

Article

Prototyping a Geospatial Atlas for Wildfire Planning and Management

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Abstract: Wildland fire managers are increasingly embracing risk management principles by being more anticipatory, proactive, and “engaging the fire before it starts”. This entails investing in pre-season, cross-boundary, strategic fire response planning with partners and stakeholders to build a shared understanding of wildfire risks and management opportunities. A key innovation in planning is the development of potential operational delineations (PODs), i.e., spatial management units whose boundaries are relevant to fire containment operations (e.g., roads, ridgetops, and fuel transitions), and within which potential fire consequences, suppression opportunities/challenges, and strategic response objectives can be analyzed to inform fire management decision making. As of the summer of 2020, PODs have been developed on more than forty landscapes encompassing National Forest System lands across the western USA, providing utility for planning, communication, mitigation prioritization, and incident response strategy development. Here, we review development of a decision support tool—a POD Atlas—intended to facilitate cross-boundary, collaborative strategic wildfire planning and management by providing high-resolution information on landscape conditions, values at risk, and fire management resource needs for individual PODs. With the atlas, users can rapidly access and assimilate multiple forms of pre-loaded data and analytics in a customizable manner. We prototyped and operationalized this tool in concert with, and for use by, fire managers on several National Forests in the Southern Rocky Mountains of the USA. We present examples, discuss real-world use cases, and highlight opportunities for continued decision support improvement.

Keywords: risk assessment; decision support; fire behavior; modeling; analytics

1. Introduction

Management of wildland fire in the western USA and globally continues to increase in complexity due to a multitude of factors, including increased fire activity and lengthened fire seasons due to climate change [1–3], increased demands for fire suppression and structure protection due to expansion of the wildland–urban interface [4,5], and elevated safety risks and suppression difficulty due to increases in tree mortality from fire and other disturbances [6–9]. To address these challenges, wildland fire managers are increasingly embracing risk management principles by being more anticipatory, proactive, and “engaging the fire before it starts” [10–12]. This idea is codified in the USDA Forest

Service's Wildland Fire Risk Management Protocol, which calls for National Forests to "predetermine" optimal response strategies based on a risk analysis completed with key stakeholders and partner agencies [13]. Fundamental aims of such pre-season planning are dampening time pressures, reducing uncertainties, expanding decision space, and clarifying risk–risk tradeoffs associated with incident response, ultimately to help managers arrive at high-quality response decisions consistent with broader land and resource management objectives [14–16].

As the complexity of wildland fire management has increased, so too has the need for risk-based decision support designed to enhance the safety and effectiveness of large fire management [17–28]. In recent years, the fire science community has developed a wide range of operationally focused assessment and planning tools. This body of work includes various risk assessment tools to estimate the social and ecological consequences of fire [29–33]; models of suppression difficulty, resistance to control, and potential fire control locations that speak to firefighting challenges and opportunities [34–38]; and models of fire responder safety zones, escape routes, and falling tree (snag) hazards to help suppression resources avoid harm [39–42]. Despite the proliferation of risk-based information, its use in fire management and decision support remains limited in part due to the lack of attention paid towards engineering the delivery and communication of this information to key users and decision makers [43,44].

Here, we focus on a recently developed spatial fire planning concept called potential wildland fire operational delineations (PODs). PODs are spatial management and analysis units whose boundaries are relevant to fire containment operations (e.g., roads, ridgetops, and fuel transitions), within which potential fire consequences, suppression opportunities/challenges, and strategic response objectives can be analyzed [45–48]. PODs form a logical basis for designing efficient wildfire response strategies based on the varying potential to contain fire at barriers that form POD boundaries [49,50]. They are also relevant analysis units to identify protection priorities across large landscapes [51] and to optimize fuel treatment placement [52]. As of this writing, PODs have been developed on more than forty landscapes encompassing National Forest System lands across the western USA, providing utility for planning, communication, mitigation, prioritization, and incident response at multiple time scales and levels of decision making [11,48,53–55]. Specific management applications of the PODs concept include designing and implementing wildfire response strategies, facilitating use of wildfire as a restoration tool, hardening or creating POD boundaries through timber and vegetation management to enhance control opportunities, and serving as burn blocks for prescribed fire planning and implementation.

In this paper we describe the development and application of a new geospatial decision support tool—a POD Atlas (i.e., a collection of maps and spatial data)—intended to facilitate strategic and tactical wildfire management decisions. The atlas provides high-resolution information on landscape conditions, values at risk, and fire management resource needs at the scale of the individual POD. Users can rapidly access and assimilate multiple forms of pre-loaded data and analytics, in a customizable manner. We prototyped and operationalized the POD Atlas in concert with, and for use by, local fire managers on National Forest System lands in the Southern Rocky Mountains of the USA. This work results from a multi-year, collaborative science-management partnership between National Forest leadership and staff, Forest Service Research, and the Colorado Forest Restoration Institute, along with other local and regional stakeholders and partners. Our intent is to broadly expand the user base throughout the western USA where local managers have developed POD networks and seek additional analytics and decision support. In the following sections, we provide background information on wildfire planning and management, detail development and application of the POD Atlas, and highlight opportunities for continued decision support improvement.

2. Wildfire Planning and Management with PODs

2.1. Background on PODs

A fundamental aim of the PODs concept is to deliver operationally relevant planning and decision support, a key need and priority for the fire management research community [21,24,25]. More broadly, goals include supporting safe and effective wildfire response, facilitating co-management of risk, and facilitating preseason engagement and coordination across boundaries. Like the phrase “fire knows no boundaries”, opportunities for safe and effective fire control do not necessarily align with ownership boundaries. Cross-boundary planning can help align expectations for wildfire response across jurisdictions, coordinate containment efforts at locations with the highest likelihood of success, and increase transparency of decisions that must balance tradeoffs between responder safety and fire management objectives. Use of PODs as a cross-boundary planning tool is consistent with the USDA Forest Service’s Foundational Doctrine for Wildfire Response, which states that the “interdependence of wildland fire jurisdictions requires the collaborative, proactive engagement of cooperators, partners, and the public in response activities” [13]. More broadly, use of PODs as a cross-boundary planning tool is consistent with the “all hands, all lands” emphasis and the risk science underpinning the National Cohesive Wildland fire Management Strategy in the USA [56].

In its simplest form, a POD is a spatial container bounded on all sides by pre-identified potential control locations (PCLs; [10,38,48]). PODs vary in size, typically ranging from hundreds to thousands of acres, often being smaller near development and larger in remote areas, due in part to factors such as road density. An iterative process of identifying PCLs, connecting them to form closed polygons (i.e., PODs), and expanding across the landscape of interest results in a POD network. POD production has normally occurred in a workshop setting pairing some of the aforementioned decision support models with local knowledge and expertise (Figure 1, [47]). Two fire analytics models are foundational to POD identification, which, combined, help managers identify locations on the landscape where responder safety and probability of control are highest. First is the suppression difficulty index (SDI), an expert-based system, which is based on fire behavior as a forcing agent and operational factors such as responder accessibility and mobility as resistance mechanisms [10,34,35]. Second is a predictive model of PCLs built with a machine learning algorithm that analyzes patterns of historical fire perimeter locations in relation to topography, fuel transitions, roads, and other landscape features that influence fire spread [38,48].



Figure 1. Photos from potential operational delineation (POD) workshops (left), and digitized POD network showing cross-boundary overlap (right). Note that PODs are not a kind of ownership but rather span ownership boundaries. Bottom left photo shows maps of advanced fire behavior analytics provided to support development of PODs.

Once POD boundaries have been digitized, a variety of spatial information can be summarized and mapped to communicate fire management information to a range of audiences (e.g., resource and communication specialists, incident managers, local fire departments, public officials, and agency leadership). Vector polygon and attribute data on PODs, along with updated POD boundaries, can also be uploaded into current wildfire decision support systems [47]. Notably, many National Forests in the USA have attributed PODs with information from their quantitative risk assessments [29] to guide the establishment of wildfire response strategies [16,45]. Categorical simplifications of a response continuum from resource protection to resource benefit can be assigned to PODs to document the planned response strategy to align the multiple levels of decision making both within and between fire management organizations [11,55,57]. The process of drawing PODs and assigning response strategies continues to expand; as of this writing, new landscapes throughout the western USA, including federal and non-federal partners in California, Colorado, Oregon, and Wyoming, are embarking on the PODs process.

2.2. Atlas Prototype: Arapaho–Roosevelt National Forest, Colorado, USA

Feedback from managers indicated that there is rarely local capacity to complete the spatial analysis, mapping, and data visualization necessary to make PODs useful for decision making, especially under time constraints. Their desire for assistance on these tasks led us to develop a common platform, the POD Atlas, capable of attributing PODs with relevant information, mapping a variety of fire management decision support products, and visualizing POD attributes. We structured the atlas to be flexible and adaptive to information needs and decision support opportunities across fire management, seeking to both provide information to develop big picture strategic objectives and to deliver decision support products with sufficient detail to support tactical and operational decisions. We initially prototyped a POD Atlas—a map of each POD with a corresponding text summary—intended to simplify complex information on POD characteristics, ecology, fire behavior, values at risk, and fire operations into an easily digestible format. The atlas provided a snapshot of the POD's location and its boundaries in relation to landscape features, along with what type of fire behavior to expect, how difficult fire might be to suppress, and what ecological or community values may be at risk inside the POD. This information was chosen to help initial responders in the field communicate with key decision makers, some of whom may be working remotely or who may not be familiar with the physical setting and social context of the fire.

We developed the prototype with local fire staff on the Arapaho–Roosevelt National Forest in Colorado, USA (Figure 2). The authors supported POD development efforts on the Forest over the course of several workshops and have since supported expansion of POD development with other National Forests in Colorado and neighboring states. By design, the atlas reflected local management concerns, including watershed health and drinking water importance [58], wildland urban interface (WUI) protection [59], tree mortality from mountain pine beetles that create operational fire hazards [60], and modeled suppression difficulty (SDI) based on factors related to accessibility, topography, and fire behavior [35]. The prototype was built using ESRI ArcGIS and Microsoft Access. Initial manager feedback was promising. However, the atlas lacked functionality for user customization or streamlined incorporation of additional geospatial data, which we address in the next section.

Our intent was to develop a tool to streamline the classification, analysis, and summarization of diverse spatial data into a common geodatabase, which could then be queried and customized to display results to a variety of end users. As with the atlas, the foundational summary unit is a polygon corresponding to a user-defined POD. Desired functionality included a template for input GIS data (see Table 1, next Section); standardizing national and local data sources (e.g., extent, resolution, and spatial projection); and performing pre-set and user-specified analyses for each POD in the geodatabase. With this platform, we can then streamline addressing management-focused questions such as what percentage of the POD is likely to experience extreme fire behavior, where critical

communications infrastructure is located, the number and area of affected land ownerships, the extent and density of the wildland–urban interface, etc.

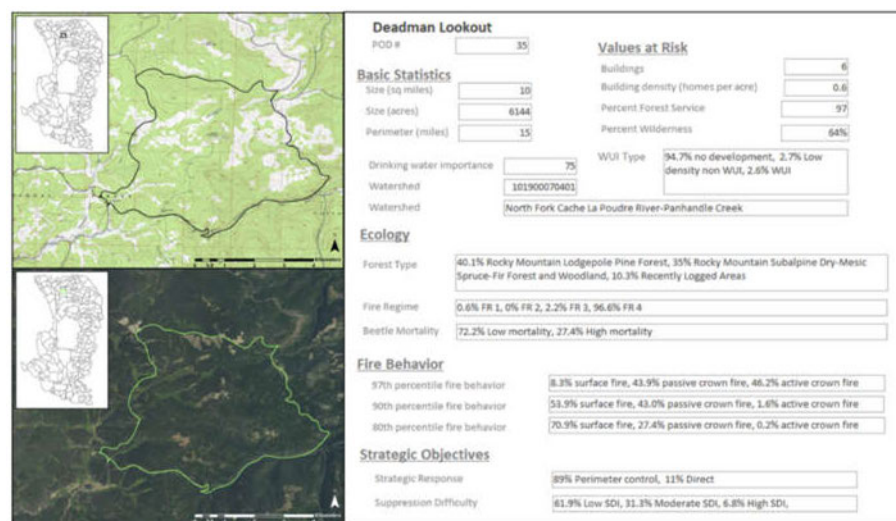


Figure 2. Prototype developed with local fire staff on the Arapaho–Roosevelt National Forest in Colorado, USA. Left panels show location of POD in relation to broader POD network, with different underlying reference layers. Right panel shows text-based summary information.

Table 1. Common data layers extracted and summarized by the POD Summarization Tool. Asterisk (*) indicates local data available in some locations where advanced risk modeling analyses have been performed.

Basic Statistics	Ecology	Fire Behavior	Values at Risk	Strategic Objectives	Operations
Area	Vegetation type	Fire history (ignitions and area burned)	Population density	Ownership	Road density
Perimeter	Lifeform	Burn probability	Water supply	Land designation	Trail density
Burnable area	Topography	Flame length probability	Net value change *	Strategic response zone *	Suppression difficulty
					Treatment history
					Potential control locations *

2.3. Atlas Development

Development of the POD Atlas proceeded in two phases (Figure 3), beginning with a Python-based (Python version 2.7, utilizing the ArcPy module within ESRI ArcGIS) standalone POD Summarization Tool. Table 1 summarizes some of the common data themes that are extracted from various sources, reformatted by summary type (e.g., count, mean, and categorical proportion), and summarized for every POD. The categories of results roughly follow those designed in the initial atlas prototype. Data sources include land cover, vegetation type, wildland–urban interface, national-scale stochastic fire simulation results, west-wide suppression difficulty results, fire ignition history, population density, watershed importance, and treatment and disturbance history commonly used in fire assessments [35,61–67]. Note that the POD Summarization Tool relies on very large, national datasets that are not practical nor appropriate to share online because of the sensitive nature of some information.

Additionally, a key feature of the POD Summarization Tool is the functionality to upload local datasets, notably quantitative risk assessment results, corresponding strategic response zones, and a PCL probability of control surface. These examples are also included in Table 1. Flexible application of the tool and constant improvement in data means we do not uniformly impose default datasets, and in

application we extensively document what data sources are used in a guide to accompany summary and atlas products. Various summary types are available for local datasets, such as sum, total area, and min/max/mean. Although not presented here, we have also seen managers request summaries of different information, for example simulated fire behavior across multiple weather scenarios, calibrated fuel models, other natural hazards (e.g., landslide potential), and habitat. The geodatabase output from the POD Summarization Tool provides decision support in its own right and provides useful information for assessment and prioritization purposes. To date, we have provided managers with a geodatabase compiling all the input data sources used in the assessment be they from national or local data sources (Figure 3). We do not presently have a mechanism to alter the national data used in the assessment and doing so may not be wise. Instead, data revisions or substitutions are handled with the local inputs. For example, if a better data source on population is available locally, the user can specify the raster data product representing population and select a function to sum the values within each POD.

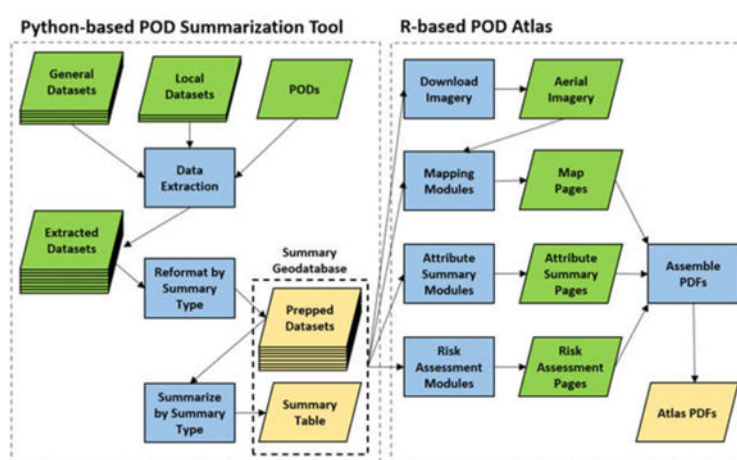


Figure 3. Workflow of POD Summarization and POD Atlas creation. Green parallelograms = input or intermediate data (e.g., spatial data and map page); blue rectangles = process; yellow parallelograms = final products. Asterisks denote fixed data in the atlas; all other atlas outputs are created with optional modules that can be run in parallel to create the desired map or data pages. Stacked symbols indicate multiple data sets are processed.

The second main component of development was the creation of an R-based (R Core Team 2019) POD Atlas Tool to generate customizable visual displays for each POD. The POD Summarization Tool provides data inputs to the Atlas Tool. Key processes include overlaying digitized POD boundaries with aerial imagery, mapping recent wildfire and fuel treatment activity, mapping raster spatial data such as PCL and SDI, mapping risk assessment results, presenting summary attributes in graphs or tables, and assembling a PDF book for each POD. The end result is a transition from a single-page text summary (Figure 2) to a multi-page visual summary (atlas), which can be accessed on a computer or mobile device, or printed and brought by crews into the field. The POD Atlas has a modular workflow so the end user can decide what information is relevant for their decision making and what order it will be displayed in. At present, generating the POD Atlas is performed by a small set of users with strong GIS and coding skills, and with access to key spatial datasets.

3. Next-Generation Prototype of POD Atlas: Carson and Santa Fe National Forests, New Mexico, USA

We worked with local fire managers on the Carson and Santa Fe National Forests to update and improve the prototype POD Atlas. Leadership and staff from that National Forest, with support from the authors, performed a quantitative risk assessment and collaboratively developed a POD network in 2018. PODs, risk assessment results, and strategic response zones (SRZs) facilitated communication

and informed strategic and tactical response decisions on multiple wildfires during the 2019 fire season [57]. For the purposes of adding functionality to the POD Atlas, local managers indicated that it would be helpful to map and summarize information from the risk assessment, such as the locations of highly valued resources and assets (HVRAs) and their response to fire (net value change), to better understand the negative and positive effects of fire across the landscape. This information could help them focus protection efforts where fire effects on HVRAs are predicted to be negative. We added this, and other, map and summary options to the tool (Figure 3; Table 1) and present results here. As of this writing, the authors are continuing to work with local managers to refine and tailor decision support in response to their evolving information needs.

Figure 4 presents results obtained from the POD Summarization Tool, specifically charting the expected net value change (eNVC) risk assessment results (y -axis), total area rated as low PCL (x -axis), and total area rated as high SDI (bubble size), for each POD. Collectively these risk metrics can indicate problematic PODs where expected loss is high and control opportunities are restricted, which can be useful for strategic prioritization and mitigation. Three PODs are highlighted (PODs 31, 38, and 77), reflecting a spectrum of conditions. Specifically, POD 31 has a positive expected net value change—reflecting potential for ecosystem benefits from fire—along with low concerns over PCL and SDI, suggesting opportunities for management strategies other than full suppression. PODs 38 and 77, by contrast, have potential for significant loss (negative eNVC values). POD 77 in particular is problematic due to large areas of low PCL and high SDI. Note that we could have also compared PCL and SDI for PODs on the basis of proportional area, but chose total area to reflect that POD size and associated fire size potential are also drivers of suppression demand. We describe these PODs in more detail with corresponding atlas examples below, beginning with operational concerns.

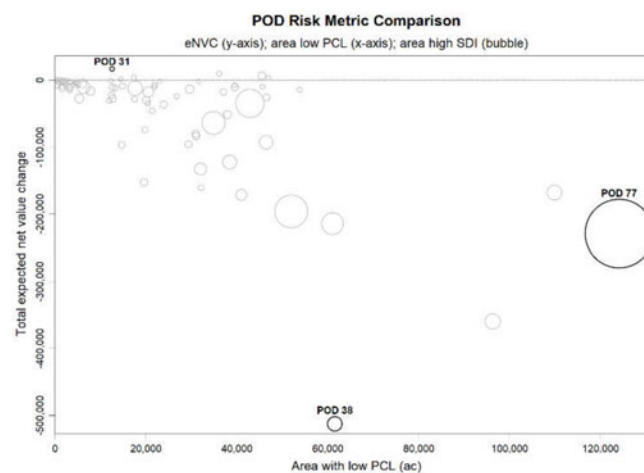


Figure 4. Bubble chart comparing the sum of expected net value change (eNVC; y -axis) to total area rated as low probability of suitable potential control location (PCL; x -axis) to total area rated as high in the suppression difficulty index (SDI; bubble size). Three PODs are highlighted to reflect a range of conditions.

Figure 5 presents the standardized cover page of the PDF book for POD 77, which displays the focal POD in relation to aerial imagery, road layers, adjacent PODs, and SRZ categories. Percentage land ownership within the POD is also summarized, which can be an important determinant of cross-jurisdictional management and incident complexity. Next, Figure 6 shows additional information on the landscape context for POD 77; in this case, displaying information on fire behavior (burn and flame length probability), operations (road density), and values at risk (population density and watersheds supplying drinking water). Users can specify which information to be displayed based on available layers from the POD Summarization Tool (Figure 3). The atlas provides histograms and cumulative distribution lines that contextualize the focal POD in relation to all PODs, also providing

percentile indicators. In this specific case, POD 77 has relatively higher potential for fire activity, relatively low road density indicating low accessibility and control opportunity, and relatively high concerns for values at risk.

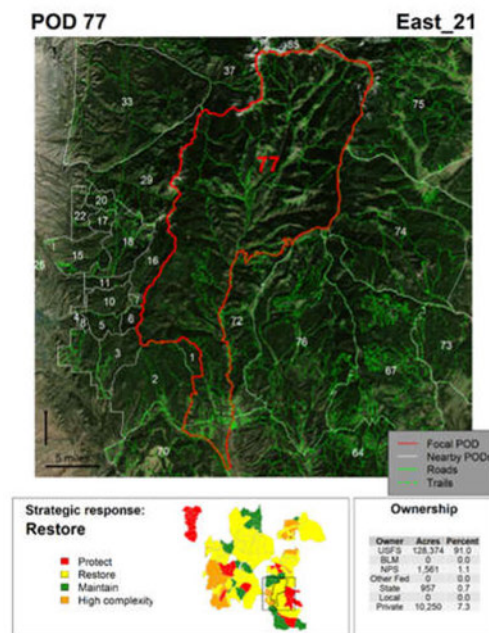


Figure 5. First page of POD Atlas showing focal POD boundaries in relation to aerial imagery, road layers, adjacent PODs, and strategic response categories, and describing land ownership in the POD.

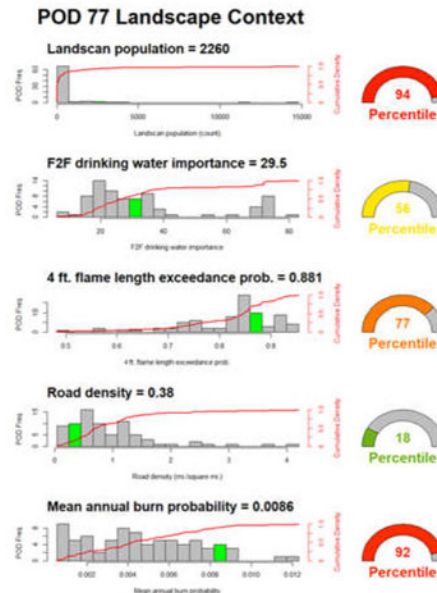


Figure 6. Graphical attribute summary for POD 77, showing the focal POD in relation to histograms, cumulative distributions, and percentiles across all PODs, for Landscan-based population, drinking water importance (F2F = Forests to Faucets), simulated flame lengths, road density, and simulated burn probability.

POD 77 also has the greatest area rated as low suitability for potential control locations and the highest area rated as high suppression difficulty, further highlighting operational challenges. Figures 7 and 8 map PCL and SDI model results, respectively, for POD 77 and its surrounding landscape to guide decisions of where to send responders so they can safely and effectively engage fire (Stratton 2020). For

this analysis (and that presented above in Figure 4) we defined low PCL suitability as an area with 25% or lower probability of fire containment. Roads and trails are mapped to communicate complementary information on responder accessibility and mobility. For example, the high road density in the southern portion of the POD results in relatively high PCL and low SDI. In other locations, control opportunities seem more severely restricted. Part of the reason POD 77 stands out is simply due to size—it has the largest perimeter and third largest area of all PODs, but as POD size is dictated by operational concerns such as the presence of suitable control locations, size is by definition an operational factor. Further, POD 77 ranks 17th (of 77) for percent area of low PCL suitability, and 14th for percent area of high SDI.

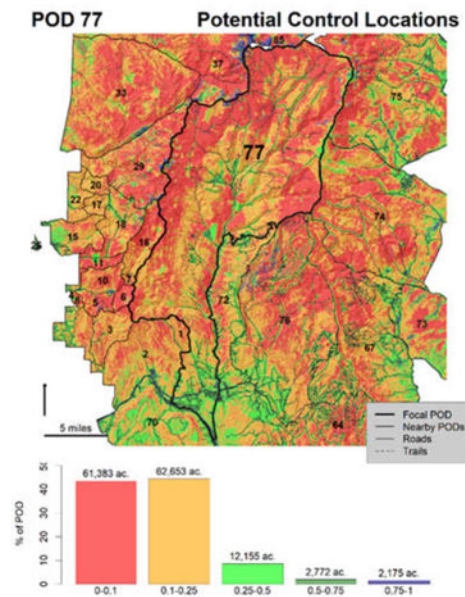


Figure 7. Model-based potential control location (PCL) probability surface for POD 77, with histogram displaying total and percent area in each of five quantitative PCL suitability classes.

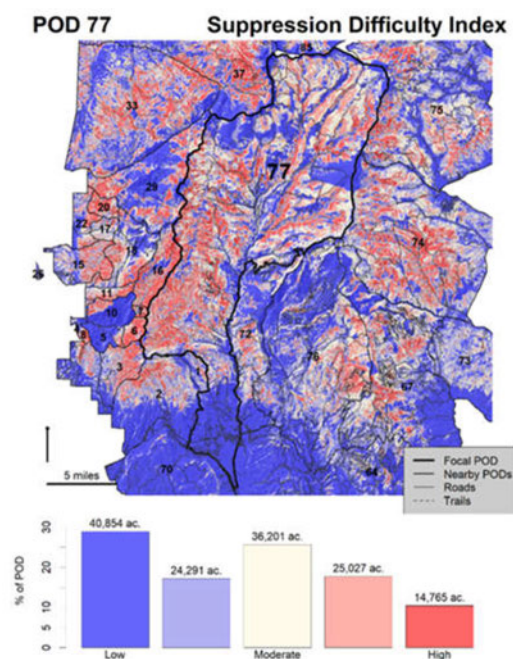


Figure 8. Model-based suppression difficulty index (SDI) surface for POD 77, with histogram displaying total and percent area in each of three categorical SDI classes.

The POD Atlas can also summarize key information on land and resource risks. Figure 9 presents risk assessment profiles for PODs 31 and 38, which have contrasting levels of risk. Risk assessment results are broken down according to seven categories of HVRAs: cultural resources, ecosystem function, infrastructure, timber resources, water, wildlife, and wildland–urban interface. The total eNVC value for POD 31 is a net positive, indicating that the appropriate strategic response may be to maintain the natural (beneficial) role of fire. The POD also presents limited operational challenges (Figure 4), indicating potential to effectively manage natural fire within pre-defined POD boundaries, as has been done elsewhere (see [11]). The absolute magnitudes of eNVC values are far greater for POD 38, with overall expected net losses due to fire. Figure 10 displays spatially explicit estimates of conditional Net Value Change (cNVC) from the quantitative risk assessment for a subset of HVRAs in POD 38. In contrast to eNVC, cNVC excludes the likelihood of experiencing fire and focuses on the interaction of value susceptibility and fire intensity [29,30]. The ecosystem function HVRA is widely distributed and mostly expected to benefit from fire, but it overlaps in some places with HVRA expected to be negatively impacted by fire (e.g., municipal water supply), indicating the complexity of fire management balancing multiple objectives.



Figure 9. Risk assessment profiles for POD 31 (top) and POD 38 (bottom), breaking down total expected net value change (eNVC; Figure 4) into individual eNVC scores for seven categories of highly valued resources and assets (cultural resources, ecosystem function, infrastructure, timber resources, water, wildlife, and wildland–urban interface).

A range of other summarizations and visualizations are possible, for instance the POD Atlas can map recent fire activity to identify areas where falling trees may present a hazard, or recent fuel treatments to identify areas where control opportunities may be enhanced. Similarly, a range of intra-POD comparisons could be explored beyond what was presented in Figure 4. Further, the POD Atlas can facilitate strategic response assignments by streamlining the process of overlaying risk assessment results with potential control locations and other information. Our primary aim here is to illustrate the potential of the POD Summarization and Atlas Tools, contextualized on a real-world landscape where local managers have found great utility in PODs and provided feedback to support tool development.

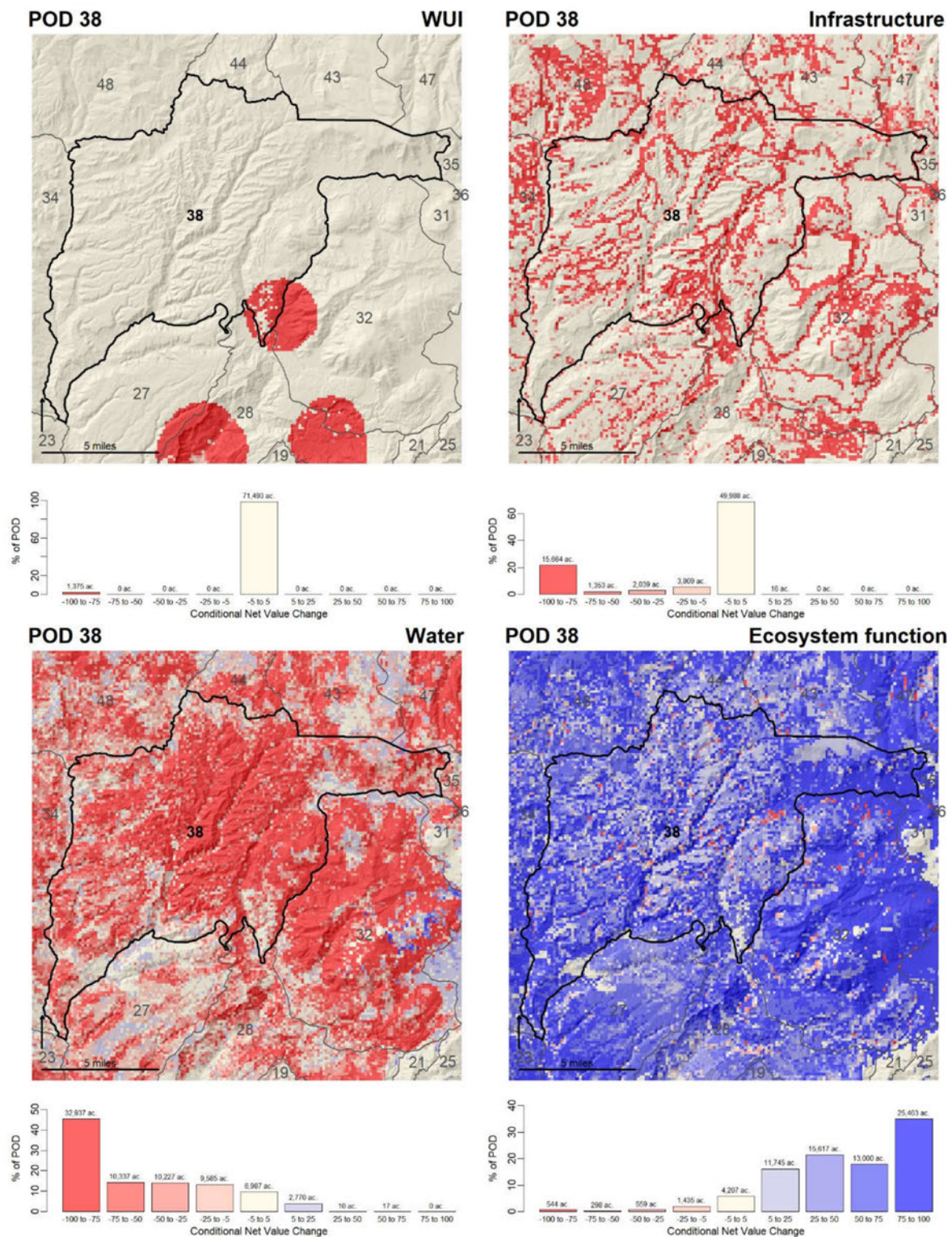


Figure 10. Spatial risk assessment results for POD 38, for a select set of HVRAs: wildland–urban interface (top left); infrastructure (top right); water (bottom left); and ecosystem function (bottom right).

4. Discussion

The POD Summarization and Atlas Tools join an emerging portfolio of strategic fire planning tools being operationalized on National Forest System and adjacent lands throughout the western USA, including maps depicting suppression difficulty, potential control locations, and quantitative

risk assessment results [48]. PODs can inform fire management decisions, facilitate communication and outreach, support prescribed fire planning and implementation along with use of natural fire as a restoration tool, help identify problem areas and prioritize risk mitigation, and help identify areas where hardening POD boundaries through timber and vegetation management could enhance control opportunities. Key decision makers, on-the-ground fire staff, local emergency response agencies, non-governmental organizations, and stakeholders, among others, have participated in POD workshops and the process of collaboratively developing PODs with a diverse group of stakeholders is facilitating co-management of cross-boundary wildfire risk [54].

Early and iterative engagement with managers has helped us craft tools that have been operationalized for real-world use, and iteratively improved over time. The POD Atlas can streamline the process of summarizing risks, suppression opportunities/challenges, and strategic response objectives, supporting decisions ranging from long-term implementation plans to boots-on-the-ground initial response to a newly detected ignition. The connected workflows of the POD Summarization and Atlas Tools help to assimilate a range of information that users can query to aid comparative POD assessment and prioritization exercises, and translate this information into fire management resource needs in a flexible and customizable manner. Ultimately, our aim is to provide actionable decision support that informs development of safe and effective response strategies and tactics, and secondly to help infuse analytics into planning and operations more widely [16,47].

The flexible and modular approach of the POD Summarization and Atlas Tools can be complementary to existing wildfire decision support providing standardized fire modeling, risk analysis, and decision documentation tools for incident management [43,44,68,69]. Low-cost investment in scripting to automate analysis, mapping, and data visualization workflows in Python and R provides a means primarily to expand access to information that local units deem useful for their fire management decision needs. This style of decision support tool provides great flexibility to customize information delivery and with minimal end user requirements. We originally pursued a web-based platform designed to assimilate rapidly changing information but instead chose a PDF booklet for the initial rollout of the POD Atlas because mobile internet access is often poor in the wildlands that fire and land managers operate in. The PDF format facilitates data storage and access on low-performance mobile computing devices such as phones and tablets.

Another key strength of the POD-based approach is the explicit and targeted inclusion of local managers, experts, and stakeholders. A fundamental idea here is that the POD Atlas provides regional and national data for a baseline degree of standardization, augmented by locally relevant data that may be more specialized, accurate, recent, or field validated and trusted. Local feedback and input enters into the process via several pathways: (1) contribution of local data, knowledge, and values to develop risk assessment products; (2) interpretation of national or local products to delineate the PODs and assign them strategic responses; and (3) selection of data to visualize in the atlas products. There is also opportunity for managers to critique and revise the local application of SDI and PCL models by contributing locally accurate data. Additionally, both these analytical products have continuous values, so it is straightforward for managers to adjust visualization and summary metrics to align with their desired interpretation.

Based on the current implementation of these tools in management, we envision that POD Summarization and Atlas products will be updated on an annual or biannual basis to best reflect current landscape conditions. Any modeled fire behavior or effects delivered in the POD Summarization and Atlas products are based on either expected or user-specified fire weather conditions, which may not match the conditions of a specific fire incident, but this can be mitigated by modeling fire behavior under a wider range of fire weather scenarios. It is important to acknowledge this limitation, but much of the information being requested by managers so far focuses on the spatial extent of fire-sensitive resources and assets, whether their responses are mostly negative or positive, and suppression effectiveness and safety indices that are not highly sensitive to variation in fire behavior.

There are limitations to acknowledge with these tools and PODs in general. First, the utility of PODs is largely dependent on the process of creating them, including questions of who participated in workshops, the breadth of expertise captured, the range of stakeholder concerns addressed, and the degree of trust and support for moving forward with cross-boundary planning. Including a broad range of participants can be desirable to establish a common understanding of management challenges, opportunities, values and concerns, but it can also introduce potential for conflict. One proposed solution to diffuse contention and foster inclusive participation is use of third-party facilitators [54].

Second, the precursors to use of the tool—notably facilitation of POD workshops, geospatial analysis of PCL and SDI, and fire behavior simulation—can be time and resource intensive and those skills may not be available in all places. As one example, although we have recognized the value of documenting PCL attributes including feature type (e.g., road, trail, and stream), width, slope position, and accessibility, we have yet to develop a consistent process to collect and communicate this information. Our experience has been that it is very labor intensive to collect this information at high resolution when digitizing the PODs. In our initial efforts, managers primarily identified and mapped PCLs at coarse resolutions on paper maps, which were later digitized into PCLs and then converted to PODs. One issue is that the GIS staff may not have the local expertise to properly assign attributes when digitizing the PCLs. Additionally, there are questions about the appropriate scale for these data and whether PCLs should be split at each transition between feature types or conditions, or aggregated over some larger distance (say the unique edge between PODs) and attributed with the majority attributes.

Third, reliance on fire behavior models means introduction of model error and uncertainty, hence the emphasis on also relying on local expert knowledge. Capturing expert judgment requires preparation, especially in terms of defining an elicitation protocol [70]. In practice, we often aim to stimulate deliberative thought with a pilot round asking experts to identify control locations and containment polygons for various ignition scenarios, and then expand to the landscape scale through discussion, feedback, and iteration. Improving processes and ensuring rigor in elicitation of expert judgment remain an important research direction [31,71].

Fourth, as a POD map is intended to be a living document that is updated in response to changing landscape conditions, there are workload requirements for updating geospatial data and analyses over time. As stated above, we anticipate that these products will be updated on a biennial basis to align with fuel data revisions from LANDFIRE [61] and the need to revise products based on recent fuel modifications from wildfires, forest management, and other disturbances. Although this timeline means products may be temporarily out of date for parts of the landscape, managers are generally aware of recent activities and their likely impacts on fire behavior and effects.

5. Conclusions

In summary, we reviewed spatial wildfire management and planning using the POD framework, briefly discussed emerging analytics used to support wildfire decisions, and introduced new complementary geospatial decision support tools. The POD Atlas workflow extracts, reformats, and assimilates a wide range of operationally relevant information on PODs including basic statistics, ecology, fire behavior, values at risk, strategic objectives, and operations, and then streamlines the process of summarizing and displaying a range of user-specified geospatial data and model results. These decision support tools were designed with flexibility in mind to meet the diverse information needs of fire managers on National Forest System and surrounding lands in the western USA where POD-based planning and management is common. Ideally, the POD Atlas complements and adds value to existing assessment and planning efforts, specifically helping to operationalize risk assessments and to make spatial data more useful for land and fire management planning. Collaboration with managers was critical for our initial prototyping and we expect that their continued feedback will improve the form and content of future updates to these POD-based decision support tools. Future uses and refinements of the tools will ideally support risk-informed

and science-based decision making in the context of wildfire management. Interested practitioners wanting to learn more about implementing these tools can find more details and contact information here (<https://www.fs.usda.gov/rmrs/groups/wildfire-risk-management-science-team>).

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