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# A collaborative, cloud-based decision support system for structured wildfire risk mitigation planning

Hugh Safford[a,b,*], Colton Miller[b,1], Danielle Perrot[b], Sophie Gilbert[d], Tyler Hoecker[b,e,g], Michael Koontz[f], Kailey Kornhauser[b], Matt Thompson[b,g], Joe Shannon[b], Nathan Rutenbeck[b], Joe Scott[b,g], Scott Conway[b], Katharyn Duffy[b,c,*]

[a] University of California, 1 Shields Avenue, Davis, CA 95616, USA
[b] Vibrant Planet, Truckee, CA, 96161, USA
[c] Northern Arizona University, 1295 Knoles Dr, Flagstaff, AZ 86011, USA
[d] Property and Environment Research Center, 2048 Analysis Drive A, Bozeman, MT 59718, USA
[e] University of Montana, 32 Campus Dr, Missoula, MT 59812, USA
[f] U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Ave #C, Fort Collins, CO 80526, USA
[g] Pyrologix, 111N. Higgins Avenue, Suite 404, Missoula, MT 59802, USA

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ABSTRACT

Multi-stakeholder planning and prioritization for ecosystem management and wildfire risk mitigation are complicated by the need to balance a multitude of values, goals, viewpoints, and interests across large landscapes. Doing so requires quantifying current conditions, defining management feasibility constraints, modeling complex system responses under different management and disturbance scenarios, quantifying outcomes in terms of social values, weighing and assessing tradeoffs, and identifying optimal strategies. Beginning in the 2010s, structured wildfire risk assessment tools were developed to provide a framework for prioritizing management actions based on wildfire hazard, ecological response, and decision-maker values. Yet, more than a decade later, operationalizing risk assessments remains challenging and limited by disconnected tooling, static data, and workflows that are difficult to scale or adapt for collaborative decision-making. Here, we present the Vibrant Planet Platform (VPP), a modular, cloud-based decision-support system that integrates fire simulation, ecological response functions, multi-objective optimization, and user input into a unified planning environment. The platform enables risk-based scenario planning across landscapes up to millions of hectares by linking validated modeling tools (e.g., FSim, FVS, ForSys) with high-resolution, up-to-date vegetation and infrastructure data. We describe the challenges inherent to operationalizing risk assessments, demonstrate how VPP addresses them through architectural and methodological design, and highlight real-world deployments in U.S. risk-exposed landscapes and communities. We outline a multi-tiered validation framework for assessing model relevance, internal coherence, predictive performance, and field alignment. VPP illustrates how structured decision-making can be operationalized at broad scales, offering a model for ecological planning tools that are rigorous, transparent, and participatory.

## 1. Introduction: from policy to practice

Human-driven changes to ecological disturbance dynamics are key drivers of ecosystem degradation, and reducing the negative impacts of disturbance regime change – to humans as well as to ecosystems – has become a major component of ecosystem restoration and global change adaptation around the world (Colding et al., 2003; Johnstone et al., 2016; Buma and Schultz, 2020). Among the ecological disturbances most impacted by humans is fire. More than half of the world's ecoregions are considered 'fire-dependent', and fire regime degradation has affected >60 % of the globe (Shlisky et al. 2007). This has had major effects on biodiversity, old forests, ecosystem services, and human communities and economies (Bowman et al., 2011; Kelly et al., 2020; McDowell et al., 2020). Looking forward, projections suggest that – in

* Corresponding authors.
*E-mail addresses:* hdsafford@ucdavis.edu (H. Safford), katharyn@vibrantplanet.net (K. Duffy).
[1] Current address: Washington Department of Natural Resources, 1111 Washington St. SE, Olympia, WA 98504.

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the absence of mitigations – fire regime change will quicken, leading to accelerating impacts to many of the world's ecosystems and their human residents (Cary et al., 2012; Safford and Vallejo, 2019; Abatzoglou et al., 2021)

In seasonally dry ecoregions, anthropogenic changes to land use, fire frequencies, ecosystem structure, fuel loadings, and the climate have led to particularly severe effects of fire on ecosystems and humans (McLauchlan et al., 2020; Kobziar et al., 2024). Policy and management responses to changing fire regimes in these landscapes have been generally slow and reactive however, with a primary focus on techniques and technologies to extinguish fires after they are ignited (Stephens and Ruth, 2005; North et al., 2015; Moreira et al., 2020). This approach is having diminishing success, because suppressing fires in ecosystems adapted to frequent burning may be ecological degradation in itself; because many years without fire in such ecosystems leads to fuel accumulation and uncharacteristically severe burning when fire returns; and because an unbalanced prioritization of resources toward fire response infrastructure and tactics is starving proactive and cost-efficient stewardship practices (Kauffman, 2004; Steel et al., 2015; Moreira et al., 2020; UNEP, 2022).

Under the guise of "Integrated Fire Management", nations are beginning to consider a broader range of tools, ranging from increased funding for research, analytics, and monitoring; to fire prevention and education; risk mitigation; and postfire recovery (UNEP, 2022; FAO, 2024). Efforts to mitigate wildfire risk before ignition have enjoyed special emphasis, because fuel is the only member of the fire behavior triangle that responds directly to human manipulation, risk reduction activities are well-aligned with the tools and skills that characterize agency workforces, and governments prefer to spend tax dollars in ways that are tangible and visible. Nonetheless, wildfire risk reduction efforts continue to command a small part of the budget of most fire and fuel management organizations worldwide, because they are aimed at reducing theoretical and future threats rather than at responding to extant and immediate emergencies.

The international wildfire crisis is a wicked problem (Rittel and Webber, 1973), where incomplete and contradictory knowledge, shifting requirements and conditions, and strong internal and external feedbacks interact to complicate the development of appropriate and effective management responses. Exacerbating issues include changing environmental baselines driven by land use and climate change, the accelerating rate at which the problem is evolving, and the multiscale complexity of affected landscapes and human communities. Affected landscapes often span political boundaries, watersheds, varying management jurisdictions and plans, broad environmental gradients, and user groups representing different, often competing social strata and value systems (Balint et al., 2011; Gill et al., 2013). Under these conditions, arriving at management consensus is a daunting task. Some considerations of the options facing managers in these challenging circumstances focus on the importance of 'collaborative governance'; equal access to data and participation in the decision-making process; and transparency in planning processes, recommendations, and projected costs and benefits (USDA, 1999; Scarlet and McKinney, 2016; Yung et al., 2022). At the same time, as the speed and scale of fire regime changes accelerate, there is a seemingly competing need to increase efficiency and speed in wildfire risk mitigation planning and implementation (e.g., Drury, 2016; Palaiologou et al., 2020; Day et al., 2023). Effectively addressing these rival challenges at the same time requires a more holistic, structured decision-making type of approach that – among other things – works across jurisdictions, incorporates end-user input, is manager- and collaboration-friendly, and leverages advanced technology (Allen et al., 2011; Thompson and Calkin, 2011; Colavito, 2021; O'Mara et al., 2024).

Over the last two decades, a number of decision support tools have been developed to help fill important components of this gap,

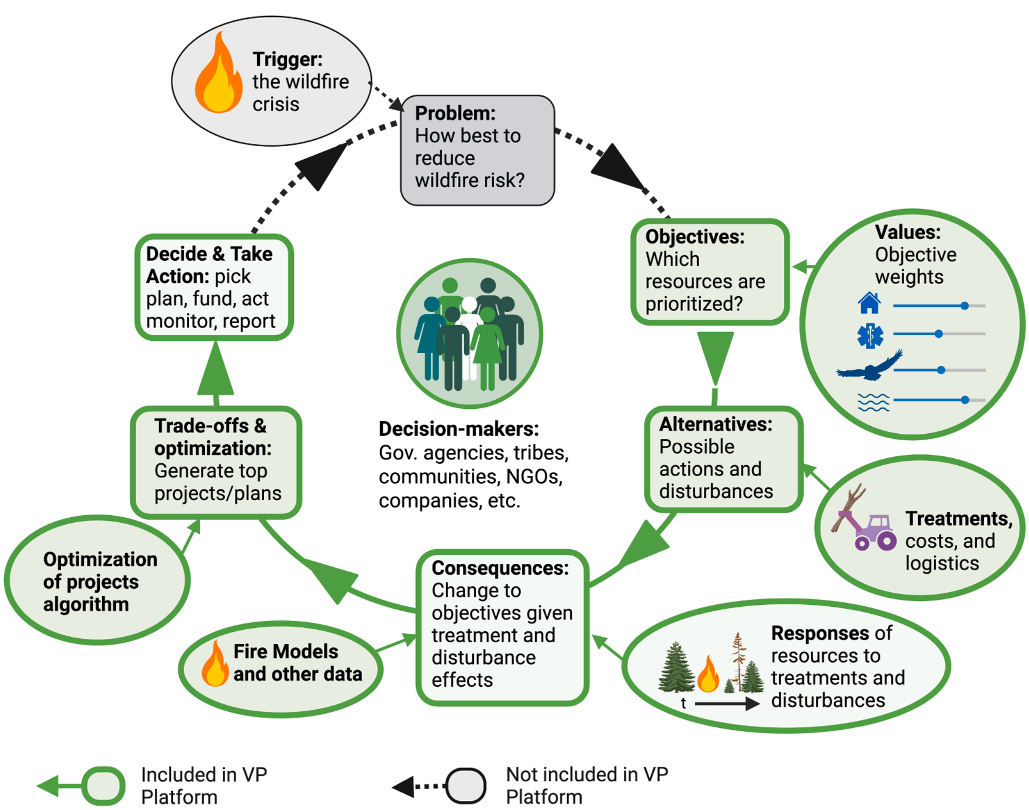


**Fig. 1.** The structured decision-making process for managing wildfire risk in ecologically and socially complex systems. The Vibrant Planet Platform (VPP) prioritizes objectives and determines alternatives, calculating consequences of those alternatives, and optimizing outcomes while considering tradeoffs. The platform directly addresses steps of the process represented by green boxes and solid green lines, and informs steps shown in black boxes.

representing some but not all steps in the structured decision-making process (Pacheco et al., 2015; O'Mara et al., 2024; Ager and Safford, 2025; Fig. 1, Table 1). In much of the United States the how-to guide for wildfire risk assessment – the first step in risk mitigation planning – is the US Forest Service (USFS) General Technical Report 315 (Wildfire risk assessment framework for land and resource management; Scott et al., 2013). "GTR-315″ offered a robust conceptual framework for conducting quantitative wildfire risk assessments (QWRAs), addressing the need for cohesive strategy-building, leveraging theory and practice for risk-based planning from other domains (Calkin et al., 2011), and providing a blueprint for the integration of spatial data and modeling of wildfire likelihood, intensity, and resource response to guide management. Today, risk assessment practice in the US continues to be hugely influenced by the general workflow introduced by GTR 315. However, as the speed and scale of the wildfire crisis accelerate, a growing gap has emerged between the relatively slowly-developed and somewhat siloed outputs of traditional QWRAs and the accelerating needs for management decision support on large, complex, and multi-jurisdictional landscapes (Colavito, 2021; O'Connor et al., 2016; Thompson et al., 2016).

Existing tools address individual components of the risk assessment process—such as fire spread, forest structure, or economic cost—but lack the integration, accessibility, and unified data resolution required for real-world planning, outcome reporting, and monitoring of effectiveness (Drury et al., 2016). Platforms and/or data provided in reports are siloed, rely on static or outdated datasets that may lack validation or may not have sufficient accuracy or precision for their intended uses, and require specialized expertise to operate (Thompson and Calkin, 2011; Drury et al., 2016; O'Mara et al., 2024). Critically, assessments often fail to support the social processes necessary for collaborative governance—especially in multijurisdictional or contested landscapes (USDA, 1999). Adoption of the QWRA approach by national and regional resource management partnerships is pushing risk assessment workflows to become more collaborative and actionable in cross-boundary contexts (Metlen et al., 2021; Huayhuaca et al., 2025). However, rapid development of accurate and robust risk assessments remains socially and technically difficult, limiting their use in the places where they are most urgently needed. Additionally, although risk assessments are a critical first step in the risk mitigation planning process (Scott et al., 2013), alone they do not provide guidance on (a) the locations and characteristics of priority areas, (b) how risk in different areas can be mitigated through vegetation management treatments, (c)

**Table 1**
Comparison of wildfire hazard and risk modeling tools and platforms widely used in the United States.

| Tool/platform name[a] | Wildfire hazard assessment[b] | Wildfire risk assessment | Wildfire risk mitigation decision support | | | | Spatial scale | | | Citations |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Optimization of risk reduction acitivities | Identification of best treatment options and quantification of risk reduction to HVRAs[c] | Impacts of risk reduction activities to HVRAs in absence of fire | Economics (costs and outputs) | Local/ stand (1–10 s ha) | Mid-scale (100s-1000s ha) | Landscape (≥10,000 s ha) | |
| BehavePlus | X | | | | | | X | | | Heinsch and Andrews, 2010 |
| **FVS-FFE** | X | | | | | | X | | | Rebain 2022 |
| FOFEM | X | | | | | | X | | | Reinhardt et al., 1997 |
| NEXUS | X | | | | | | X | | | Scott, 1999S |
| **FlamMap** | X | | | | | | | X | X | Finney 2006 |
| **FSim** | X | | | | | | | | X | Finney et al. 2011 |
| LANDIS-II | X | | | | | | | | X | Scheller et al., 2007 |
| Reburn | X | | | | | | | | X | Prichard et al., 2023 |
| **ForSys** | | | X | | | | | X | X | Day et al. 2023 |
| RiskMonitor | x | X | | (x) | | | | | X | USDA Forest Service, 2023 |
| ArcFuels | x | X | | (x) | | | X | X | X | Vaillant et al. 2013 |
| **IFTDSS** (QWRA)[d] | x | X | | (x) | | | X | X | X | Drury et al. 2016; Scott et al. 2013 |
| Vibrant Planet Platform | x | X | X | X | X | X | X | X | X | This paper; VP 2024 |

[a] Tools indicated in bold underlined text provide important underlying inputs to Vibrant Planet Platform (see text)
[b] Lower-case "x" indicates that hazard is assessed by submodules based on FlamMap, Fsim, or a combination thereof
[c] Highly valued resources and assets.
[d] Quantitative wildfire risk assessment
(x) - effects of wildfire risk reduction activities on HVRAs not integrated into platform, but effects can be determined postfacto by changing underlying fuels data and rerunning fire models.

the ecological impacts of disparate treatments in the absence of disturbance, (d) the impacts of various mitigation plans on important metrics related to risk and ecological outcomes that are not directly used in the traditional risk assessment itself (e.g. kilometers of critical access roads or riparian areas that change hazard class, changes in potential post-fire soil erosion rates, etc.), or (e) economic costs or outputs (Table 1).

The Vibrant Planet Platform (VPP) was developed to accelerate the pace, broaden the scale, and expand the scope of wildfire risk assessment and planning—advancing from more standard GTR-315-influenced risk assessments to decision support for risk mitigation and resource management. The platform integrates broadly used and validated fire and vegetation modeling systems with the most current or user-supplied spatial data products, ecologically and operationally homogeneous treatment units, ecological response functions that include treatment effects, and a participatory interface for scenario planning. The platform's architecture prioritizes usability, speed, and transparency—allowing decision-makers to rapidly explore, compare, and iterate on management scenarios in real time. VPP embeds QWRA's core principles in a modular, cloud-based decision support system, enabling structured, evidence-based planning that is scientifically rigorous and socially inclusive.

In this contribution, we show how the design of the VPP systematically addresses key bottlenecks in the wildfire risk mitigation process. We lay out a "theory of change" underlying the platform, first outlining the persistent technical and institutional barriers to implementing risk assessment frameworks for hazard mitigation and ecological restoration, then describing how the platform overcomes those barriers, and finally reflecting on its implications for collaborative land management. We argue that the ability to operationalize and extend wildfire risk assessments at landscape scales requires not only integrated modeling, optimization, and up-to-date spatial data, but also a deep commitment to transparency, user trust, and shared learning. VPP offers one pathway toward that future.

## 2. Background: the GTR-315 framework

GTR-315 (Scott et al., 2013) established a foundational framework for conducting QWRAs in the United States. Its approach is based on a structured risk assessment framework that integrates four core elements:

(1) Likelihood of wildfire occurrence
(2) Expected intensity of fire
(3) Response of high-value resources and assets (HVRAs) to fire intensity, typically represented through response functions
(4) Relative importance weights that support quantitative comparison of exposure and vulnerability among differing HVRAs

Together, these components produce spatially explicit estimates of risk derived from the expected change in resource and asset values across a landscape resulting from wildfire exposure. GTR-315 and subsequent risk assessment advances formalized this structure into a modular, repeatable workflow that has shaped national, regional, and local wildfire risk assessments and underpins tools such as ArcFuels (Vaillant et al., 2013), IFTDSS (Interagency Fuel Treatment Decision Support System; Drury et al., 2016), and RiskMonitor (USFS, 2024). The emphasis on transparency, defensibility, and alignment with resource management objectives has made the QWRA model one of the most widely adopted conceptual models for risk-based planning in the US (Aven, 2011; Thompson et al., 2011, 2016).

At the same time, QWRA implementation remains non-standardized. Traditional wildfire risk assessments typically produce static reports or GIS-based outputs that provide valuable hazard and values mapping, but are not consistently packaged in ways that support dynamic, scenario-driven planning and collaborative decision-making. Key limitations have included the difficulty of generating or updating response functions, the lack of high-resolution and current spatial data on resources and wildfire hazard, limited capacity to compare management alternatives (particularly the effects of management interventions), and insufficient engagement with the collaborative governance processes that increasingly define landscape-scale planning.

Yet the core logic and structure of GTR-315-influenced risk assessments remain highly relevant for reducing wildfire risk to high-value resources. Their fundamental insight—that wildfire risk can be understood and acted upon through the combined lenses of hazard, exposure, and response—continues to guide federal fuel management strategy at the national level in the US. The next challenge is translating that logic into operational, collaborative planning systems that support timely and effective action.

## 3. Challenges in operationalizing quantitative wildfire risk assessment

While the QWRA framework provides a numerical and structured approach to wildfire risk assessment, applying it in practice—particularly at the landscape or regional scale—requires overcoming a number of persistent technical and institutional barriers (Pearman and Cravens, 2022). Below we outline five key challenges that have constrained operationalization in real-world settings.

### 3.1. Data fragmentation, accuracy, and spatiotemporal resolution

Effective wildfire planning requires spatial data that are current and comprehensive, and are sufficiently accurate at the spatiotemporal scales relevant to support planning and decision making. However, key inputs such as vegetation structure, fuel characteristics, topography, values at risk, and management constraints are often outdated, inconsistent across jurisdictions, or available only at coarse resolution (Rollins, 2009; Scott et al., 2013). The uneven spatial and temporal coverage of LiDAR, reliance on national baseline products, and lack of integration between ecological and administrative datasets all contribute to misalignment between data availability and the spatial grain of planning decisions. These limitations are particularly acute in fire-prone landscapes where conditions can shift dramatically in short periods, necessitating rapid data updates (Chang et al., 2025).

### 3.2. Response function construction and lack of ecological nuance

Response functions —the linchpin of GTR-315-influenced wildfire risk assessments—quantify how different resources or assets are expected to respond to varying fire intensities. Yet few tools provide support for response function development, and most assessments rely on expert elicitation or coarse, categorical ratings (Scott et al. 2013; Drury et al. 2016). Further, response function workshops are often missing key experts, as the number of valued resources and assets can be high and their nature diverse, often ranging from structures to recreation, and water resources to animal and plant habitat. Subject-matter experts often lack time to engage deeply in response function development among competing work duties. Lastly, responses are often difficult to measure and thus poorly quantified. This limits ecological realism and sensitivity, particularly for outcomes beyond fire (e.g., restoration, succession, or treatment effects in the absence of fire). While some platforms beyond VPP have begun incorporating response functions into risk modeling (Table 1), they generally lack support for data-driven, empirical, time-dynamic, or treatment-specific response function construction. Without flexible, transparent response functions grounded in expert opinion, ecological data, or process models, the ability to evaluate outcomes across diverse objectives remains constrained.

### 3.3. Decision-maker engagement and scenario planning

Landscape-scale wildfire planning is increasingly collaborative, involving federal, state, and local agencies, tribes, NGOs, private landowners, utility providers, and community representatives. However, most decision support tools were not designed for this kind of multilateral planning. They often lack intuitive interfaces, run times that support iteration, or outputs that communicate tradeoffs transparently (Thompson and Calkin, 2011; O'Mara et al., 2024; Ager and Safford, 2025). As a result, decision-makers and project partners may be asked to weigh in on scenarios they had no role in shaping, eroding trust and undermining buy-in. While structured decision frameworks call for decision-maker input in defining objectives and value tradeoffs, most implementations fail to realize this in practice, contributing to delays, confusion, or process fatigue (Yung et al., 2022). Decision support systems that build buy-in through co-development and iterative engagement build trust amongst participants and legitimacy for process outcomes (Palaiologou et al., 2021).

### 3.4. Fragmentation of modeling tools and absence of direct decision support

Operationalizing QWRA within a structured decision-making process requires integration of disparate modeling domains—fire behavior, vegetation dynamics, ecological response, and multi-objective optimization—but the tools that serve these domains are esoteric, were generally not designed to interoperate, and do not provide built-in support to risk management decision-making. For example, FSim and WildEST model wildfire behavior, FVS (Forest Vegetation Simulator; Rebain, 2022) simulates forest growth and structure, and ForSys supports prioritization and sequencing, but none of them directly identify best treatment options, quantify impacts of risk reduction activities to resources and assets, or measure economic impacts and inputs (Table 1). Each tool operates in a different environment, requires unique data inputs, and uses distinct assumptions and file formats (Scott et al., 2013; Day et al., 2023). Connecting them requires substantial data preprocessing, data engineering, and manual calibration. As a result, risk assessments are typically ad hoc, resource-intensive, and dependent on a small set of technical experts—undermining transparency, reproducibility, and broad adoption (Colavito, 2021; Drury et al., 2016).

### 3.5. Decision-Making bottlenecks

Even when the components of wildfire risk are individually characterized, they often fail to accelerate the actual decision-making process (Thompson et al., 2019). Outputs are hard to update, and difficult to interpret for non-technical decision-makers. The inability to rapidly iterate on scenarios or visualize their consequences in real time undermines the very premise of risk-based planning amidst the dynamic nature of wildfire and forest management (Ager and Safford, 2025). This disconnect contributes to the persistent lag between scientific insight and actionable decisions, particularly in risk-exposed, high-consequence landscapes (Thompson and Calkin, 2011). For structured decision frameworks to influence outcomes on the ground, they must be not only scientifically robust, but also facilitate rapid and flexible iteration, while remaining accessible to the full range of end-users.

## 4. Bridging the gap: the vibrant planet platform

The VPP was developed to support refinement and integration of the QWRA framework into a set of structured decision-making processes for planning, prioritization, and implementation (Fig. 1) and to make such processes feasible, scalable, and accessible. Built as a modular, cloud-based decision support system, the platform integrates fire behavior modeling, vegetation response, optimization, and decision-maker engagement into a unified workflow that is designed for both scientific rigor and practical use. Below we describe the key features of VPP that address the challenges outlined in Section 3.

### 4.1. Modular architecture and cloud-native design

At its core, VPP functions as a decision support system that links together spatial datasets, simulation models, and collaborative scenario tools within a single user interface (Fig. 2). Its modular design allows individual components—fire hazard modeling, response functions, economic outputs—to be updated or replaced as data, models, and science evolve. Cloud-based deployment provides access to large-scale spatial processing that addresses the issue of planning across multiple scales (Munson et al. 2024). This also allows for computing independent of local resources and avoids issues around data duplication, software version control, file sharing, and the like, which frequently plague users of decision-support tools. This architecture supports deployment across landscapes from thousands to millions of hectares and enables rapid iteration in collaborative settings.

To resolve the model fragmentation described in Section 3.4, VPP integrates inputs from widely used tools including FSim (Finney et al., 2011; Moran et al., 2025) and WildEST (Finney, 2004; Farthofer et al., 2009; Scott et al., 2024) for fire hazard (Box 3, Fig. 2), VibrantVS for forest structure and biomass (Chang et al., 2025), and ForSys for optimization (Day et al., 2023). Rather than requiring users to manage intermediate formats (e.g., .lcp, .fw13, .frisk), the platform handles model interoperability internally, enabling users to work with outputs rather than wrestle with inputs. Optimization is handled by a real-time implementation of ForSys that sequences projects using a greedy spatial heuristic, balancing management objectives and user-defined constraints such as budget, number of projects, and treatment type. This enables project prioritization in a matter of seconds for landscapes up to hundreds of thousands of hectares in size. See Supplemental Information for Vibrant Planet's wildfire ignition probability data for the western and southeastern US, and for links to the externally developed tools that drive our wildfire hazard determinations and management planning optimization.

### 4.2. High-Resolution, benchmarked, continuously updated multi-source data

To overcome the challenge of fragmented and outdated inputs, VPP harmonizes and serves data from a variety of sources, both publicly available and internally generated where critical gaps exist. Management unit delineation (Box 2, Fig. 2) is based on a forest structure machine learning model (VibrantVS) that infers a canopy height model and canopy cover as well as derivatives for basal area, quadratic mean diameter, biomass, volume, and trees per acre. The model was trained on LiDAR and applied to NAIP imagery using the most current machine learning methods (Chang et al., 2025). These data at 0.5–2 m resolution enable the segmentation of a landscape into areas (averaging 3–4 ha) that are relatively homogenous in their vegetation structure, topography, and anthropogenic features (e.g. roads), and can serve as meaningful planning units for describing landscape conditions, determining treatment feasibility (which is based on VPP's extensive catalogue of potential management actions), and determining treatment impacts on risk and other metrics. See Supplementary Information for the VibrantVS canopy height model validation dataset.

Additional base layers used in the platform include customized LANDFIRE fuels data (Scott and Burgan, 2005; Pyrologix, 2024), topography from the USGS 3DEP program, wildfire likelihood (Moran et al., 2025) and intensity data, including representations of hazard under different treatment types, and locally sourced HVRA layers (Box 1A, Fig. 2). Data are regularly refreshed as new and more accurate source data become available. For example, post-fire impacts are detected utilizing changes in the seasonal remote sensing-based indices to delineate large areas of tree mortality, thus creating a dynamic spatial foundation that reflects current landscape conditions.

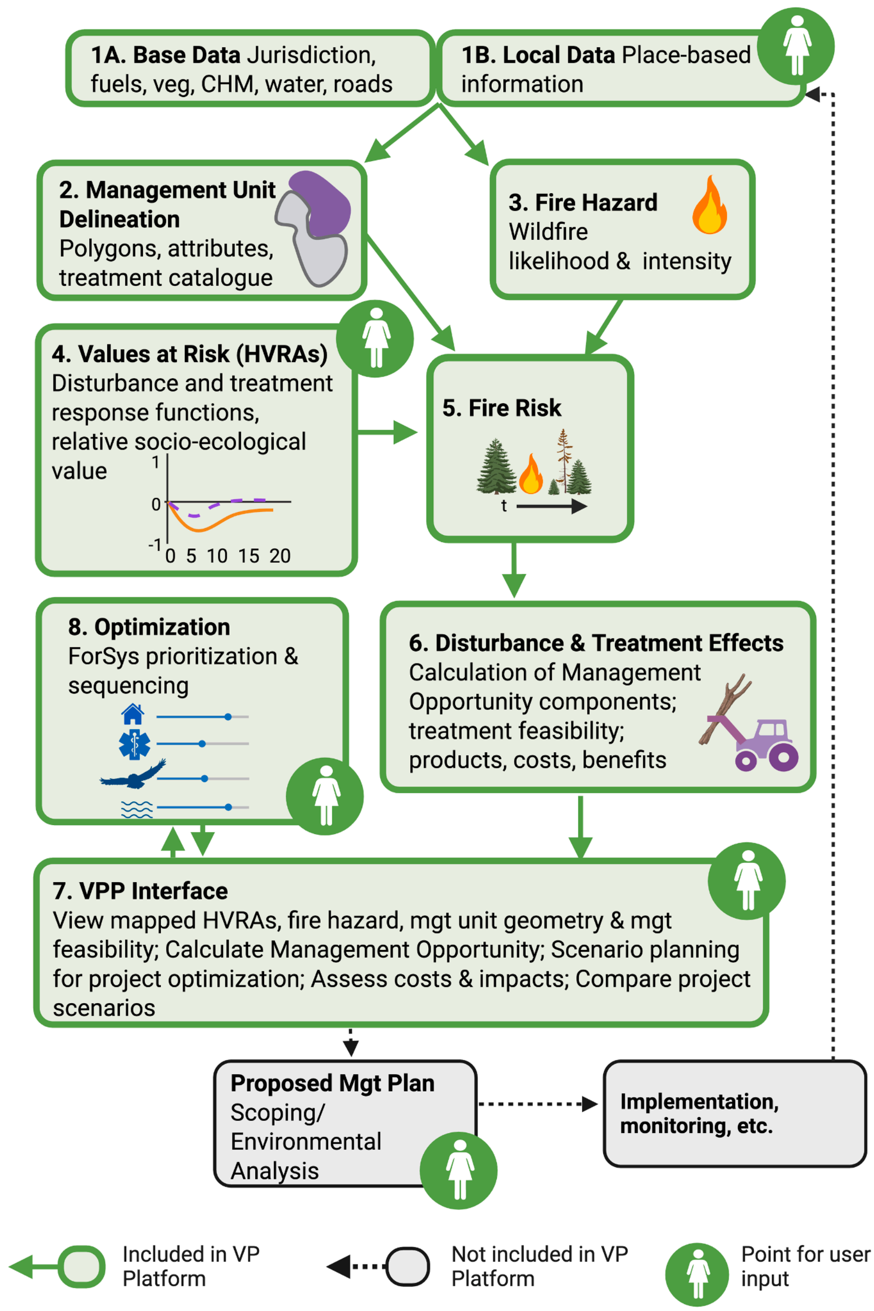


**Fig. 2.** Vibrant Planet Platform (VPP) workflow and key steps. Green, solid lines and green boxes indicate steps carried out within the VPP workflow. Dashed lines and black boxes indicate management steps outside of the platform. Important user input/participation indicated by green circles. CHM = canopy height model; HVRA = Highly valued resources and assets; mgt = management. See VP (2024) for details.

### *4.3. Place-based data*

Wildfire resilience planning is inherently local. While VPP has base datasets that can be used for a set of HVRAs, the platform also supports integration of custom, place-based datasets (Box 1B, Fig. 2) alongside default high-resolution hazard and resource/asset layers, ensuring region-specific priorities—such as cultural heritage sites, municipal water infrastructure, collaboratively defined restoration areas, or locally important habitat—are visible in the decision space. By embedding local knowledge directly into scenario design, the platform bridges the gap between generalized science and context-specific stewardship needs, improving both ecological and operational relevance.

### *4.4. Dynamic, quantitative, and treatment-aware response functions*

Many ecological resources and assets currently lack well-defined quantitative response functions for values at risk, particularly for treatments. Where response functions do exist, they are often categorical, static, or derived from broad generalizations that cannot fully capture local variability. VPP addresses this gap by enabling a spectrum of response function development—from expert-informed to data-informed—through its open-source "response function generator" (Gilbert and Duffy, 2025) (Box 4, Fig. 2; Fig. 3). This approach allows response functions to be initially parameterized from expert knowledge, literature synthesis, and place-based experience, and then progressively refined as empirical monitoring and quantitative modeling become available.

For forest-structure-dependent HVRAs, the response function

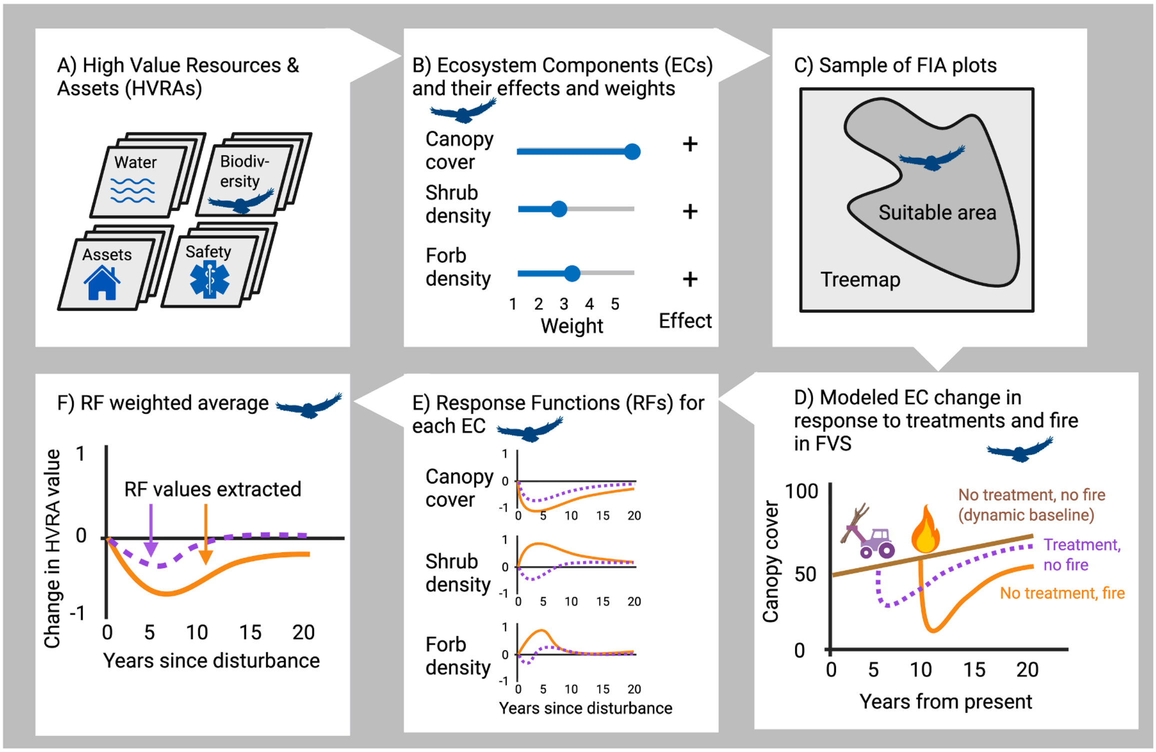


**Fig. 3.** Workflow example for the VP Response Function Generator for an HVRA focused on habitat for a high value avian species. Some high value species with spatially complex life histories may be represented by multiple resource and assets focused on different habitat components, or - as here - the habitat components may be weighted and combined in a single HVRA. The VPP uses a quantitative, model-based approach whenever possible. FIA = US Forest Service Forest Inventory and Analysis program.

generator can leverage tools such as the Forest Vegetation Simulator (FVS) and its Fire and Fuels Extension (FFE) (Rebain, 2022) to simulate the impacts of treatments and disturbance on vegetation structure through time, and the cascading consequences for habitat, carbon, or other values (Fig. 3). Where treatment response functions are absent, expert- or community-driven knowledge can fill critical gaps, providing a transparent starting point that can later be updated with empirical data or mechanistic modeling.

All response functions—whether qualitatively informed or quantitatively derived—are expressed on a continuous [−1, 1] scale and estimate treatment effects with or without fire. Applied spatially, they adjust HVRA values within their footprint under treatment and disturbance scenarios, thereby informing optimization. Importantly, the response function framework is iterative: response functions can be revised as new data, monitoring results, or scientific insights emerge. This dynamic, hybrid approach both acknowledges the incompleteness of current ecological response functions and creates a clear pathway for integrating local expertise with advancing quantitative science. See Supplementary Information for code and instructions for Vibrant Planet's Response Function Generator and the HVRA Risk Reportcard.

### 4.5. Participatory scenario planning and stakeholder weighting

To support collaborative governance (Section 3.3), VPP includes a scenario planning interface (Box 7, Fig. 2) that allows users to assign relative weights to eight management objectives (Table 2) across a landscape or within distinct management areas. The management objectives represent groups of HVRAs. The weights influence computation of a composite relative score per segmented management unit, representing the avoided risk and/or direct effects of feasible treatments for each management unit on the resources and assets located there, according to the objective weights selected by the user (VP 2024). The system uses these scores to identify the treatment for each unit that generates the highest composite score based on the user's selections, and uses the score for each identified treatment per management unit to rapidly optimize prioritized vegetation management projects via ForSys (Box 8, Fig. 2; Ager et al., 2012; Day et al., 2023).

**Table 2**
Objective descriptions and example Highly Valued Resources and Assets (HVRAs).

| Objective | Description | Examples of HVRAs |
|---|---|---|
| Assets | Aspects of the built environment on the landscape | Structures, Power distribution lines |
| Biodiversity | Plant and animal species or specific habitats in need of special protection | Northern goshawk suitable habitat, Whitebark pine |
| Ecological Commodities | Areas where economic activity is tied directly to the landscape | Managed timberlands, Mines |
| Recreation | Features that are primarily used for recreational purposes | Campgrounds, Trails, Ski areas |
| Safety | Aspects of the landscape or built environment that provide critical safety features | Critical access roads, Hospitals |
| Science & Culture | Scientific monitoring infrastructure and areas of cultural significance | Historic structures, Tribal cultural sites, Monitoring stations |
| Water | Surface water features and flows | Surface water, Perennial rivers and streams |
| Wildlands Health | Plant formations or other HVRAs that represent wildland health, function or resilience | Forest carbon, Freshwater wetlands |

The result is access within minutes to maps and reports, such as prioritized project maps; maps of resource/asset risk and value; the composite score used in prioritization (based on avoided risk and direct effects of treatment); no-action vs. post-treatment hazard, burn probability, and flame length; summaries of ownership, treatment costs, and economic outputs; and scenario comparison tools. This allows decision-makers and project partners to see tradeoffs, explore alternatives, and iteratively refine their priorities.

The platform is designed to then facilitate consensus by revealing areas of alignment among diverse interest groups. Traditional wildfire risk assessments typically generate maps of risk to help further inform decision-making about priority areas; the VPP's extension of that process is to create landscape units for prioritization, use a multi-objective optimization algorithm for grouping and prioritizing project areas, and also use avoided risk and/or direct effects of treatment from feasible treatments as part of the optimization (rather than wildfire risk alone).

### *4.6. Outcome-focused metrics and proposals*

Expanding beyond traditional wildfire risk assessment, the VPP incorporates outcome-focused metrics that connect modeling outputs to tangible, real-world impacts (see Vibrant Planet Knowledge Base, 2025). Rather than only reporting relative changes in resource/asset values or management objectives, the platform expresses results in concrete terms—such as reductions in flame length and fire spread, hectares of high-value habitat improved, kilometers of road made accessible for emergency response, hectares of Wildland Urban Interface made safer for incident response, or metric tons of carbon retained in live trees. These metrics translate complex model outputs into measures that are more easily understood and directly relevant to decision-making.

These outcome-focused measures are integrated into the platform's "proposals" function, which can generate outputs for any combination of projects and scenarios (see Vibrant Planet Knowledge Base, 2025). Users can download spatial layers (e.g., wildfire risk and outcome metrics) as well as document templates designed for both general project proposals and specialized planning needs, such as Community Wildfire Protection Plans. In practice, these tools are commonly used in grant applications and to communicate potential project impacts to diverse audiences.

By providing accessible, spatially explicit, and context-rich metrics, VPP reduces the technical burden on stakeholders, accelerates consensus-building, and supports transparent evaluation of trade-offs across projects. In doing so, outcome-focused metrics strengthen communication with the public, policymakers, and funders, helping to bridge the gap between technical modeling and the practical realities of planning and implementation.

## 5. Vibrant planet platform model implementation

### *5.1. Model use*

Since its initial deployment in 2021, the VPP has been implemented across a wide range of forested and fire-prone landscapes in the western United States. These applications have spanned spatial scales from tens of thousands to several million hectares and have supported diverse planning objectives—from fuel treatment prioritization and ecological restoration to forest carbon and emissions reduction planning, collaborative scenario design, grant application support, and project reporting. The platform is now deployed across >30 million ha in eight states. Its use cases span from fuels reduction and forest planning on large landscapes to more localized applications such as prioritized home inspection plans based on exposure.

### *5.2. Pike-San Isabel case study*

Beginning in 2024, the Pike-San Isabel National Forests and Cimarron and Comanche National Grasslands (PSICC) in Colorado and western Kansas utilized the VPP in a collaborative effort to assess risk across 800,000 ha and collaboratively prioritize fuels reduction projects across the landscape (see Story Map at https://storymaps.arcgis.com/stories/5280f7910af8449b98f752690336c33b). They began with a customization process that involved over 40 local partner organizations coming to agreement on which values to map and considering the impacts of potential wildfire and management options. Through multiple collaborative meetings, partners provided local data to support the mapping and experts worked to develop response functions for each value they agreed to include (Fig. 4). This collaborative process resulted in a customized VPP with 39 distinct HVRAs ranging from critical structures to Mexican spotted owl (*Strix occidentalis lucida*) habitat. The multi-meeting approach to selecting values and developing their response functions developed relationships across partner organizations and initiated a level of group coherence that facilitated ongoing collaboration. The ability for partners to customize the platform to reflect their own values and local knowledge developed trust in the decision support system.

After customizing the VPP to better represent local landscape resources and assets, partners formed three regional subgroups to carry out a collaborative planning exercise using the platform. Each subgroup utilized the VPP inputs to determine their management priorities and identify the greatest management opportunities based on those priorities. The VPP allowed partners to also consider their management objectives as well as real-world constraints such as capacity, budget, and treatment limitations, across millions of hectares. This collaborative process resulted in the identification of 240,570 priority ha for treatment. Partners continue to use these priority hectare areas to plan cross-boundary projects for implementation using VPP. The platform allows partners to consider multiple management objectives, risk reduction co-benefits, and real-life constraints at many scales across their landscape.

Utilizing the VPP-predicted metrics, partners were able to consider the potential impacts to wildfire hazard, product benefit, and more if they were to implement all identified hectares. They found that by treating 29 % of the over 800,000 ha they would accomplish a 42 % predicted reduction in wildfire hazard across the whole landscape. Partners utilized the planning and outcome metrics from the platform to create a Story Map (see Story Map link) for a broad audience and they continue to use these metrics to fundraise for implementation.

### *5.3. Utilization across scales and collaborative objectives*

The PSICC case illustrates how VPP can be customized and embedded within a collaborative process at the scale of a national forest. Other implementations demonstrate the platform's flexibility across both larger and smaller contexts.

At the largest scales, federal and regional partners have used VPP to standardize data and segment landscapes consistently across millions of hectares. For example, the Bureau of Indian Affairs Northwest Region

**Fig. 4.** Collaborative meeting hosted by the Pike-San Isabel National Forests and Cimarron and Comanche National Grasslands and Vibrant Planet to identify Highly Valued Resources and Assets (HVRAs) and quantify values to support Vibrant Planet Platform deployment.

applied VPP analytics to evaluate wildfire risk to structures, utilities, biomass, and water across >5.47 million ha, directly informing budget decisions for fuels reduction. Similarly, the Southwestern Idaho Wildfire Crisis Strategy Landscape used the platform to prioritize fuels reduction opportunities across 744,000 ha, customizing values and objectives with input from state, local, NGO, and industry partners (see SIL Story Map for additional details).

At regional and community scales, VPP outcome-focused metrics have been particularly valuable for monitoring and fundraising. As noted above, PSICC partners used predicted outcome metrics to highlight co-benefits of fuels reduction projects and secure funding. In Southern California, partners are using the platform to quantify the avoided loss and hazard reduction achieved by fuelbreaks and other treatments across 3.52 million ha, tailoring outputs to communicate with funders and community stakeholders.

At the local scale, fire protection districts and CAL FIRE (California Department of Forestry and Fire Protection) units have employed VPP to create dynamic, collaborative planning processes. In California, the Truckee Fire Protection District used the platform to support an annually updated Community Wildfire Protection Plan, while the CAL FIRE Amador–El Dorado Unit developed a strategic fire plan that identified cross-boundary opportunities and prioritized parcels for inspection based on wildfire vulnerability. These local applications demonstrate how VPP can support both long-range planning and operational decisions tied to community protection.

Across all scales, the VPP's ability to ingest local HVRAs and accommodate partner-specific response functions and ecological models (Haugo et al. 2015; DeMeo et al. 2018; Laughlin et al. 2023) has proven critical in aligning federal, tribal, state, and NGO priorities within a common planning framework. Together, these deployments show that structured decision frameworks can be operationalized at scale, integrating high-resolution data, established models, and decision-maker input into real-world workflows (Table 3).

## 6. Validation and limitations

Validating complex decision support systems is inherently challenging—especially when they incorporate stochastic models, simulate long-term ecological change, and are embedded in human-influenced decision environments. Following Borenstein (1998), we adopt a multi-tiered validation framework to assess the reliability, relevance, and usability of the VPP. This includes face validation, subsystem validation, predictive validation where feasible, and decision-maker/practitioner feedback from active deployments (Table 4)

### 6.1. Face and subsystem validation

Face validation—whether the tool is relevant and salient to its intended users—has been central to VPP's design since its inception. Ongoing collaborations with federal and state agencies, NGOs, and community-based organizations have shaped the platform's architecture, scenario design interface, and data products. These engagements confirm that the platform addresses common pain points identified in the wildfire decision support literature (Colavito, 2021).

Subsystem validation relies on the well-established peer-reviewed models that underpin VPP's core functions. Burn probability data generated using FSim were validated against observed fire occurrence (Moran et al., 2025). Structural vegetation data products, such as the CHM and CC layers, have been benchmarked against LiDAR-derived reference datasets and other regional canopy models, showing superior performance across most height classes and ecoregions (Chang et al., 2025). Optimization outputs from ForSys have shown >95 % concurrence with linear programming benchmarks (Ager, 2024), while offering faster runtime and higher usability and transparency.

### 6.2. Predictive and field validation

Formal predictive validation of the FSim wildfire likelihood and spread modeling tool was recently published in two separate studies (Carlson et al., 2025; Moran et al., 2025). Importantly, Moran et al. (2025) – who compared 4 years of burn probability maps with subsequent fire activity across California (2020–2023) – showed that annually updated fuels input data improved predictive accuracy. Results showed that up to 80 % of the burned area occurred in the top 20 % of mapped burn probability, and mean burn probabilities in burned areas were up to 350 % greater than in unburned areas.

Limited preliminary field validation of VPP-generated management unit segmentation has been conducted through on-the-ground comparison with professional forester prescriptions and layout. In a validation set of 200 management units, 77 % were determined to be spatially sufficient to support a single prescription; the remaining 23 % were judged to require split treatments, often due to slope heterogeneity not captured in segmentation. It should be noted that the management units delineated in the platform are meant to help package the landscape into reasonable units for prioritization, but are not meant to be a replacement for layout and prescription in the field.

Similarly, validation of VPP-generated treatment recommendations against forester-determined options showed high overlap in the set of feasible treatments (~85 %) but more modest agreement on the "optimal" choice (often <50 %). Discrepancies typically stemmed from fine-scale structural variation or social factors not yet integrated into the

**Table 3**
Examples of the diversity in Vibrant Planet Platform (VPP) use cases, deployment acres, and collaboration objectives. WUI = Wildland urban interface; CAL FIRE = California Department of Forestry and Fire Protection.

| Use Case | Example Landscapes | VPP Deployment (hectares) | Collaborative Objectives |
|---|---|---|---|
| Large Landscape Prioritizations | Bureau of Indian Affairs - Northwest Region | 5,471,698 | Quantify and assess wildfire risk across a large and diverse region to inform budget decisions. |
| | Southwestern Idaho Landscape | 744,284 | Consider multiple management objectives ranging from protection of species habitat to WUI in a prioritization exercise to identify high-value risk-reduction fuels implementation opportunities. |
| Monitoring and Fundraising | Pike-San Isabel National Forests and Cimarron and Comanche National Grasslands | 879,510 | Assess predicted outcome metrics for high-impact fuels reduction projects in order to track progress and to secure funding by highlighting cobenefits achieved through each project, Communicate wildfire risk and risk reduction opportunities community-wide. |
| | Southern California | 3,521,603 | Analyze hypothetical fuelbreak and fuels reduction treatments to quantify potential avoided loss in the event of wildfire. |
| Community Protection | Truckee Fire Protection District | 57,730 | Informed collaboratively developed community wildfire protection plan through analytics, create ongoing dynamic processes by regularly updated data |
| | CAL FIRE Amador-El Dorado Unit | 1,075,821 | Created a strategic fire plan and coordinate implementation opportunities with partners, assessed individual parcels for wildfire vulnerability to prioritize parcels for inspection |

**Table 4**
Summary of validation approaches applied in the Vibrant Planet Platform (VPP). Validation spans face validation with end-users, subsystem benchmarking against established models, predictive validation (including recent burn probability validation; Moran et al., 2025), and field validation with practitioners. Together, these approaches illustrate both the current state of validation and areas where additional testing is ongoing.

| Validation Type | Definition | Applied In VPP | Key References |
|---|---|---|---|
| **Face Validation** | Assessment of relevance and usability by end-users and decision-makers | Yes – ongoing user feedback during deployments and co-design processes | Thompson and Calkin, 2011; Colavito, 2021 |
| **Subsystem Validation** | Testing of internal models (e.g., fire, growth, optimization) against known benchmarks or published accuracy | Yes – fire modeling (FSim, WildEST), canopy height model validation, ForSysR benchmarking | Finney et al., 2011; Chang et al., 2025; Ager, 2024 |
| **Predictive Validation** | Comparison of model outputs with observed real-world outcomes (e.g., fire severity, burn probability) | Demonstrated for burn probability (Moran et al., 2025); additional validation ongoing for other components | Moran et al., 2025 ; Thompson et al., 2024; Scott et al., 2024 |
| **Field Validation** | Comparison of segmentation and treatment outputs with expert forester judgment on the ground | Yes – 77 % agreement on segmentation sufficiency; 85 % overlap in feasible treatment options | Internal validation reports; practitioner feedback |

platform's logic, such as treatment visibility or jurisdictional preferences.

### 6.3. Limitations and areas for improvement

While VPP has significant strengths, it also faces limitations that highlight opportunities for improvement. For example, although the platform supports high-resolution modeling of vegetation structure, subcanopy fuels (e.g., shrubs, litter, duff) are approximated with modified LANDFIRE fuels data. This approach can miss heterogeneity in the understory environment, even though annual updates are informed by collaborative workshops and expert rulesets applied to recent disturbances.

Another limitation stems from the response functions that drive many of VPP's analyses. Their robustness ultimately depends on the quality of underlying data and knowledge. Expanding empirical integration—particularly through post-treatment monitoring—remains a critical area of ongoing research (e.g., Yackulic et al., 2025). Similarly, the platform does not yet dynamically simulate post-treatment changes in burn probability. Instead, treatment assumptions are applied to pre-treatment burn probability, and post-treatment changes in fire intensity are approximated through heuristically modified fuels inputs to WildEST. Development of more dynamic capabilities is underway.

Valuation of resources and assets poses another challenge. Current approaches are relatively simple, relying on non-market valuation methods that do not fully account for spatial scarcity, heterogeneity, or complex social and ecological dynamics unique to each landscape. Future work could explore alternative valuation frameworks or optimization approaches to address these shortcomings. Likewise, reporting of landscape-scale effects is constrained by the priorities and data available to the sponsoring group. If, for example, biodiversity is excluded from resource and asset prioritization, VPP cannot optimize with biodiversity in mind, although outcome-focused metrics can still provide insight into potential ecological or permitting implications. If biodiversity data are lacking altogether, the platform cannot report on biodiversity impacts. Finally, barriers to entry—whether financial or organizational—may limit access, since VPP has not yet been sponsored or funded by government entities or philanthropies to provide access across all available areas.

The extent of validation also varies across subsystem models (see Section 6). While each has undergone some form of testing and most are based on long-established industry or government standards, predictive validation and benchmarking remain incomplete. Further validation is a priority, and we encourage both user-driven and independent evaluation.

Finally, while VPP facilitates decision-maker scenario design, it does not replace governance nor resolve the challenges inherent to collaborative planning. The platform provides a robust foundation for defining strategic interventions at broad scales, but it is not a substitute for the finer-scale logistical work required for implementation, such as stand-level prescriptions or workforce planning. Like other decision support systems, VPP also encounters institutional and cultural barriers in agencies and other groups that have not historically approached risk-informed planning with technology (Colavito et al., 2021). To mitigate these pitfalls, the platform has been intentionally designed to encourage broad participation and local customization, fostering trust and buy-in for the planning process (Fillmore and Paveglio, 2020). Stronger institutional alignment with VPP or similar systems would enable more integrated use, but broader adoption will ultimately require robust training, workflow alignment, and cultural shifts across agencies (Fillmore and Paveglio, 2023). These shifts represent not only challenges but also opportunities for institutional innovation, where decision support systems can help reshape planning cultures to be more adaptive, collaborative, and risk-informed.

## 7. Discussion: broader implications for wildfire risk assessment

The structured risk assessment framework outlined in GTR-315 remains one of the most comprehensive, standardized, and defensible approaches to wildfire planning in fire-prone landscapes. However, turning that framework into an operational system focused on how risk can be changed requires more than technical alignment—it demands rethinking how models, data, and users interact. The development and deployment of the VPP illustrate how a modular, integrated, and user-centered platform can overcome long-standing barriers that limit real-world impact of ecological modeling tools.

### 7.1. Reframing integration as infrastructure

Rather than treating each submodel—fire behavior, forest growth, treatment cost, or ecological response—as an isolated product, VPP *treats integration itself as infrastructure*. It builds connections between high-performing modeling tools and manages the data flows, assumptions, and interoperability requirements that typically burden users. This shift allows practitioners to focus on questions and decisions rather than data wrangling or model execution, lowering the barrier to entry and increasing uptake. More broadly, this approach follows a replicable design philosophy for ecological modeling: build platforms that assemble and translate models for use in a modular fashion, rather than expecting users to assemble them individually in an ad hoc fashion.

### 7.2. Improving accessibility to complex modeling power

By embedding structured decision-making in a cloud-based platform with real-time feedback, VPP makes it possible for decision-makers to engage meaningfully with fire risk, ecological tradeoffs, and scenario outcomes (Marcot, 2012), which would typically require individual groups of highly specialized scientists to collaborate on and communicate with decision-making groups. This aligns with calls for radical transparency and participatory governance in landscape planning (Yung et al., 2022). Traditional ecological models are often inaccessible to the very communities most affected by management decisions. Tools like VPP suggest that improving access to powerful, integrated data from complex modeling platforms is not just a social goal, but a technical design challenge—one that must be solved for ecological science to inform decision-making at scale.

### 7.3. Redefining validation in decision support systems

The multi-tiered validation approach in VPP underscores an important tension in ecological modeling and forecasting: what does it mean for a system to be valid when the goal is to predict complex, probabilistic, or counterfactual outcomes in the future, given imperfect data, and understanding that decisions and action are critical *now* (Borenstein, 1998; Roy, 1993)? Traditional models often emphasize predictive accuracy, but decision support tools must also optimize for usability, interpretability, and robustness across scenarios to offer actionable utility under imperfect and constantly evolving information. VPP's framework reflects this hybrid goal, combining model benchmarking and field validation with an emphasis on decision-maker trust and practical utility.

As decision support systems become more deeply embedded in policy and investment processes, the ecological modeling community will need to embrace pluralistic, use-oriented definitions of validation that still take seriously the accuracy thresholds that define utility. One of the largest obstacles to this goal is the lack of high quality and comprehensive publicly available benchmarking datasets and testing frameworks for models and data products that are pivotal to informed decision-making. This challenge is not unique to any one domain, but is true across the spectrum of models, from vegetation structure and disturbance, to a large suite of ecological processes. Given this vacuum of scientifically rigorous benchmarking frameworks, some components of VPP remain incompletely validated. Building durable trust and transparency requires continuous—and ideally independent—evaluation of both subsystem models and the platform as a whole. Such efforts can illuminate where uncertainty is greatest, where performance is stronger or weaker, and where systematic biases may arise.

### 7.4. Scaling structured decision-making

Perhaps most importantly, VPP demonstrates that structured decision-making – often hindered by multi-scale challenges – can now be operationalized at landscape and regional scales (Munson et al., 2024). Through automation, modularity, and pre-integration of key models, the platform enables risk-informed planning at previously unattainable speeds and scales.

In practice, a current user of VPP can apply the standardized western-US-wide HVRAs to assess risk and effects of treatment across upwards of 4–5 million ha, while also creating a fuels reduction plan across an area of <2000 ha (Table 2). This capacity to operate seamlessly across scales reflects a critical advance for risk-based planning.

While challenges remain—particularly around ecosystem uncertainty, multi-benefit accounting, and data quality—the model offered here points to a future in which ecological modeling is not just a back-end process but a central, accessible pillar of collaborative governance that meets decision-makers at the scale in which they are managing (Ellis et al., 2025).

## 8. Conclusion

The VPP was designed to solve a practical problem: how to turn a scientifically rigorous but operationally fragmented QWRA framework into a usable, scalable system for collaborative wildfire planning. Earlier tools addressed pieces of this challenge, but in ways that left critical gaps (Table 1). ForSys, for example, provided powerful optimization capacity but relied on hazard, exposure, or risk data from external sources, often requiring intensive data preparation and creating fragmentation in workflows. IFTDSS, meanwhile, standardized access to fuels and fire behavior modeling, but was not designed to integrate multi-objective optimization or collaborative prioritization at landscape and regional scales. VPP builds on these foundations by unifying risk assessment, response functions, optimization, and participatory scenario planning into a single platform.

In doing so, VPP demonstrates that the structured risk assessment framework envisioned more than a decade ago can now be implemented with sufficient speed, transparency, and ecological fidelity to inform real-world decisions at the scale demanded by the current wildfire crisis. Processes that once required years of modeling, review, and iteration can now be completed in minutes, allowing decision-makers to explore, refine, and act on scenarios in near real time.

By integrating high-resolution data, established models, and collaborative planning tools into one system, VPP lowers the barriers between ecological modeling and land management action. As the changing climate and intensifying disturbance regimes accelerate both the urgency of planning and the complexity of trade-offs, platforms like VPP represent a new generation of ecological tools—designed not only to model possible futures, but to enable decision-makers and communities to shape them.

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## CRediT authorship contribution statement

**Hugh Safford:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Colton Miller:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Danielle Perrot:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Sophie Gilbert:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Tyler Hoecker:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Michael Koontz:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Kailey Kornhauser:** Writing – review & editing. **Matt Thompson:** Methodology, Investigation, Formal analysis. **Joe Shannon:** Methodology, Investigation, Formal analysis. **Nathan Rutenbeck:** Writing – review & editing. **Joe Scott:** Methodology, Investigation, Funding acquisition, Formal analysis. **Scott Conway:** Methodology, Investigation, Funding acquisition, Formal analysis. **Katharyn Duffy:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Hugh Safford reports financial support was provided by Vibrant Planet. Hugh Safford reports a relationship with Vibrant Planet that includes: consulting or advisory and equity or stocks. All co-authors either currently work for Vibrant Planet or worked for Vibrant Planet in the past. Some of the co-authors have stock equity in the company. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2025.111464.

## Data availability

This study is descriptive and does not present the creation or analysis of any new datasets. The VPP ingests a combination of public (see Acknowledgements and References), and proprietary or client-provided datasets. The VPP Interface itself is proprietary and accessible by contract with Vibrant Planet. Interested parties are able to access the Interface and a demonstration landscape by requesting a guest license at the Vibrant Planet website (https://www.vibrantplanet.net/) or by contacting the last author. All of the key submodules described in this manuscript are open access, as described in Supplementary Materials:

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