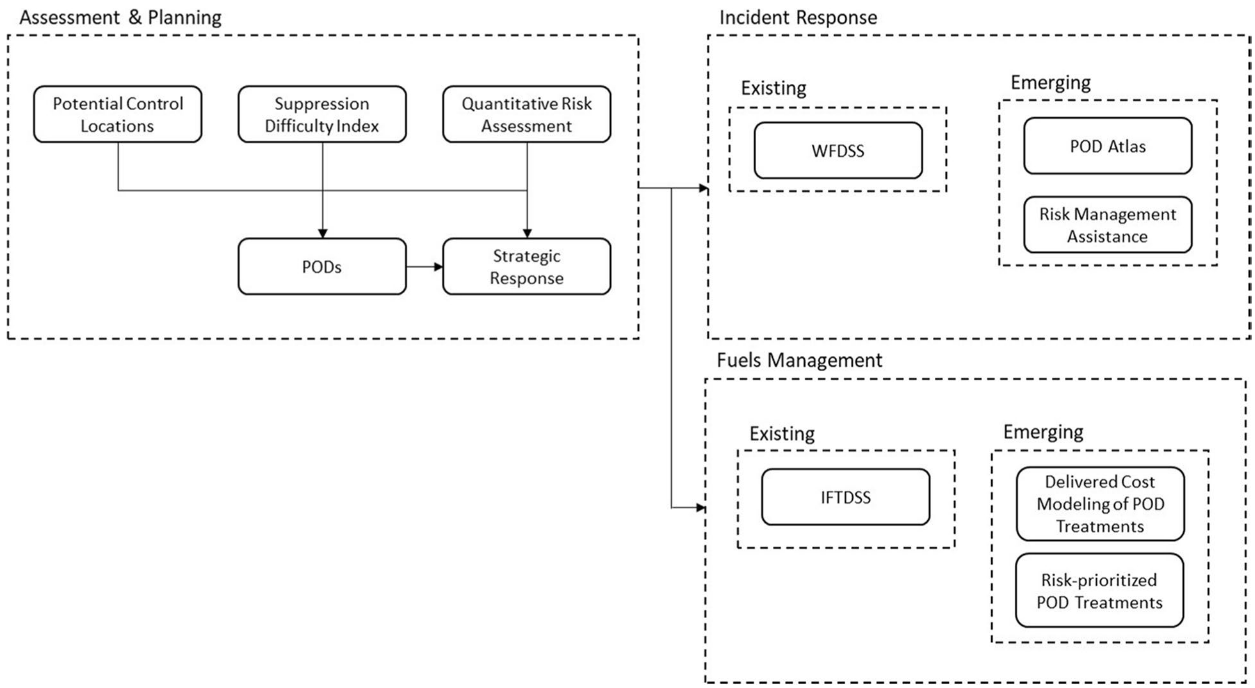

Fig. 2 Stylized depiction of decision support products related to PODs. WFDSS, Wildland Fire Decision Support System; IFTDSS, Interagency Fuel Treatment Decision Support System

Table 1 Key themes and focal areas of PODs and related risk analysis products, along with relevant publications

Key themes	Sub-themes	Sources
Guiding frameworks	Risk management; socioecological systems; boundary spanning	Davis et al. (2021), Dunn et al. (2017, 2020), Stratton (2020), Thompson et al. (2016a, b, 2018a, 2019)
Analytics, modeling, and planning	Fire control opportunity; suppression difficulty; responder hazard; fire impacts	Dunn et al. (2019), Gannon et al. (2020), O'Connor et al. (2016, 2017), Rodríguez y Silva et al. (2020), Thompson et al. (2016c, 2018b, 2020, 2021)
Optimization and prioritization	Values and objectives; forest and rangeland restoration; fuel treatment strategy; incident response strategy	Hogland et al. (2021), Metlen et al. (2021), Thompson et al. (2017), Wei et al. (2018, 2019, 2021), Wollstein et al. (2022)
Iterative improvement from user feedback	Practitioner feedback; incident summaries; informational documents and overviews; third-party assessment	Caggiano et al. (2019, 2020, 2021), Calkin et al. (2021), Greiner et al. (2020), O'Connor and Calkin (2019), Schultz et al. (2021)

relative susceptibility to fire, and a detailed network of vetted control features to assist with rapid, risk-informed development of response objectives. Pre-planned objectives are then augmented with additional information on forecast conditions, available resources, and other dynamic components to adjust the strategy to the specifics of the incident. PODs can therefore serve as a useful decision support tool when planned in advance of a fire and embed within broader conceptual frameworks for strategic wildfire management that address aspects of firefighting safety, landscape resilience, and social values (e.g., Castellnou et al. 2019).

The pre-positioned, mapped information can assist with information sharing, developing a common operating picture, and communicating fire management strategy internally and during public engagement before, during, and after a fire. The framework is rooted in risk management principles (e.g., addressing uncertainty, being proactive, and seeking out the best available information), blends advanced spatial fire modeling analytics with local expertise, emphasizes place-based engagement with local managers and stakeholders, co-produces actionable science-informed knowledge, and facilitates communication, coordination, and decision making across wildland fire and land management jurisdictions. Furthermore, PODs have emerged as useful boundary spanning objects and concepts (i.e., concrete objects such as maps that allow shared meaning and flexible interpretation, and notions that facilitate communication using a common vocabulary and shared meaning) that help bring more stakeholder voices to the table and more readily bridge ownership and disciplinary boundaries (Wyborn 2015; Davis et al. 2021).

At the time of this writing, the authors and partners are actively developing data standards and implementation plans, compiling emerging best practices, preparing a practitioner-oriented technical report, engaging in strategic workforce and capacity planning, and designing monitoring and evaluation workplans. The point of this paper is not to review all those ongoing or past efforts, but rather to highlight promising future directions for both research and management in the areas of adaptation, allocation, and performance. We provide citations to previous work for readers interested in more information, with additional links to the Wildfire Risk Management Science Team PODs page (https://www.fs.usda.gov/rmrs/groups/wildfire-risk-management-science-team/potential-operational-delineations-pods), the PODs Story Map (https://usfs.maps.arcgis.com/apps/Cascade/index.html?appid=073b66277b6540328f40b772dfab7c6f), and recordings from the PODs Collaborative Planning Workshop featuring manager testimonials (https://vimeo.com/showcase/8231822).

As the PODs concept has expanded into a boundary spanning and organizing framework for coordinated preparedness and response, and as analysts and practitioners have developed familiarity and insight, there are emerging opportunities to further enhance risk management acumen in the fuels and fire management community. Here, we focus on how PODs are a natural platform for improvement related to two core elements of risk management: how we leverage anticipation and foresight to better prepare for the future; and how we learn from the past to better understand and improve performance and its alignment with strategy.

These elements are reinforcing, in that building learning into adaptation strategies facilitates performance measurement, and in that better understanding factors driving performance facilitates more effective management in the face of an uncertain future. With these themes in mind, we organize the remainder of the paper around the following three areas, along the way offering brief rationales for each problem area and then offering key opportunities, with attendant explanations and illustrations:

1. Climate mitigation and adaptation
2. Agile and adaptive allocation of suppression resources
3. Risk-informed performance measurement

Climate mitigation and adaptation

Rationale

Climate change will present multiple challenges and changes for the wildland fire and land management community and calls for more proactive and adaptive management strategies (Hagmann et al. 2021, 2022; Hessburg et al. 2021; Prichard et al. 2021). Society is likely to see growing emphasis on fire management as part of a broader portfolio of nature-based climate solutions, in large part through increasing forest resilience to catastrophic fire and managing for forest carbon in a manner that accounts for fire risk dynamics (Fargione et al. 2018; Griscom et al. 2017). In the US, government policy now emphasizes climate-smart forestry practices that decrease wildfire risk fueled by climate change (White House 2021). The science underpinning that policy continues to emphasize restoring low-to-medium intensity fire regimes in frequent-fire forests, typically through mechanical thinning and prescribed burning as well as managing wildfires for resource benefits, to reduce the potential for high-severity wildfires and stabilize carbon in fire-prone forests (Krofcheck et al. 2018). Thus, in frequent-fire forests, climate mitigation (i.e., maintaining or increasing forests' ability to sequester carbon) and climate adaptation (i.e., maintaining forest ecological integrity in the face of climate change) overlap and can both be achieved simultaneously by prioritizing management activities that main low fire severity and the persistence of fire-resistance species and large fire-resistant individuals, which can in turn stabilize carbon stocks and storage capacity (Liang et al. 2018; Hurteau et al. 2019). In cases where intentional management of wildland fire is expected to maintain carbon stability, PODs provide a basis for identifying the most beneficial places to reintroduce fire grounded in operational relevance.

As we use it here, climate-smart fire management includes not only strategies that manage for carbon into a changing future but also strategies that grapple with the inevitable increases in fire activity and loss of forest area expected with climate change and the resulting challenges for fire response (Coop et al. 2020; Davis et al. 2019; Parks et al. 2019). To alter forest structure or composition to reduce the risk, severity, or extent of wildfire, the scholarship calls for treatment prioritization systems and new "pyrosilviculture" paradigms that manage to optimize future fire incorporation (Ager et al. 2021; North et al. 2021). Because the PODs framework intentionally integrates and summarizes results of wildfire risk assessments (see Fig. 1), PODs are a logical platform for treatment prioritization under this paradigm (Thompson et al. 2017; Hogland et al. 2021). PODs also facilitate landscape-scale prioritization to mitigate risks and maintain desired conditions with prescribed fire and other fuel treatments.

The potential of the PODs framework lies in integrating pre-season planning for both land management and fire response, recognizing the inevitability of fire as part of a land management strategy, and intentionally adopting risk principles and a systematic approach to asking forward-looking questions about possibilities, probabilities, and options. Strategies might incorporate fire response options under a range of future conditions as well as land management activities. In other words, PODs can enable more risk-informed scenario analysis, and by leveraging insight from enhanced performance evaluation can forecast the likely efficacy of alternative management strategies under different futures.

Key opportunities

We propose that PODs and associated risk analysis products can help enhance climate adaptation and mitigation strategies in the following areas:

1. Providing a planning framework to align climate-smart forest and fire management goals in an integrated strategy
2. Operationalizing these goals in land and fire management contexts

PODs and corresponding risk analysis products can help to strategically align forest management and fire response activities in an integrated planning framework (Table 2). Information is broken down according to pre-fire land management and fire response phases. In both cases, PODs and PCLs provide the spatial foundation for identifying opportunities for implementation, while strategic response categories, which integrate risk assessments, establish strategic priorities and objectives against which performance can be evaluated. One key opportunity lies in supporting the return of fire to fire-adapted systems through prescribed fires and reducing the likelihood and occurrence of large, severe wildfires. This can be done by integrating forest management activities before and during fires to reduce fuels in particular PODs based on risk assessments (Caggiano et al. 2020) and strategically designing and implementing fuelbreak networks to enhance control likelihood (Hersey and Barros 2022). Done effectively, the collaborative, cross-boundary approach of PODs can not only engender broader stakeholder support for developing programs of work to restore fire-adapted ecosystems, but it can also facilitate cross-boundary implementation. The last row of Table 2 points to likely adaptive shifts in incident strategies and tactics in the face of increased extreme fire behavior and exacerbated response hazard. Climate adaptive strategies will need to grapple with the growing prevalence of extreme fire behavior that severely degrades suppression

Table 2 Illustrative crosswalk from climate mitigation and adaptation strategies to PODs frameworks, in both planning and response contexts. Strategies partially adapted from Ontl et al. (2020)

Climate mitigation and adaptation goal	Relevance to PODs framework	
	Pre-fire planning and land management activities	**Fire response activities**
Restore or maintain beneficial fire in fire-adapted ecosystems and reduce likelihood of state transition	Define "restore" and "maintain" strategic response categories to identify needs and opportunities for prescribed and managed wildfire Use PODs and PCLs to define areas for thinning and prescribed burning to restore natural fuel profiles	Use PODs and strategic response categories to establish incident objectives Manage wildfire within PODs to attain desired fire effects Leverage PODs and PCLs in fire operations
Reduce the likelihood, severity, or extent of extreme wildfire	Use PODs and strategic response categories to define landscape fuel treatment priorities Implement treatments in PODs where they are likely to affect fire behavior, strengthen PCLs, or support incident response Design fuelbreak system and treatment needs based on PODs and PCLs	Use PCLs and treated areas for control opportunities Harden existing fuelbreaks with vegetation management
Adapt incident response to more extreme fire conditions and exacerbated hazard to fire personnel	Identify PODs with potential for extreme fire behavior or exacerbated responder hazard Identify POD boundaries and interior PCLs that are suitable for indirect operations Pre-identify or create suitable safety zones through fuels management Harden PCLs and travel routes to support fire personnel egress	Switch to indirect response operations when direct operations are likely to be ineffective or results in unacceptable responder hazard Leverage treated areas for control opportunities, as well as lookouts, safety zones, and escape routes

effectiveness and presents substantial hazards to fire personnel (Tedim et al. 2018). A growing suite of decision support tools focused on fire personnel safety provide actionable information to assess the risks and opportunities of alternative tactics, including hazards associated with snags, egress, and potential safety zones (Dunn et al. 2019; Campbell et al. 2019; Campbell et al. 2022), many of which are now provided through the Risk Management Assistance program and can be integrated with PODs. As one example looking ahead, increased fire activity may lead to greater standing dead tree densities, resulting in increased hazard to personnel. Another growing concern is that extreme fire behavior may be poorly captured in existing operational fire behavior models (Stephens et al. 2022) as well as in PCL models built from historical fires (O'Connor et al. 2017). By exploring extreme and worst-case scenarios, PODs workshops can ideally move beyond the limitations of modeling to capture more recent operational experiences and expectations or concerns. Furthermore, as operational tools PODs and predefined PCLs provide vetted opportunities for conducting indirect operations safely and effectively when conditions necessitate tactics other than direct attack. A coherent system of PODs can be used during incident management in tandem with incident-specific fire weather forecasts to determine which PODs and PCLs are most suitable.

POD-based planning can support the restoration and maintenance of fire in fire-adapted systems (Fig. 3). Here we provide information from the 2019 fire year on the Santa Fe and Carson National Forests in New Mexico, USA, where local managers had collaboratively developed PODs and strategic response categories and used an atlas summarizing critical information for each POD as decision support (Thompson et al. 2020; Gannon et al. 2021; Caggiano and Brown 2020). Six of the seven wildfires occurred in PODs with strategic response categories where prior assessment and planning had determined that fire under the right conditions could be used to restore desired ecological conditions and lead to resource benefits. POD-related information proved beneficial for several purposes, including gaining rapid situational awareness, streamlining communication between local staff, the incident management team, and the public, and determining incident strategies and objectives (Caggiano et al. 2020). Operational examples of POD and PCL use on these fires include defining planning areas within the Wildland Fire Decision Support System, using POD boundaries as primary control features along portions of the fire perimeter, and constructing control lines along interior PCLs such as existing roads and trails. O'Connor and Calkin (2019) describe a similar example from the Tonto National Forest, Arizona, USA, where predetermined PODs informed decisions to manage wildfires for ecosystem and hazard reduction benefits. Pre-identifying similar strategies in other landscapes and building the culture to manage fire for resource benefit under the right conditions could meaningfully increase the pace of fuels reduction and forest restoration.

To explain our second proposition, that PODs support operationalization of climate adaption and mitigation goals, we discuss the use of PODs on the Arapaho-Roosevelt National Forest in Colorado, US (Fig. 4). The photos provide several examples of forest and fire operations building or improving fuel breaks on the Cameron Peak Fire, where managers were able to leverage POD boundaries to strategically locate indirect and contingency lines. Identifying suitable control features was paramount as high winds and extreme fire behavior, along with heightened firefighter hazard from extensive insect-cause tree mortality, rendered direct tactics ineffective in many instances. Although local managers had begun using PODs to inform treatment planning and prioritization, implementation had not occurred before the Cameron Peak Fire. Future post-fire hazard tree removal and fuels projects may be prioritized along POD boundaries to strengthen them. In addition to addressing near-term wildfire response objectives, all these activities expand opportunities to anchor burning and wildfire suppression operations in the future (Caggiano et al. 2021). Looking forward, local managers on the Arapaho-Roosevelt National Forest have begun to leverage PODs for conceptual development of landscape scale treatment strategies (Fig. 5). In this case, the objective is to create a north-south ribbon of large treatments spanning multiple high-priority PODs that can interrupt the predominant west-to-east direction of large fire spread.

These cases present ample research opportunities, including optimally designing fuel management strategies including fuel break networks along POD boundaries, optimally scheduling prescribed fire operations within PODs, and assessing the effectiveness of suppression operations in containing a wildfire along PCLs based on PCL attributes, resource allocation, topography, and weather conditions. It also demonstrates there is much to be learned about how PODs can inform fuels treatments and how this will affect fire response. Future research should more fully explore the linkages between planning, management activities, and fire response with PODs.

Agile and adaptive allocation of suppression resources

Rationale

In addition to incorporating mitigation and adaptation into fire management strategies, another growing emphasis area will be addressing how climate change

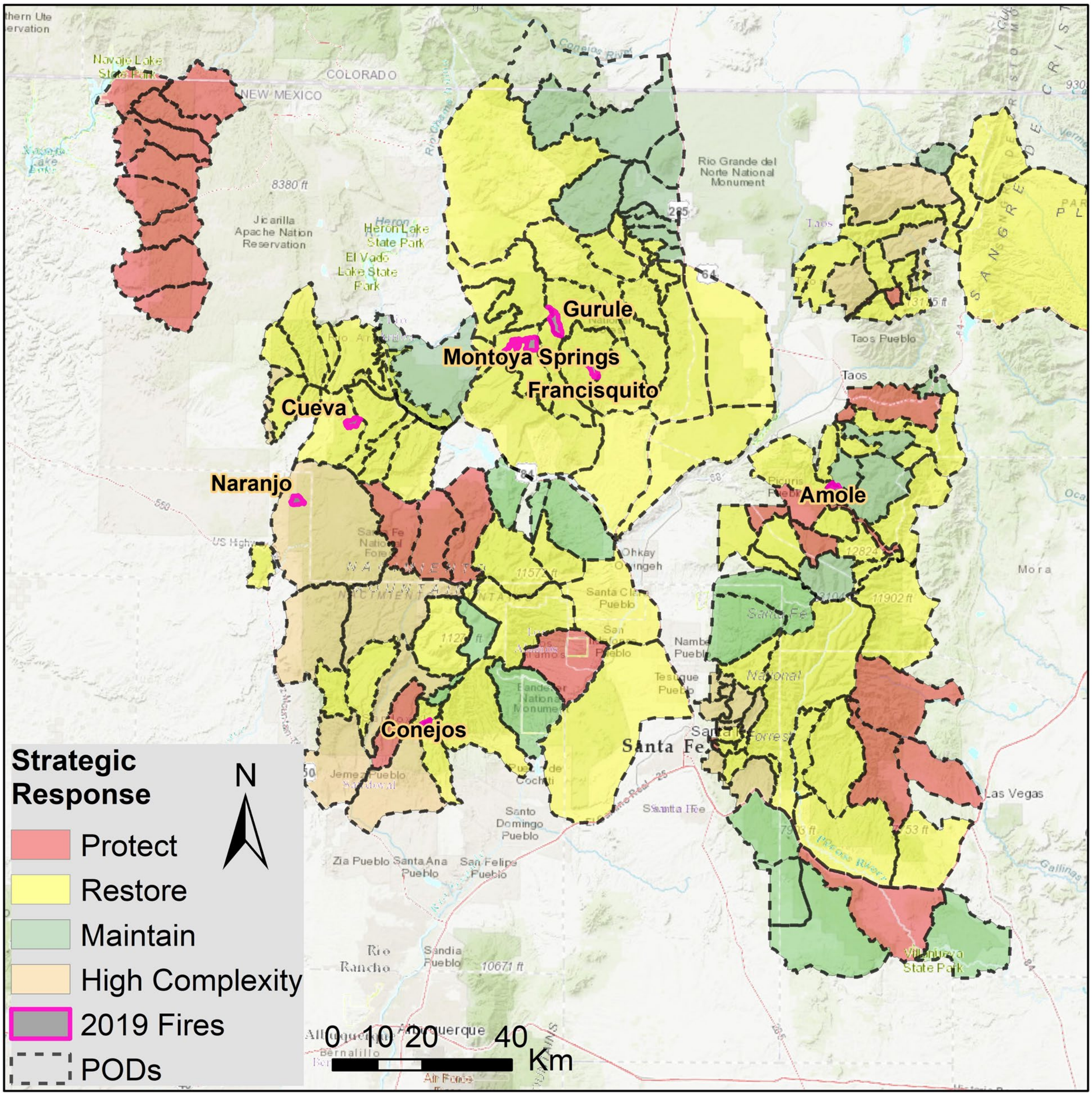

Fig. 3 Locations of seven wildfires in relation to PODs on the Santa Fe and Carson National Forests in 2019, many of which were managed to achieve resource benefits and risk reduction. From Caggiano et al. (2020)

and synchronous fire activity will affect the function of the wildland fire system (Abatzoglou et al. 2021). It is becoming more and more evident that this system is showing signs of strain, calling greater attention to the efficiency of suppression resource allocation and use. Increasing fire activity and challenges with recruitment and retention, among other factors, have led to greater resource scarcity and greater workloads, which can result in unfilled resource requests and missed opportunities for achieving management objectives as well as fatigue and burnout (US Forest Service 2021; Belval et al. 2020). Anticipating increased fire response workloads coupled with more extreme conditions, it is not just a question of more response resources, but also a question of deploying them more intelligently and efficiently (Thompson and Belval 2021).

In addition to information on local and forecasted conditions, how managers arrive at and implement

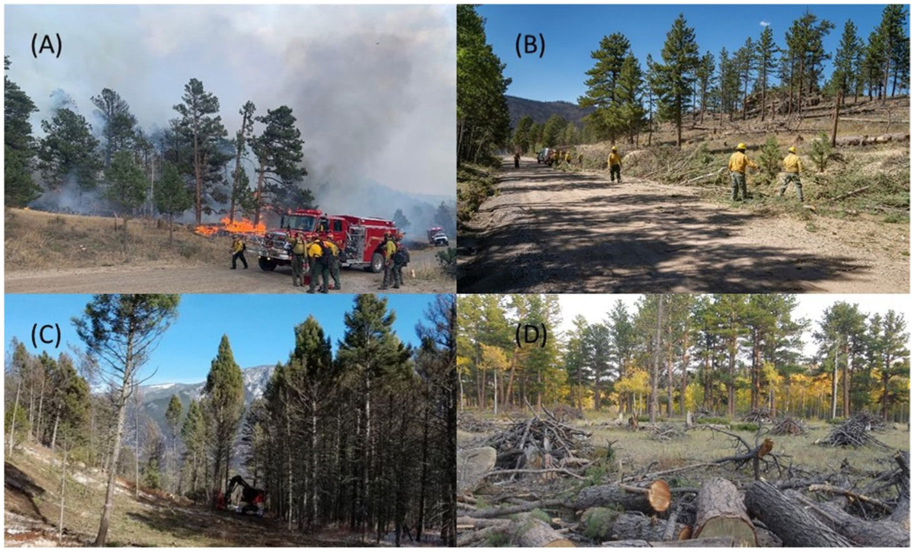

Fig. 4 Various forms of fire and forest operations associated with roads and fuelbreaks on the Cameron Peak Fire in Colorado, USA. Photos from InciWeb (inciweb.nwcg.gov). Panel **A** shows active fire operations, specifically fire personnel conducting a burnout operation from a forest road into an area that was previously treated with mechanical thinning. Panels **B**–**D** by contrast show equipment and personnel performing preparatory work to enhance control likelihood. Panel **B** shows roadside brushing operations, panel **C** shows a fuelbreak being cleared by a feller-buncher, and panel **D** shows piles of cut trees from an operation creating a fuelbreak near a forest road to serve as a contingency line

wildfire response strategies can be highly dependent on the availability of suppression resources. These resources are moved around the country by regional and national coordinating centers in response to demand and priority. During periods with high levels of fire activity, there may not be enough trained personnel and equipment to go around, forcing regional and national managers to make hard decisions about which fires get resources and which do not. Examining the tradeoffs associated with these resource assignments is critically important. In recent years, the use of PODs and Risk Management Assistance has increased, as have pilot efforts supporting situational awareness and prioritization at Multi-Agency Coordinating Centers, suggesting promise for improved system efficiency (Belval et al. 2022; Calkin et al. 2021).

Key Opportunities

We propose that pre-fire planning with PODs, rapid assessment of fire response options from the Risk Management Assistance program, and their common set of analytical and decision support products can enhance performance of the wildland fire system through:

1. Prioritizing across multiple wildfire events
2. Developing more agile, right-sized, and right-timed deployments of fire management personnel and equipment

Improved analytics can provide managers with information on projected fire impacts and opportunities for containment in the coming days, using unbiased and objective methods that allow managers to directly compare across incidents. Thus, analytics that better characterize risks and opportunities are valuable because they allow for more robust and complete tradeoff analyses. The analytics underpinning PODs meet many of these informational needs, including pre-season analyses spanning a range of scenarios, but oftentimes managers will request results with higher precision or tailored to unfolding conditions. Hence similar analyses within projected growth areas, currently provided through the Risk Management Assistance program, can increase information utility for incident decision making. Table 3 illustrates categories of information from fire modeling, risk assessment, and analytics that were delivered to regional and national coordination centers via Risk Management Assistance in 2021 to facilitate comparisons and inform prioritization across wildfire incidents.

It is conceivable that more refined information at the POD- rather than incident-level could streamline and simplify time-pressured, high-stakes prioritization efforts. A range of information can be summarized for each POD within atlas-based decision support tools, like what was described earlier for the Santa Fe and Carson National Forests (Fig. 6) Thompson et al. 2020; Gannon et al. 2021). Such products can provide a quick estimate

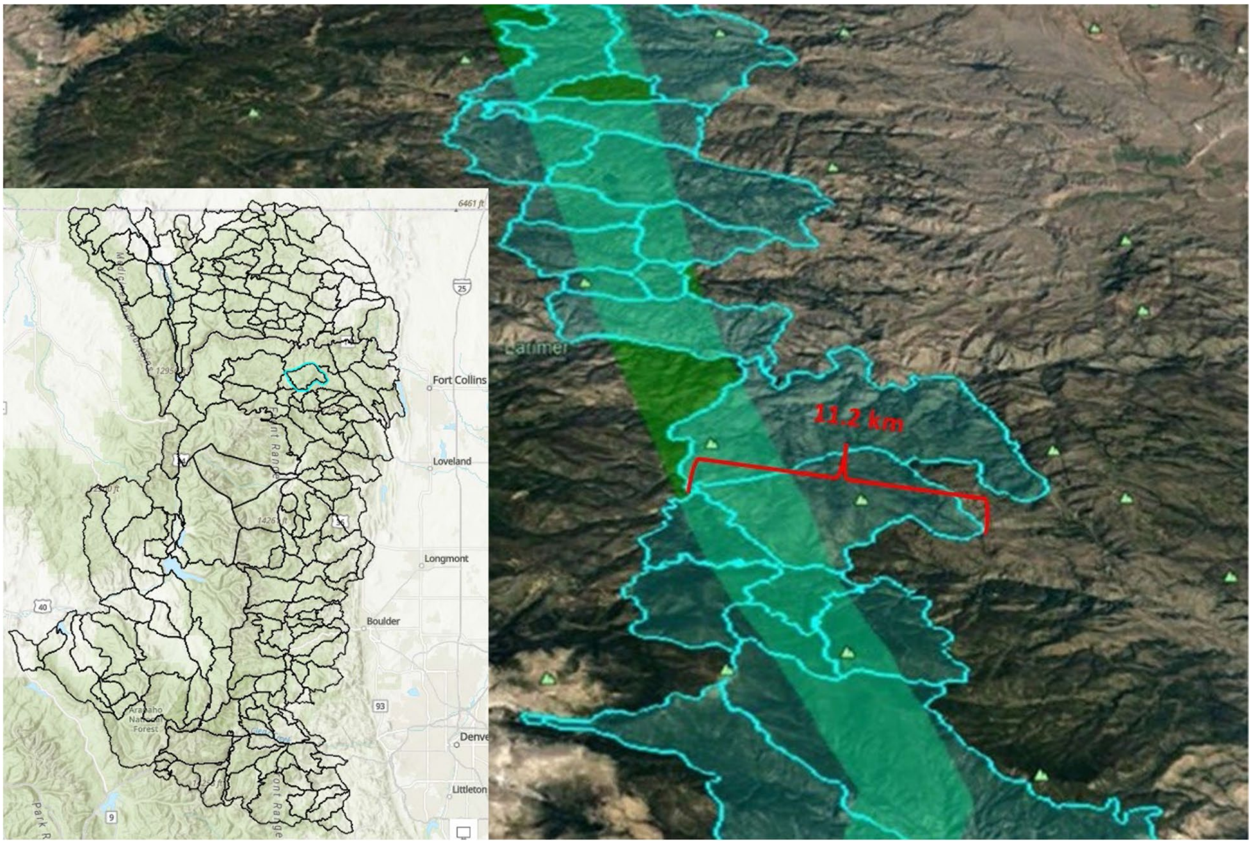

Fig. 5 Highlighted PODs intersecting a conceptual north-south "ribbon" of strategically connected fuel treatments that intercept predominant fire spread patterns to reduce fire intensity and enhance containment opportunity, on the Arapaho-Roosevelt National Forest and surrounding ownerships. Image from Monte Williams. Inset shows the broader POD network across the landscape; the blue highlighted POD on the left corresponds to the POD on the right with the length identified for scale

Table 3 Risk information compiled and delivered to key decision makers at regional and national coordination centers to support prioritization. Elements with asterisks correspond to common elements embedded within POD-based assessment and planning processes

Categories	Data and analytics
Basic information	Incident name Geographic area
Wildfire risk	Fire growth potential Housing and population* Municipal water supplies* Critical infrastructure* Major roads*
Control opportunity	Suppression difficulty index* Potential control location*
Responder safety	Suppression difficulty index* Snag hazard* Ground evacuation time*

of what HVRAs could be exposed as the fire grows as well as identify control opportunities and resource needs. Real-time fire modeling quantifying the probability of fire reaching different PODs could be coupled with information on HVRA impacts along with attributes such as fuel type and length of intended control features to estimate necessary resource allocations, probability of success, and time horizons.

In addition to prioritization, effective functioning of the wildfire system is premised on timely mobilization and deployment of shared resources to meet the time-sensitive demands of local managers so they can implement their preferred strategies. Because there is a lag between when the personnel are ordered to the fire and when they arrive, basing deployment decisions on projected fire impacts and opportunities not only provides for more robust decisions, but it also allows personnel to arrive in the right place at the right time to capitalize on containment opportunities. Reducing the lag between when resources are ordered to a fire and when they arrive can have substantial benefits, and fire analytics could

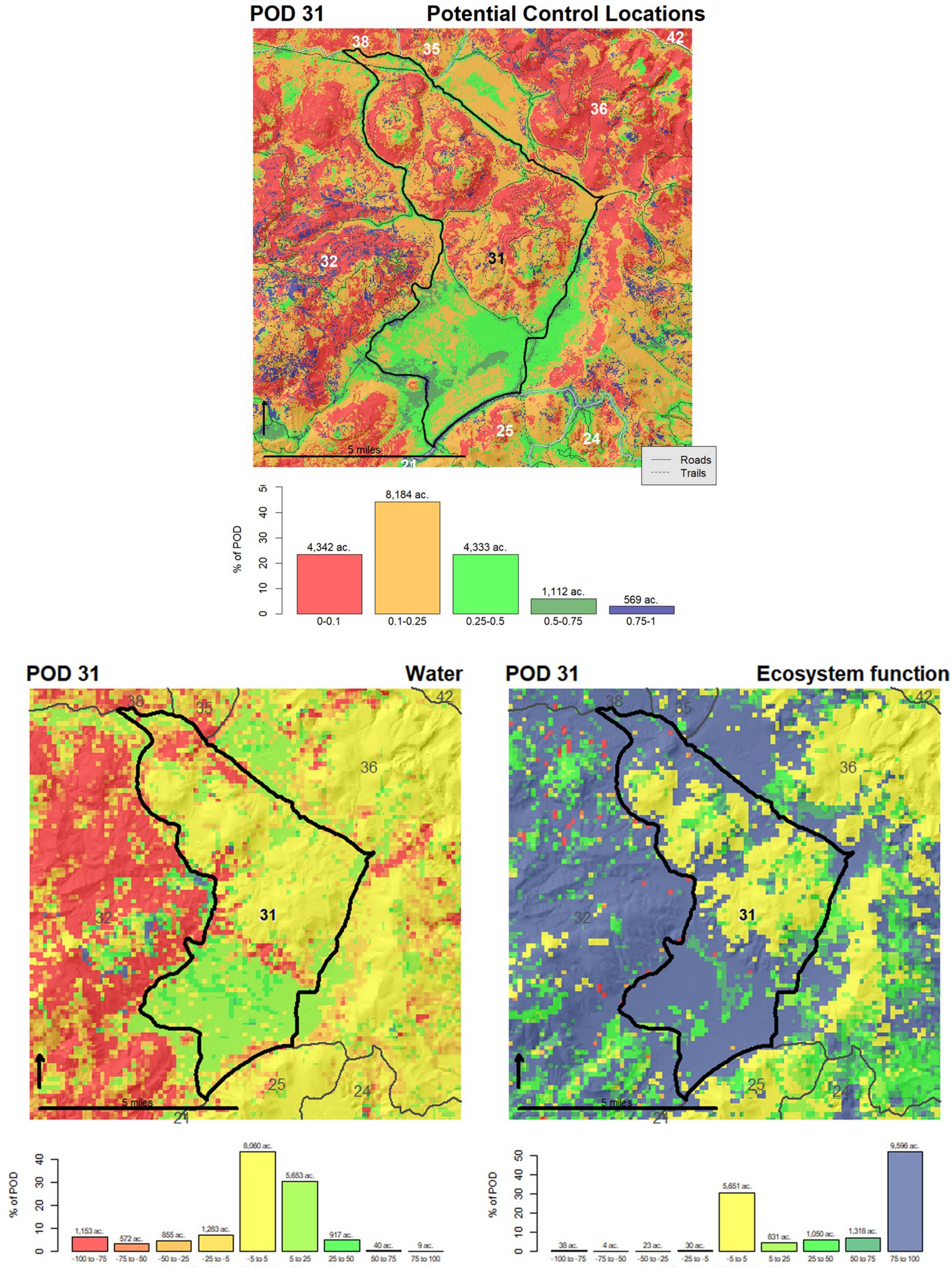

Fig. 6 Examples of POD summaries that provide quick estimates of control opportunities (top panel) and risk to resources and assets (bottom panel) that can inform fire management resource needs

help here by supporting more intelligent routing and prepositioning of resources as well as meeting time-sensitive surge capacity needs.

Furthermore, using analytics to "right size" deployments that best align strategic and tactical needs with resource capabilities can help improve likelihood of success while preserving capacity to meet other continuing or emerging needs. PODs and related risk analysis products could support more right-sized, right-time, and agile resource deployments. For example, in the response planning phase managers could identify a target fire management organization and expected time horizon to burn a POD. Similarly, in the incident response phase managers could leverage information on containment opportunities and needed resources to document and justify a surge capacity request, or they could tactically redirect resources away from point protection to capitalize on a window of opportunity for containment. At higher levels, managers at national and regional coordinating centers could leverage weather forecasting and analytics to identify times and places where bolstering resources to capitalize on a period of high probability of containment would justify temporarily diverting resources from other incidents where near-term conditions suggest greater firefighter exposure or lower containment probability.

Risk-informed performance measurement

Rationale

Meaningful performance measurement in wildfire management and forest restoration has been a persistent challenge, related to a range of issues including bureaucratic incentives, competing or incomplete problem definitions, difficulties accounting for uncertainty, data availability and quality, knowledge gaps, limited analytical capabilities, and the challenge of measuring outputs and outcomes (Schultz et al. 2015; GAO 2015; Thompson et al. 2018a, b; Wise 2022). These issues can interact with other decision biases and heuristics, lead to misaligned incentives, restrict opportunities to learn, and present challenges to evaluation of the effectiveness of restoration activities, fuels mitigation, and fire response operations. Improving performance measurement during fire response is gaining salience as wildfire activity and management are growing in complexity, and as recent legislation provides an infusion of money and resource to address wildfire risk while requiring effectiveness monitoring and reporting (Public Law 115-141 Section 104).

PODs and corresponding strategic response categories enable nuanced approaches to performance measurement based on alignment of decisions, actions, and outcomes with strategic response objectives. In large part this is because PODs are already established as essential elements to support risk-informed planning and incident response decision-making. Here we argue further that strategic response categories—and the processes of risk assessment and objective setting that generate them—can facilitate both generation and interpretation of risk-informed, objective-based performance measures.

Key opportunities

We propose that PODs and their respective strategic response classifications can enhance monitoring and evaluating performance in the following areas:

1. Adjustment of management objectives by tracking risk trajectories over time, including changes in risk that are both within and outside of the scope of managerial control
2. Defining and interpreting risk-informed performance measures that speak to restoration, fuels mitigation, and fire response operations

PODs and strategic response maps for the Tonto National Forest, AZ, USA, can be assessed over two different time periods, with key changes highlighted in ovals (Fig. 7). Although tracking risk dynamics over time was always a key design element of the risk assessment process, embedding strategic response updates can expand the management questions of "how and why have conditions and risks changed" to include "how and why do those changes *affect our strategic management objectives*." Transitions from "protect" to "restore" or from "restore" to "maintain" are generally considered desirable and reflect an expected improvement in ecological condition and resilience to future fire. Some strategic responses however may remain in the "protect" category despite significant investments in prevention and mitigation, because of factors such as mixed ownership and the presence of homes, critical infrastructure, or other fire-sensitive resources and assets that necessitate an emphasis on fire suppression. Other strategic response categories may downgrade to "protect" due to factors such as worsening fuel hazard that has not been mitigated or expanded development of human assets. These issues highlight the critical importance of consideration of factors that managers can and cannot change, such that change of strategic response may be limited in its application as a performance measure, particularly at the national level, or may instead be used more for updating strategic objectives or identifying priorities locally through time.

Although tracking changes in strategic response category as a performance measure is complicated by scope of control, the categories themselves present a logical framework for defining and tailoring performance measures. Strategic response categories can be aligned with conditions, management emphases and objectives, and

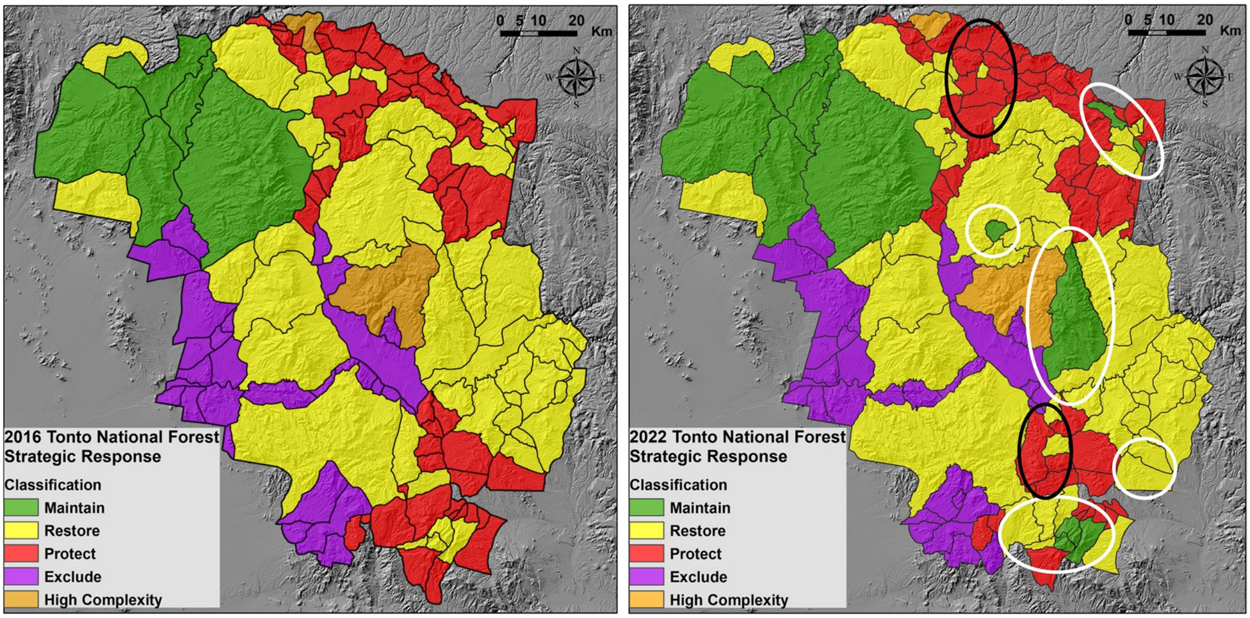

Fig. 7 Tracking risk through time with quantitative wildfire risk assessment and updating strategic response categories. Black ovals indicate where potential for loss has increased, whereas white ovals indicate where potential for benefit has increased. High Complexity and Exclude categories were defined by the Tonto National Forests for locally specific reasons, noted in Fig. 1 and in O'Connor and Calkin (2019)

performance measures for both land management (i.e., restoration and fuels mitigation) and fire management (i.e., incident response) (Table 4). For example, initial attack success may be emphasized in response categories with asset protection objectives, whereas increasing area burned may be emphasized in strategic response categories with land and resource management objectives. Strategic response categories and management emphases can also daylight temporal tradeoffs—for instance in protect zones the risk management strategy may avoid short-term losses at the expense of transferring risk to the future, whereas in restore and maintain zones incorporation of unplanned wildfire is more accepting of short-term risks for long-term risk reduction.

Lastly, strategic response categories provide an informative lens to better interpret existing performance measures on operational effectiveness of built fireline. Here the framework expands beyond area treatment targets to include length-based measures for POD boundaries hardened by treating along potential control locations to dampen transmission potential and facilitate containment. The basic premise is that such mitigations would be reflected in frameworks that evaluate fireline effectiveness based on how much fireline was built in relation to the final fire perimeter and how much of this line either held, never engaged the fire, or burned over (Thompson et al. 2016c, 2018b). Furthermore, the expectation is that fireline construction and performance are influenced by factors affecting suppression effort, such as proximity to vulnerable assets (Gannon et al. 2020). Two primary metrics of fireline effectiveness (Tr, the ratio of the total amount of fireline to final fire perimeter, and HTr, the ratio of the amount of held fireline to total amount of fireline) can be contrasted in terms of interpretations and expectations for "protect" versus "maintain" strategic response categories (Table 5). In protection categories, it may be reasonable to expect higher rates of line construction (high Tr) to afford as many containment opportunities as possible. It may also be reasonable to expect construction of some lines with a relatively low likelihood of success but high payout if successful in terms of avoided loss (low HTr). By contrast, in maintenance zones, it may be reasonable to expect lower rates of line construction (low Tr) that capitalize on areas with a high likelihood of containment (high HTr).

Observations of fireline performance do tend to align with expected variation on the basis of strategic response (Table 6) using historical examples from the Tonto National Forest (see containment line identified in Fig. 1). The Highline Fire was in a protect zone and had by far the highest Tr and the lowest HTr. By contrast, the Brooklyn Fire was in a maintain zone and had the lowest Tr and the highest HTr. The Pinal Fire was in a restore zone and is included as a benchmark. While taking care to emphasize

Table 4 The three main categories of POD strategic response, their typical risk profiles, management activities emphasized, and potential risk-informed performance measures

Strategic response category	Typical area characteristics	Management emphases	Potential performance measures	
			Land management	Fire management
Protect	Resources and assets at high risk of loss from wildfire (e.g., homes, infrastructure, municipal watersheds, critical wildlife habitat)	Fire prevention and suppression, reduction of hazardous fuels, proactive protection of built assets, post-fire recovery	Fuels mitigation treatment area targets Hardening POD boundaries with length-based targets	Initial attack success Fireline effectiveness
Restore	Resources and assets under moderate risk of loss to wildfire, or potential for beneficial fire	Mitigation of risk to key resources and assets via fuel treatment, hardening of POD boundaries, use of prescribed fire to maintain desired conditions, modified suppression response allowing for wildfire to maintain ecosystem resilience and provide ecological benefits	Fuels mitigation treatment, forest restoration, and prescribed burn area targets Hardening POD boundaries with length-based targets	Balance initial attack and wildfire area burned targets based on conditions Fireline effectiveness
Maintain	Resources and assets under low risk of loss to wildfire, with many expected to benefit from fire	Use of prescribed fire to maintain desired conditions, modified suppression response allowing for wildfire to maintain ecosystem resilience and provide ecological benefits	Prescribed burn area targets Hardening POD boundaries with length-based targets	Attainment of wildfire area burned targets Fireline effectiveness

Table 5 Summary of three primary metrics developed to calculate fireline effectiveness, across two contrasting strategic response categories, with possible interpretations and explanations

Effectiveness metric	Protect strategic response	Maintain strategic response
Tr *Ratio of total amount of fireline to final fire perimeter*	• Tr ≥ 1 • Suppression strategy full perimeter control • Significant amount of fireline burned over • Significant amount of indirect or contingency line that never engaged fire	• Tr < 1 • Suppression strategy not full perimeter control
HTr *Ratio of amount of held (successfully engaged) fireline to total amount of fireline*	• HTr << 1 • Engaged fireline not effective in all locations	• HTr ≤ 1 • Engaged fireline generally more effective

Table 6 Strategic response category and fireline effectiveness analysis for three historical wildfires on the Tonto National Forest, calculated using the fire perimeter and fireline data shown in Fig. 1

Incident	Strategic response	Tr	HTr
Highline	Protect	2.97	0.36
Pinal	Restore	1.17	0.83
Brooklyn	Maintain	0.75	0.9

that the idea here is to track patterns of performance over broad spatial and temporal scales rather than isolating individual incidents, this example does provide some real-world grounding to the logic of how interpretations of fireline effectiveness vary with risk and strategic response designation in ways that can be anticipated.

Discussion

Through a combination of conceptual strategic frameworks and real-world examples, we have demonstrated the potential value of PODs to support wildfire preparedness and response as well as fuels mitigation and forest restoration. A key argument here is that PODs can provide rich opportunities for innovation in both backward-looking evaluative and forward-looking anticipatory frameworks, by leveraging place-based collaboration, science-driven analytics, and risk management principles. We argue that PODs help us prepare for the future by facilitating more informed and adaptive wildfire management strategies and help us learn from the past by providing a logical platform for nuanced performance measurement clearly linked to locally defined fire management objectives. Key aspects of the PODs concept include (1) instilling boundary spanning and anticipatory lenses into wildfire planning efforts; (2) stressing monitoring, learning, and improvement of best practices; (3) co-producing knowledge and infusing analytics with expert knowledge; and (4) delineating fire management and analysis units in ways that are relevant to fire containment operations by linking features like roads, water bodies, and fuel type transitions.

Three salient areas of opportunity for PODs highlighted in this paper are supporting climate-smart forest and fire management and planning, informing more agile and adaptive allocation of suppression resources, and enabling risk-informed performance measurement. These efforts can be synergistic, as the presence of robust plans and decision support can for example support timely identification and communication of incident resource capacity needs, which in turn can support effective response, which in turn will be captured in next-generation performance measures. Similarly, effective assessment and planning based on risks and control opportunity can inform development of fuel break networks and strategic containment units that facilitate both intentional restoration of beneficial wildland fire as well as containment efforts to slow the spread of undesired fire. In sum, enhanced performance of the wildland fire system is premised in large part on enhancements in planning capacity and capability at local levels, and we believe PODs can play an important role in this space.

PODs are by no means a panacea and real challenges remain. The pace and scale of environmental, social, and organizational change is leading to ever more extreme wildfire behavior and consequences. Within this environment, we will likely continue to experience increased negative outcomes even where planned mitigation efforts and response strategies are well organized and based on the best available science. The PODs planning framework is no exception. We outline some potential pitfalls, broken down by thematic area with a description of potential failure modes (Table 7). Some of the themes relate to social aspects of the collaborative process planning process, and lessons learned from previous studies have found that a dedicated and coordinated effort is essential (Greiner et al. 2020; Caggiano 2019) and recommend following the best principles for collaborative engagement and stakeholder involvement to ensure PODs are designed effectively (Talley et al. 2016). Other themes

Table 7 Potential pitfalls and failure modes for use of PODs for assessment, planning, and decision support

Themes	Description
Inclusion and cross-boundary collaboration	Failure to invite and recruit all relevant stakeholders (e.g., resource areas beyond fire and fuels, other land management agencies, community members), failure to work across ownership or administrative boundaries to draw operationally relevant PODs, failure to capture all salient values and concerns
Facilitation	Failure of facilitator to be viewed as trusted or neutral party, failure to effectively navigate conflict and ensure all voices are heard
Expertise	Failure to capture all relevant local fire management expertise, due to lack of experts (e.g., new fire staff from other locations), or exclusion of locally relevant experts such as those with traditional ecological knowledge
Maintenance and updates	Failure to devote sufficient time or resources to ensure PODs and related products are accurate and reflect current conditions
Communication and coordination	Failure to initiate dialog and share information with relevant partners, cooperators, first responders, incident management teams, etc., in a timely manner
Incomplete or rigid analysis	Failure to devote sufficient time or resources to develop and deliver relevant scientific information and modeling, failure to incorporate new ideas or innovations into PODs processes and products
Narrow focus	Failure to capitalize on opportunities for PODs beyond incident response, including fuels management and community protection planning
Changing environment	Failure to appropriately consider changed conditions and overreliance on past operational experience and empirical models that are no longer representative, may overstate ability to control wildfire, and result in lack of confidence in planning process.

relate to the dynamic nature of the problem and highlight how outdated assessments, plans, and mental models can diminish the value of PODs. The current wildfire crisis will likely result in substantial change to our wildfire management approach including the need to engage new partners, take advantage of emerging technologies, and explore critical resource needs.

Building from some of the themes in Table 7, there are several areas for improvement to realize the potential of PODs more fully, beginning with the core components that underpin and enrich PODs. One area is improving PCL modeling, for instance by capturing more information on historical fire perimeter progression and containment operations, and by integrating with analyses of fuelbreak and fireline effectiveness (Gannon et al. 2020; Simpson et al. 2021). Risk assessments can be improved by increasing the rigor of expert elicitation, better examining low-probability, high-consequence events, and incorporating more diverse stakeholder values and perspectives (McFayden et al. 2019; McEvoy et al. 2021; Essen et al. 2021). For strategic response categories, risk-informed incident response is best described as a continuum that adapts to changing conditions (Thompson et al. 2016a), such that developing dynamic or condition-based strategic response categories is likely a needed evolution. Furthermore, as with risk assessments, adopting a more collaborative and inclusive approach into strategic response development can ideally expand partnerships and co-investment in actions to support a shared vision for land and fire management (Metlen et al. 2021). Whether it be identifying PCLs, drawing PODs, generating risk assessments, or establishing strategic response categories, the collaborative process can be as or more valuable than any final analytical product. Ensuring the continuity and relevance of PODs will also be necessary. POD boundaries are designed to be dynamic and subject to revision and improvement. On the biophysical side, this means accounting for landscape dynamics including growth, management, disturbance, and possibly non-stationary climatic changes. This in turn means periodic updating of data, models, and assessments. On the social side, this means investing in maintaining or building networks and adapting to changing socioeconomic conditions. Both aspects are necessary when it comes to updating goals and developing management strategies and require support from agency leadership and dedicated capacity to maintaining and updating PODs (Greiner et al. 2020). Deeper consideration of how PODs will operate in a dynamic world is important.

Continuing the theme of capacity, as PODs expand so too will needs for agency personnel and partners to share their expertise in POD workshops and improve their risk management acumen (Thompson et al. 2016b). Critically, this entails spanning organizational, ownership, and disciplinary boundaries to seek collective solutions under a common organizing framework. For PODs and associated tools to be utilized effectively, there will need to be interagency knowledge of such tools; this might be a fruitful topic for discussion for the newly formed wildfire commission (https://www.fema.gov/press-release/20211217/fema-usda-and-doi-jointly-establish-new-wildland-fire-mitigation-and). Skills in coordination, facilitation, and expert judgment elicitation are also essential to support productive workshops. Recruiting and retaining analytically savvy fire management personnel – at all levels – would help guide a transition to use of analytics that can enable greater objectivity and transparency, can break down information silos, and can facilitate a more forward-looking approach through analysis of leading rather than lagging indicators. Such expertise cannot be housed in specialized groups, but instead needs to be embedded throughout the organization, as research has found that use of data-driven analytics requires specialized expertise along with local trust and relationships (Schultz et al. 2021).

Furthermore, to support continual learning and organizational improvement, it is essential to expand investment in periodic monitoring and evaluating how practitioners are using evolving science (Greiner et al. 2020; Schultz et al. 2021; Colavito 2021; Rapp et al. 2020, 2021; Noble and Paveglio 2020; Noonan-Wright and Seielstad 2021). This will become more important as the adoption of PODs proliferates considering increased federal investment. It is recognized that many of the examples in this paper focused on areas with frequent, low-severity fire regimes, with more questions around applicability and management strategies in infrequent, high-severity fire regimes. In such systems, strategic response may be oriented more towards asset and community protection, and the utility of PODs may be challenged by extreme fire behavior and long spotting distances. Yet when combining POD networks with consideration of fire behavior and available resources, managers can ideally limit opportunity costs in infeasible or unworkable line locations and identify realistic opportunities for suppression. Even with more than seven years of research and practice in this arena and POD development on more than 60 National Forests, there is still a lot to learn considering the diversity of ecological, social, and policy contexts into which PODs might expand, as well as the range of wildfire scenarios that might be experienced.

The emergence of PODs and Risk Management Assistance, among other efforts, reflects a growing adoption of risk management principles and practices in wildland fire management. Expansions to the PODs framework noted here relate to the entire risk management cycle, connecting plans to response to monitoring. Learning from performance can then enhance forecasting management successes and failures in the face of future conditions, ideally supporting more climate adaptive strategies. The increasing sophistication of strategic planning with PODs more concretely links ends with means and will ideally help fire management agencies better align risk-informed strategy with land and fire management objectives and societal needs.

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Authors' contributions
MPT conceived of the article and led writing of the manuscript. BMG, CDO, MDC provided data and analysis for figures and tables and helped write the manuscript. CJD, CAS, DEC, BP, SMG, RS, and JTM helped write the manuscript. The author(s) read and approved the final manuscript.

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Not applicable.

Consent for publication
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The authors declare they have no competing interests.

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