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Review Article

Navigating the evolving landscape of wildfire management: A systematic review of decision support tools

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ABSTRACT

Wildfires have become more frequent and intense in recent years, threatening terrestrial and aquatic ecosystems and neighboring urban communities. As a result, those responsible for managing wildland fires face increasing pressure to address this challenge strategically. Over the past 20 years, these managers have turned to decision support tools (DSTs) to help guide their actions. We conducted a systematic literature review to explore the landscape of decision support tools (DSTs) for wildfire management, focusing on their functionalities. We additionally examined potential gaps in their design and implementation. The systematic review led us to group decision support tools into categories for all DSTs, such as, Fire Behavior Models or Post Fire Models. These categories are not discrete and can be nested to address land management and fire response questions. Moreover, our findings highlighted a significant gap in tools that effectively integrate ease of use with collaborative capabilities, underscoring the urgency for developing more user-friendly and collaborative decision-making tools. Our research also revealed a disconnect between the academic literature's focus and the tools' actual field usage, emphasizing the need for more accurate documentation and a streamlined approach to wildfire management tool selection. We proposed further social science research to understand the real-world use and preferences of DSTs, aiming to bridge the gap between theoretical robustness and practical utility. This comprehensive analysis of DSTs addresses current wildfire management challenges and sets the stage for future advancements in developing more effective and user-oriented decision support systems.

1. Introduction

In recent years, the frequency and severity of wildfires have increased significantly, posing a growing threat to ecosystems, communities, and economies worldwide. Combined with the history of fire suppression in the western United States, climate change has created more severe and synchronous fire seasons and increased tree mortality events (Abatzoglou et al., 2021; Williams et al., 2019). High-severity wildfires can harm forest ecosystem functions and have extended impacts on forest health, flora and fauna communities, recreation, public health, and economic commerce from woodland products (Miller and Ager, 2013; O'Connor et al., 2016). Managers in the western United States are experiencing heightened pressure to address these immediate threats to forest health and function (Ager et al., 2021a, 2021b). The urgency for faster management action is greater now than ever before.

In response to this challenge, managers have utilized wildfire risk and treatment prioritization support tools for decision-making to assess and manage wildfire planning and response. A decision support tool (DST) for wildfire is a software application, framework, or system that assists managers in assessing, analyzing, and making informed decisions about wildfire risks. DST refers to specific tools, such as the Wildfire Decision Support System (WFDSS), as well as analysis methods and frameworks, such as Quantitative Wildfire Risk Assessments (QWRA) or Potential Operational Delineations (PODs) (Colavito, 2021).

Decision support tools can fit the needs of different types and structures of management objectives and questions (Miller and Ager, 2013; Noonan-Wright and Seielstad, 2022). These tools utilize various data sources, modeling techniques, and visualization capabilities to comprehensively understand fire behavior, potential impacts, and management strategies. For example, they can help users evaluate the likelihood and severity of wildfires, identify high-risk areas, and determine appropriate actions to mitigate those risks. By leveraging these

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tools, managers can make data-driven decisions regarding fire response strategies, resource allocation, evacuation plans, and treatment prioritization. The tools may facilitate stakeholder collaboration and communication by providing a common operating picture, sharing information, and analyzing results. They enhance situational awareness, improve response coordination, and support the development of effective wildfire management plans and treatment prioritization. These tools can vary in focus, framework, functionality, and scale across different agencies and regions in the western United States.

Decision support tools have grown significantly in response to the wildfire crisis and rapidly evolving field of wildfire management, providing fire managers and land management agencies with many options to assess wildfire risks. However, the number of decision support tools available can be overwhelming, making it difficult for fire managers to evaluate and compare them effectively. Moreover, fire and land managers need more information and guidance on the strengths, limitations, and suitability of specific tools for answering wildfire planning and management questions.

While there have been several past reviews and studies of wildfire decision support tools (e.g., Colavito, 2021; Pacheco et al., 2015; Sakellariou et al., 2017; Vásquez et al., 2021), these did not address the gap in creating clarity for managers. Due to the dynamic nature of the field of wildfire management and continuous improvements in geospatial capabilities, several reviews are no longer up to date. While we acknowledge that some limitations of DSTs from these reviews remain true, such as model uncertainty, other noted limitations, including the strength of geospatial data, have somewhat diminished. This change is partly because specific tools are now obsolete, and because advances in model capabilities and geospatial layers have addressed some of the earlier constraints in decision support. (Borchers, 2005; Thompson and Calkin, 2011). Other reviews focus on the user perspective and identify user barriers within decision support tools and systems (Colavito, 2021; Finney, 2021). While these reviews provide deep insight into the challenges of fire management, they do not create clarity or reduce the complexity of navigating the abundance of tool options facing managers. Vásquez et al. (2021) conducted a global review of decision support tools focusing on big data that served a broader purpose of understanding how fire management in the United States differs globally. While an insightful comparison, it does not address the nuances of the long history of fire suppression in the western United States. We aim to create a framework to holistically understand the dynamic and interconnected wildfire management decision space and how different tools move through it regarding tool usability and functionality. We intend to clarify the overlaps among various tools and identify areas where decision-making strategies are lacking, focusing on the western United States as the primary region for future expansion and study.

Given the continual advances in decision support systems, we asked the following questions: To what extent does peer-reviewed literature comprehensively represent the diverse array of wildfire tools utilized in the western United States? How do usability metrics vary across the wildfire decision support tools available in the western United States? How can the categorization and classification of decision support tools help managers navigate the decision support space?

Classifying and organizing decision support tools based on their functionalities, intended uses, and what type of wildfire management objectives the tool can address can assist managers in gaining a clearer understanding of the suitability of the available tools. A well-defined categorization framework of decision support tools can provide insights into their distinctive features and redundancies, enabling managers to decide which tool(s) is best suited for a particular scenario. By creating an enhanced and streamlined decision space through this classification, we hope to create an effective foundational guide for this continually growing and changing landscape of decision support tools through which managers can save time, effort, and resources that would otherwise be spent on evaluating multiple tools with overlapping applications.

2. Methods

2.1. Question 1: Systematic literature review protocol

We used a systematic review methodology to address our first question and categorize DSTs found in the literature. Systematic reviews aim to provide an unbiased and comprehensive synthesis of existing literature and focus on a specified knowledge gap using explicit, reproducible methods. Systematic reviews differ from informal literature reviews by following an explicit protocol for searching for literature, and inclusion/exclusion criteria for literature selection relating to said knowledge gap. This rigid protocol removes the potential for consciously or unconsciously favoring certain studies over others in the literature selection process. Systematic reviews also provide an inclusion cap for pertinent literature. Without a strict protocol for inclusion and exclusion criteria in a review, it would be difficult to determine where and when to stop including literature, thus potentially weakening the strength of the review, or making it unmanageably large. Systematic review protocols also create a reproducible trail that anyone could recreate following the inclusion timeframe, search engines, and inclusion/exclusion criteria. Like any research study, it is essential to ensure that the research is transparent and reproducible and provides a methodology for quality control to ensure that the studies included and the results extracted all follow the same. To avoid selection bias, we reviewed our search results following these criteria and determined that each paper selected met our inclusion and exclusion criteria for selection.

We conducted a systematic literature review from September 2022 through December 2022 to address our research questions and objectives. We used the following search engines: Google Scholar, "TreeSearch" (US Forest Service Publication Archive), Web of Science, and Ingenta, to search for peer-reviewed academic scientific literature on decision support tools. "Gray" literature (not peer-reviewed) and white paper search results were excluded from the review to meet a rigor standard and ensure our systematic review's replicability. Gray literature was excluded to specifically focus on the representation of wildfire decision support tools in peer-reviewed published literature. We included literature in the initial screening of the review to see if it addressed wildfire management decision support tools or provided some foundational or background information on wildfire risk assessment and treatment prioritization decision support tools. Several review papers on decision support tools have been conducted globally or focused on different types and applications of wildfire decision support tools. These papers clarify the foundation of the work on decision support tools done prior, though due to the scale of the review or the year of publication, we did not include these papers in our review.

Our review's inclusion criteria (Table 1) stated that the papers must have been published between 2005 and the present. This range of dates

Table 1
Inclusion and exclusion criteria as part of our protocol for selecting literature to include in our systematic review.

Inclusion:	Exclusion:
○ Date Range: 2005 – present ○ Location: western United States (AZ, CA, CO, ID, NM, NV, MT, OR, UT, WA, WY) ○ Include some wildfire management or treatment prioritization DST/DSS ○ Tool or use results must be replicable. ○ Tool used for fire or forest management falls into the wildfire planning decision support space.	○ Publication Year: older than 2005 ○ Geographic Location: Outside the western United States ○ Lack of geospatial data input or deliverable component ○ Tool cannot be readily produced or used. ○ Fails to fall in the umbrella category of forest management for restoration. ○ No exclusively restoration, watershed, or silviculture tools ○ Grey literature reports on DSTs (not formally published through the peer-review process)

was decided on as it captures some of the foundational decision support tools and their development and expansion. However, it is still current enough not to include any outdated literature or tools that may have been retired or revised in recent years. Papers also needed to address decision support tools and decision support systems used in the western United States. Other examples presented in articles from outside this region were not entirely ignored but needed to include an additional example from the western United States or mention the relevance of its application in that region through case studies or other means. Papers needed to include one or more wildfire decision support tools or systems (whether a formal application commonly used in management, or an analysis created by the authors) and provide methods, results, and conclusions of their use of the decision support tool (solely referencing decision support tools did not meet our criteria). Papers also needed to specify the input data type used in the decision support tool. We selected papers focusing on decision support tools that used geospatial data (e.g., LANDFIRE) and avoided including tools that exclusively used field-based data (e.g., photogrammetry). Our review focused on all pre-, post-, and incident-based wildfire assessment and treatment planning frameworks to understand how managers can prevent large-scale fires and make decisions during and after high-severity fires when classifying and prioritizing resource risk from wildfires. We followed the standard for systematic reviews established by Pullin and Stewart (2006).

We employed the following keyword searches in our search engines:

- Decision support tools OR decision support systems AND wildfire risk assessment AND forest management OR forest treatment prioritization OR thinning treatments OR fuel treatments
- *D*ecision support tools OR wildfire risk decision support tools OR forest management OR treatment prioritization OR thinning treatment OR watershed "decision support tool AND western United States
- decision support systems AND wildfire risk assessment
- Decision support tools OR fresh management OR wildfire
- Decision support tools AND forest management
- Decision support tools risk assessment
- Decision support tools AND fire management AND wildfire risk assessment
- Decision support tools AND treatment prioritizations AND wildfire
- Decision support tools AND watershed management AND fire management

2.2. Question 2: Application metrics of tools. using non-metric multidimensional scaling (NMDS)

To better understand of how various tools fit within a broader decision-making framework, we assessed tools for their ease of application. To do this, we extracted themes from our systematic review and background literature through thematic coding and identified patterns and connections. We reviewed the existing social science literature (pertaining to our same inclusion and exclusion criteria) to search for the current barriers, challenges, and characteristics of tools that managers care about. We did not set this search to match all the existing tools we found in our review; instead, we looked for themes about the general use of decision support tools. We expanded upon these barriers to create definitions and rankings to determine the different capabilities of varying decision support tools. We created rankings for each of these metrics through an iterative discussion process and assessed tool limitations and barriers from limitation sections in our inclusion articles and references. We created a classification system to distinguish different competency levels for each tool in each category. Thus, this comprehensive approach addresses the current demands of wildfire management and paves the way for developing more effective and user-oriented decision support tools, fundamentally enhancing the efficiency and efficacy of wildfire management strategies. We categorized these themes into eight distinct application metrics: Usability, User Support, Geospatial, Scalability, Accessibility, Time Investment for Output, Data Flexibility, and Collaborative Potential.

- **Usability**: Usability refers to the ease of use and time investment in learning a decision support tool to help users accomplish their objectives. It looks at factors such as user interface design, ArcGIS experience and modeling experience, and overall user experience.
- **User Support**: User support measures the availability and effectiveness of assistance users receive while interacting with the decision support tool. This includes features such as online help pages, tutorials, FAQs, and support such as phone numbers and emails that aid users in understanding and utilizing the tool effectively.
- **Geospatial**: Geospatial refers to the capability of the decision support tool to handle and analyze high-resolution spatial data as inputs and outputs.
- **Scalability**: Scalability assesses the decision support tool's ability to function at different geographic scales and in various regions of the United States.
- **Accessibility**: Accessibility refers to the extent to which the decision support tool can be accessed and used by individuals not affiliated with a specific agency or if any fiscal barriers can limit access.
- **Time Investment for Output**: Time investment for output measures the efficiency of the decision support tool in delivering results or outputs relative to the time and effort users invest. It creates a basic evaluation and estimation of the tool analysis speed and the overall time required to achieve desired outcomes.
- **Data Flexibility**: Data flexibility assesses the versatility and compatibility of the decision support tool with various types and formats of data. It includes the ability to import, process, integrate, and manipulate data in different formats from different sources and change the weights and data formats initially included in the tool.
- **Collaborative Potential**: Collaborative potential evaluates the capability of the decision support tool to facilitate collaboration and communication among multiple users or stakeholders.

Our investigations of each tool included additional information about tool inputs, outputs, and functionalities for what questions and objectives the tool could address as well as how they rank for each usability metric (Baskent et al., 2020; Noble and Paveglio, 2020; Noonan-Wright et al., 2022). To accomplish this, we conducted further research on each tool that was found in our systematic review. We analyzed resources for each decision support tool, including tool documentation, online tutorials, previous workshop reports, and additional literature (peer-reviewed and gray). When available, we interacted with the tool platforms and dashboards to extract supplemental details regarding their usability. We compiled this information into a spreadsheet and followed the criteria we established for how to rank each tool's competency (Table 2) for each usability metric.

Each tool was evaluated in these categories on a scale from 1 to 5, where 1 signifies lower performance or partial fulfillment of the criteria within a classification. For example, a tool receiving a score of 1 for *Usability* indicates that the tool is not as user-friendly as a tool scoring a 4 or 5; thus, if a manager without much modeling experience is looking for a tool, to begin with, this metric can help distinguish a frame of reference for where to start. A tool scoring a 5 for *Scalability* has the potential to operate at a vast geographic level, whereas a one indicates the tool can work at small, localized community scales. We find it crucial to mention that in this scoring process, none of the usability metrics are more important than any other, nor does a score of 1 indicate that a tool is a poor choice. These rankings help define the decision support space and distinguish how tools, much like species, can vary from generalist to highly specialized.

Metrics were assessed in multi-dimensional space using Non-metric Multidimensional Scaling (NMDS). NMDS is a multivariate analysis method used to visualize and interpret the similarities or differences in a dataset. It projects the relationships among objects into a space of

Table 2
NMDS ordination axes and rankings for decision support tools. A higher score indicates that the tool can meet broader applications, while a lower score suggests specificity or a lesser ability to address the corresponding class barriers.

Classifier	Axis	Rank 5	Rank 4	Rank 3	Rank 2	Rank 1
Usability	1	No ArcGIS background is needed	Arc experience needed	Modeling and arc experience	Tutorial course needed	External expertise needed
User Support	2	The task can be assisted with immediately	Call/email help available	YouTube or online tutorials	Online pages for troubleshooting	There is little to no help page
Geospatial	3	Can incorporate local data; specific metrics	Data available for only a single region	Single data layer available statewide	Landfire, lower resolution	Little geospatial data
Scalability	4	Nationally	Multiple regions	Specific to one region	District level	Community level
Accessibility	5	Open source, open access	Open access	Specific agency only	Subscription or paywall	High pay wall barrier
Time for Output	6	On the scale of minutes to hour	Scale of hours	Scale of days	Several days to weeks	Monthly or longer
Flexibility	7	Can add multiple localized/updated data	Can update data layers	Specific data input layers	Adjustable weights	There is no flexibility with the input
Collaborative	8	Used for cross- boundary work	Can be used by external collaborators	Within agency collaboration	Single agency use	Single organization or decision

reduced dimensions, usually two or three, without assuming linear relationships between variables. The focus is maintaining the rank order of distances or dissimilarities between points. In the resulting ordination plot, the proximity of points indicates similarity, while distance signifies dissimilarity. The 'stress values' in NMDS indicate the effectiveness of this dimensional reduction in representing the original dissimilarities, with lower values suggesting a more accurate representation. We completed the NMDS analysis using the 'vegan' package in (Oksanen et al., 2022).

2.3. Question 3: Management applications of DSTs

We expanded our categorizations and classifications to relay information about decision support tool applications based upon the

Table 3
Decision support tool (DST) found in the systematic review, their category assignment, and example tool use found in the literature. Abbreviations in column one will be used to refer to specific tools in the rest of the report.

Abbrev	Tool	Category	Frequency	Use Type	Papers
AcF	ArcFuels	FB	1	Fire behavior modeling	Calkin et al., 2011
EMDS	Ecosystem Management Decision Support	FL	6	Landscape modeling, Future condition predictions	Abelson et al., 2022; Bollenbacher et al., 2014; Reynolds et al., 2005. Povak et al., 2022; Hemstrom et al., 2011; Reynolds et al., 2014
ERMit	Erosion Risk Management Tool	PF	1	Erosion prevention post fire	Robichaud et al., 2013
FM5	FlamMap	FB	3	Model fire behavior	Salis et al., 2014; Ager et al., 2011; Thompson et al., 2015
FNVC	FireNVC	WR	1	Landscape scale exposure and assessments	Thompson et al., 2015
FOFEM	First Order Fire Effects Model	PF	1	Predicting tree mortality post fire	Hood et al. 2017
FRST	Farsite	FB	2	Fire behavior modeling	Salis et al., 2014; Ager et al., 2011
Fsim	Large Fire Simulator Model	FB	8	Fire behavior and wildfire risk modeling	Ager et al., 2021; Dunn et al., 2020; Haas et al., 2013; Salis et al., 2014; Scott et al., 2012; Scott et al., 2016; Thompson et al., 2011b, 2016, 2016a
FSPro	Fire Spread Probability	FB	2	Fire behavior modeling	Calkin et al., 2011; Thompson et al., 2016b
FSWP	Forest Service Web Portal	PF	1	Erosion mitigation; Post fire treatments	Robichaud et al., 2013
FVS	Forest Vegetation Simulator	FL	3	Future conditions modeling	Povak et al., 2022; Ager et al., 2011; Thompson et al., 2015
FFE	Forest Vegetation Simulator Flame Fuels Extension	FB	4	Fire behavior modeling; Assess treatment tradeoffs	Chung et al., 2013; Ager et al., 2011; Povak et al., 2022; Salis et al., 2014
IFTDSS	Interagency Fuel Treatment Decision Support System	TP	1	Risk assessment, Treatment prioritization	Hyde et al., 2013
ILAP	Integrated Landscape Assessment Project	TP	1	Landscape cross boundary planning	Hemstrom et al., 2011
IRPS	Integrated Restoration and Protection Strategy	FL	1	Landscape and disturbance modeling	Bollenbacher, Graham and Reynolds, 2014
LANDIS	LANDIS II Forest Landscape Model	FL	1	Compare land management scenarios	Abelson et al., 2022;
NEXUS	NEXUS	FB	2	Fire behavior modeling	Salis et al., 2014; Ager et al., 2011
PODs	Potential Operational Delineations	TP	3	Cross boundary wildfire risk; Fire planning	Greiner et al., 2021; Thompson et al., 2020, 2022
RAVAR	rapid assess common risk assessment framework	WR	2	Wildfire risk assessment	Calkin et al., 2011; Thompson and Calkin, 2011
RMA	Risk Management Assistance	MF	2	Risk trades off	Calkin et al., 2021; Schultz et al., 2021
SDM	Structural Decision Making	MF	3	Decision making framework	Marcot et al., 2012; Ohlson et al., 2007; Thompson et al., 2013
WEPP	Watershed Erosion Protection Project	PF	2	Post fire watershed monitoring; Hydraulic modeling	Dobre et al., 2022a, 2022b
WFDSS	Wildland Fire Decision Support System	MF	5	Decision validation	Calkin et al., 2011; Noble et al., 2020; Noonan-wright et al., 2021, 2022; Thompson et al., 2016b
WHRA	National Wildfire Hazard and Risk Assessment	WR	1	Wildfire risk assessment	Calkin et al., 2011

framework established by Vásquez (2021) and Barton Smith (2022) to provide a more detailed analysis of what tools can address certain problem types. Barton-Smith (2022) developed applications of decision support tools during the typical management process. The categorization of these applications was developed iteratively with a stakeholder group of end users. We followed the same criteria in applying this assessment to all tools found in our review, organized by DST category. In our research, which expanded on each tool through assessing tool documentation, we also extracted information regarding what applications and functions each decision support tool could answer or be used for.

3. Results

3.1. Systematic review and DST categorization

Our systematic review yielded an initial total of 519 research articles. After a thorough screening using the inclusion and exclusion criteria, we identified 56 papers, including 24 unique DSTs, that fully met our criteria. Each of these papers was additionally screened to ensure that the results of each paper and the usage of specific DSTs were sound and reproducible.

For each tool, we captured the number of times it appeared in the literature and its most common use (Table 3). We list the tools (and acronyms) in Table 3; these acronyms are also used in all subsequent tables and corresponding figures.

From the systematic review, we created six basic categories (Fig. 1) for different decision support tool frameworks and wildfire risk models that capture the discrepancies and nested nature of the wildfire management decision support space. Information extracted from each tool followed a criterion that helped provide insights into the tool's functionalities and can be used to group tools with similar components together to represent shared characteristics (Appendix Table 1). We evaluated how each tool was represented by its category by cross-checking similarities between the different tool categories, as some tools do have characteristics that could fall into more than one category. Our categories account for this as they depict the cumulative nested and overlapping structure and functionalities between decision support tools. We define the decision support tool categories below and provide a conceptual framework for their placement in the decision support space.

- **Fire behavior models (FB)** estimate fire behavior under various conditions. These tools utilize input data such as weather, fuel characteristics, and topography to predict the spread and intensity of wildfires. They help capture fire behavior dynamics, identify areas at high risk, and assess the potential impacts of wildfires. FBs are crucial for tactical decision-making during active fire incidents and for planning prescribed burns.
- **Management frameworks (MF)** provide an overarching structured approach to wildfire management decision-making. These tools offer guidelines for various aspects of fire management, including preparedness, response, and recovery. Frameworks may host dashboards with tools that often include risk assessment, collaboration,

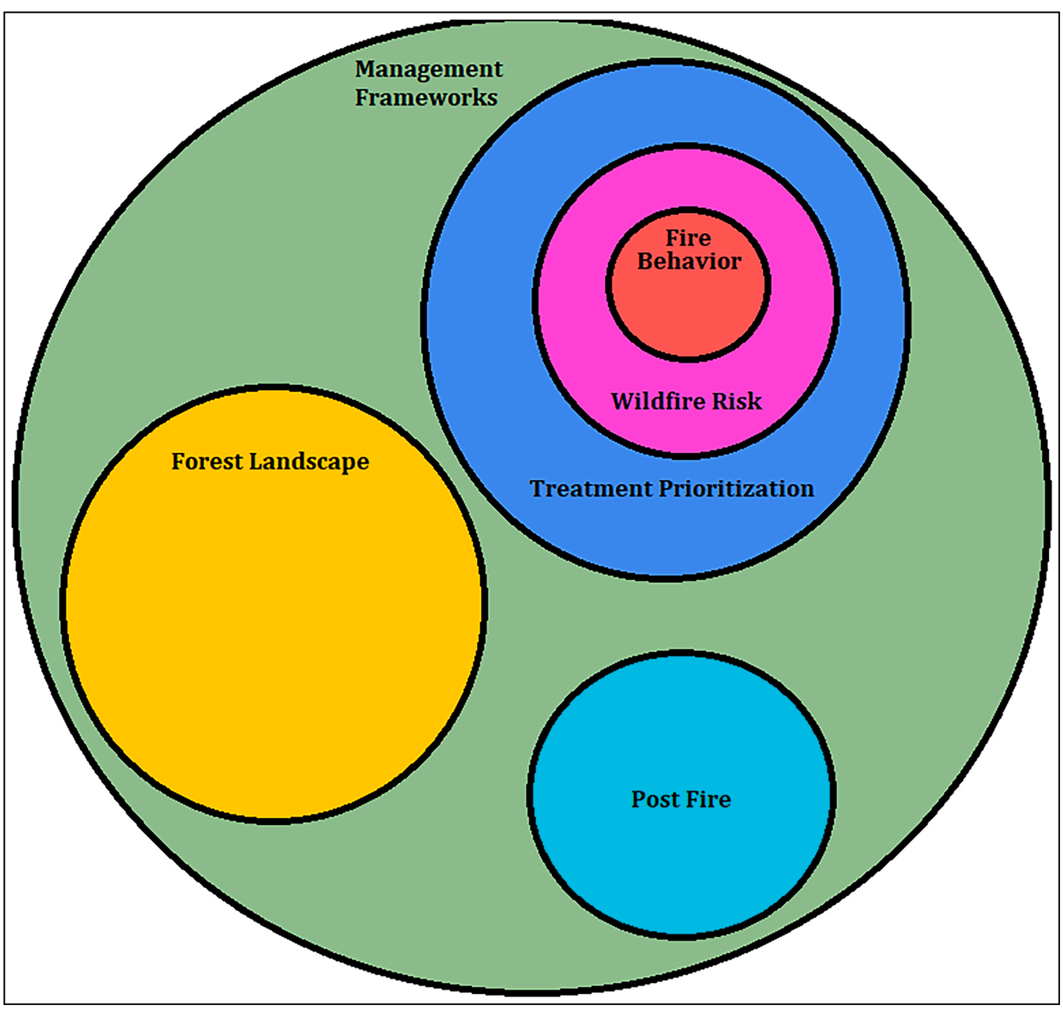

Fig. 1. This diagram depicts the relationships of various decision support tools (DST) commonly used in wildfire management.

and other modeling. They help improve comprehensive strategies, coordinate resources, and establish clear decision-making processes.

- **Forest landscape models** (FL) simulate changes in forest ecosystems over time, incorporating factors such as vegetation growth, succession, and disturbances on various scales. These models are typically used in silviculture and enable assessing the temporal changes in forest landscapes, the evaluation of the effectiveness of different management strategies, and the identification of areas needing treatment. Forest landscape models aid land-use planning, forest restoration, and ecosystem management.
- **Post-fire modeling tools** (PF) assist in assessing the ecological and environmental impacts of wildfires after they have occurred. These tools enable collecting and analyzing data related to vegetation recovery, soil erosion, water quality, flood risk, and wildlife habitat. Post-fire monitoring tools evaluate the effectiveness of post-fire rehabilitation measures, inform adaptive management approaches, and guide long-term restoration efforts.
- **Wildfire risk models (WR)** assess the potential risk of wildfires in specific areas and the impacts on the wildland-urban interface (WUI) and other high-valued assets (HVRAs). These models consider factors such as historical treatment and fire data, fuel characteristics, weather patterns, and proximity to values at risk (e.g., community infrastructure). Wildfire risk models help fire managers prioritize resources, allocate funding, and develop prevention and mitigation strategies.
- **Treatment prioritization tools (TP)** assist in identifying areas where fuel treatments (e.g., prescribed burns, thinning) should be implemented to reduce high-severity wildfire risks. These tools consider factors such as fuel loads, vegetation types, ecosystem resilience, cross-boundary collaboration, and values at risk. Treatment prioritization tools help fire managers optimize resource allocation, focus efforts on high-priority areas, and maximize the effectiveness of fuel reduction strategies. They aid in strategic

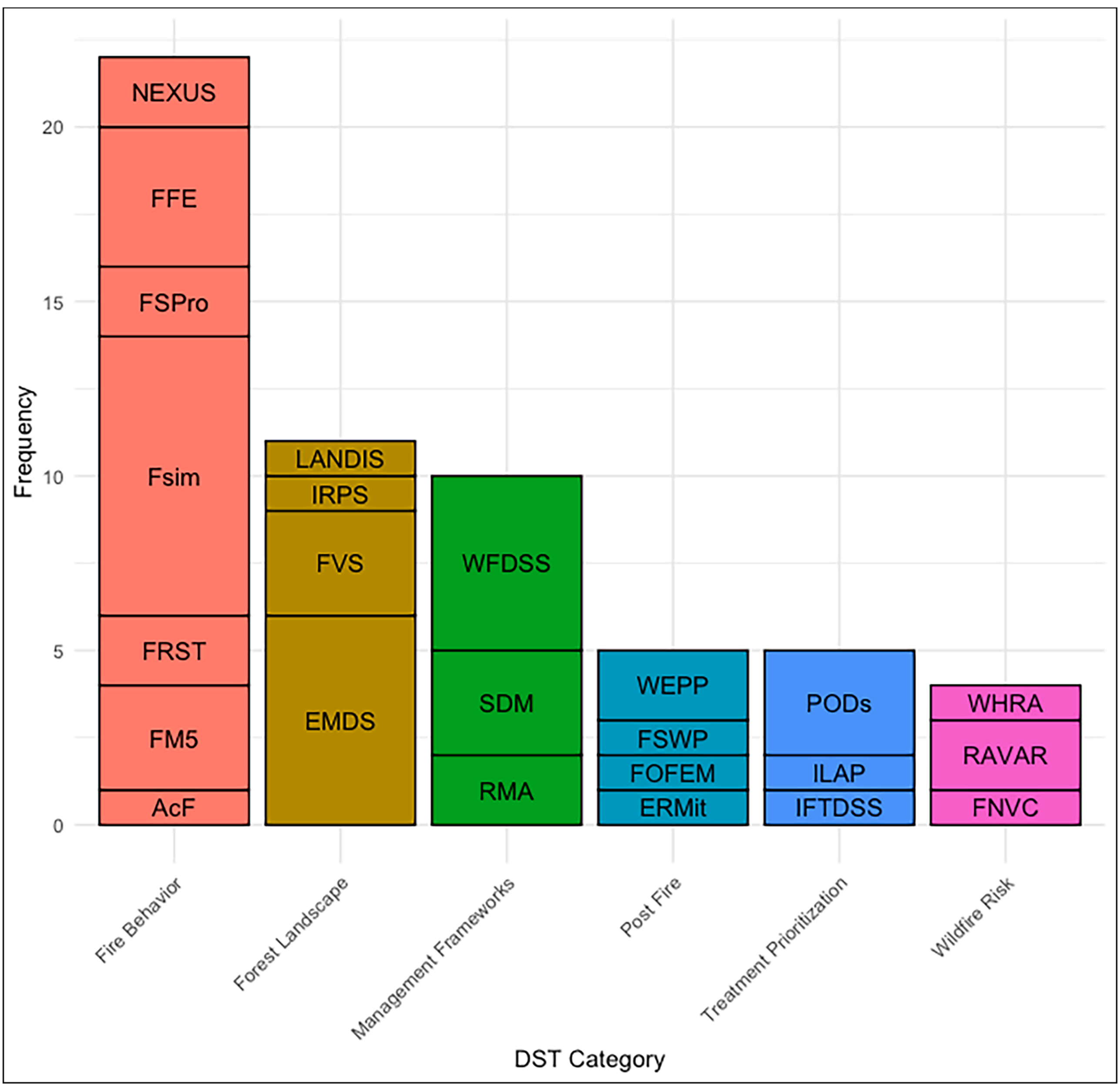

Fig. 2. Frequency of decision support tools (DST) mentioned and used in peer-reviewed articles in the systematic review. DST categories refer to those developed in this paper, and tool abbreviations are provided in Table A1.

planning and implementing proactive measures to mitigate wildfire risks.

We created a conceptual diagram to depict the macroscale of the wildfire management decision support space. These categories are not discrete and often nested, as some tool functions and categories build off the outputs and foundations in other categories. For example, "Wildfire Risk" cannot be assessed without input from "Fire Behavior Models"; thus, this category is nested within "Wildfire Risk." A tool solely used for fire behavior modeling may fall into the "Fire Behavior" category. In contrast, a tool such as an Interagency Fuels Treatment Decision Support System (IFTDSS) or Wildland Fire Decision Support System (WFDSS) relies on output from other fire behavior tools such as Flammap or Farsite. The Rapid Assessment of Values at Risk (RAVAR) is a wildfire risk model nested within WFDSS. These fire behavior inputs can then be used for wildfire risk modeling and in other tool categories, such as Treatment Prioritization and Management Frameworks. While not comprehensive for every potential configuration of nested structures, this figure emphasizes how tools can exist in multiple ways in the larger decision support space, highlighting how some tools build off each other and can vary in their focus and functionality, offering several applications to address a slew of managerial challenges and objectives.

Most tools identified from the literature fell into the third "Fire Behavior Models" or "Forest Landscape Models" category, showing that in the past several years, decision support tools have been expanded upon to meet the needs of managers and work towards answering multifaceted questions that require more complex input layers and opinions (Table 3). The most common tools (Fig. 2) that were discussed in the literature were the Wildland Fire Decision Support System (WFDSS), Ecosystem Management Decision Support (EMDS), and Large-Scale Fire Simulator (Fsim). Fsim was used in eight papers in conjunction with other tools and analyses produced by individual authors.

3.2. Case study results from the literature

Case studies from the literature reveal several critical insights regarding the use and impact of DSTs in managing wildfires. Notably, and in alignment with our review findings, fire behavior models were the most heavily referenced tool category in the case studies presented in the literature. Fsim, a highly technical DST, was selectively employed, focusing on the most intricate incidents with the potential for prolonged duration and significant size rather than being universally applied (Dunn et al., 2020; Scott et al., 2012; Thompson et al., 2016). Scott et al. (2012) utilized Fsim to model and simulate wildfires and management scenarios in Wyoming. The study aimed to analyze fire behavior and assess the effectiveness of various regional management strategies. The use of Fsim allowed for a comprehensive understanding of fire dynamics, aiding in informed decision-making for fire management in Wyoming. Additionally, it introduces a novel quantitative risk framework that approximates expected losses and benefits from wildfires on highly valued resources (HVR) at regional and national scales. This approach incorporates burn probability maps, spatially identified HVR, and response functions to assess the influence of fire likelihood and intensity on social, economic, and ecological values.

On the contrary, several studies in our review underscore the importance of creating an efficient working environment for users to interact with fire behavior models in a geospatial context. FSPro, showcased in several case studies (Calkin et al., 2011; Thompson et al., 2017), provides examples of a fire behavior model used in tandem with wildfire risk models such as WFDSS as a connection for a more usable interface. The analytical tools employed not only support pre-planning but also enhance operational learning for fire responders and offer valuable feedback for continual improvement (Abelson et al., 2022; Ager et al., 2021; Calkin et al., 2021; Thompson et al., 2016). Tools such as Potential Operational Delineations (PODs), Interagency Fuel Treatment Decision Support System (IFTDSS), and Wildland Fire Decision Support System (WFDSS) provide more collaborative approaches achieved through workshops engaging local stakeholders and fire responders, minimize biases and errors by integrating local knowledge with analytics. Social science literature on barriers regarding these tools have helped inform caveats and challenges that managers face with utilizing these different fire behavior modeling tools and collaborative efforts for planning (Greiner et al., 2021; Noble et al., 2020). Thompson et al. (2020) emphasize the significance of PODs in informing fire management decisions, facilitating communication, supporting prescribed fire planning, identifying problem areas, and prioritizing risk mitigation efforts. These case studies using FSPro and Fsim highlight that large wildfires tend to initiate near the WUI defense zone and emphasize the need for targeted strategies in critical areas (Scott et al., 2012; Thompson et al., 2020). Employing analytical tools such as Fsim, PODs, and WFDSS during pre-planning aids fire responders in learning and provides analysts with valuable feedback for improvement during operational use. Additionally, they function as communication tools for sharing fire management decisions and objectives with partners and stakeholders before and during incidents (Dunn et al., 2020).

3.3. DST Limitations from the literature

3.3.1. DST Usability limitations

We identified several significant challenges in the use of DSTs. Firstly, some fire behavior models, like FSPro, do not directly simulate suppression efforts, although users have the option to manually update landscape inputs to account for such factors. This limitation can create more hurdles for managers as they need to respond to incidents rapidly. In another study, Schultz et al. (2021) point out a significant limitation in the simulations used for fire risk assessment. It specifically mentions the inability of these simulations to accurately measure the risk posed by firebrands, or embers, that travel beyond the fire perimeter. This limitation is critical as these embers can cause buildings to ignite, potentially leading to a domino effect of building-to-building fire spread, a scenario often observed in real-life fire events. Additionally, the authors refrained from exploring the individual reasons behind classifying Relative Risk Assessments (RRA) as "high" or "low." This research contrasts with other works, such as those by Thompson et al. (2011) and Calkin et al. (2011), highlighting the progressive improvement in fire models, especially regarding the standardization of input and output data—a trend noted for its historical deficiency.

3.3.2. DST Tool limitations

Several papers also emphasize the persistent challenge of uncertainty in estimating changes in resource conditions. They recognize a misalignment between short-term goals and long-term desired future conditions and the complexity of modeling that in a rapidly changing climate (Calkin et al., 2011; Thompson et al., 2011). Calkin et al. (2011) introduced the Wildland Fire Decision Support System (WFDSS), a significant advancement developed by the US Forest Service for real-time, risk-based decision-making in wildland fire management. Now an essential tool, this system, integrates advanced fire behavior modeling with geospatial analysis to enhance decision-maker communication and situational awareness. It details critical components like FSPro and RAVAR, which are necessary in the landscape of wildland fire suppression. Simultaneously, Thompson et al. (2011) presented a comprehensive geospatial wildfire risk assessment tool for the United States that is instrumental in strategic planning and mitigation and provides vital insights for prioritizing fuel treatments and other measures.

Other lesser limitations include some geospatial interpretation using remote sensing imagery, thus suggesting a need for a larger temporal component. From a social perspective, a common limitation also sheds light on the preference among managers for experiential learning on the job and through interactions with scientists and workshops to enhance their understanding of tools. For example, studies by Scott et al. (2012), Salis et al. (2014), and Dunn et al. (2017) each underscore unique challenges and opportunities in wildland fire management. Scott et al. (2012) called for more nuanced approaches to managing wildfires, emphasizing the need for tools that better assess the risk of fires reaching urban interfaces. Salis et al. (2014) advocated incorporating more comprehensive temporal components in geospatial analyses, highlighting the limitations of current Landsat imagery interpretations. Lastly, Dunn et al. (2017) highlighted the preference among managers for experiential learning and interaction with scientists and workshops, suggesting a need for more user-friendly and collaborative decision-support tools. Each study stresses the importance of advancing and expanding the decision-support space in fire management and collectively highlights a call to action for increased usability and collaboration in developing decision-support tools.

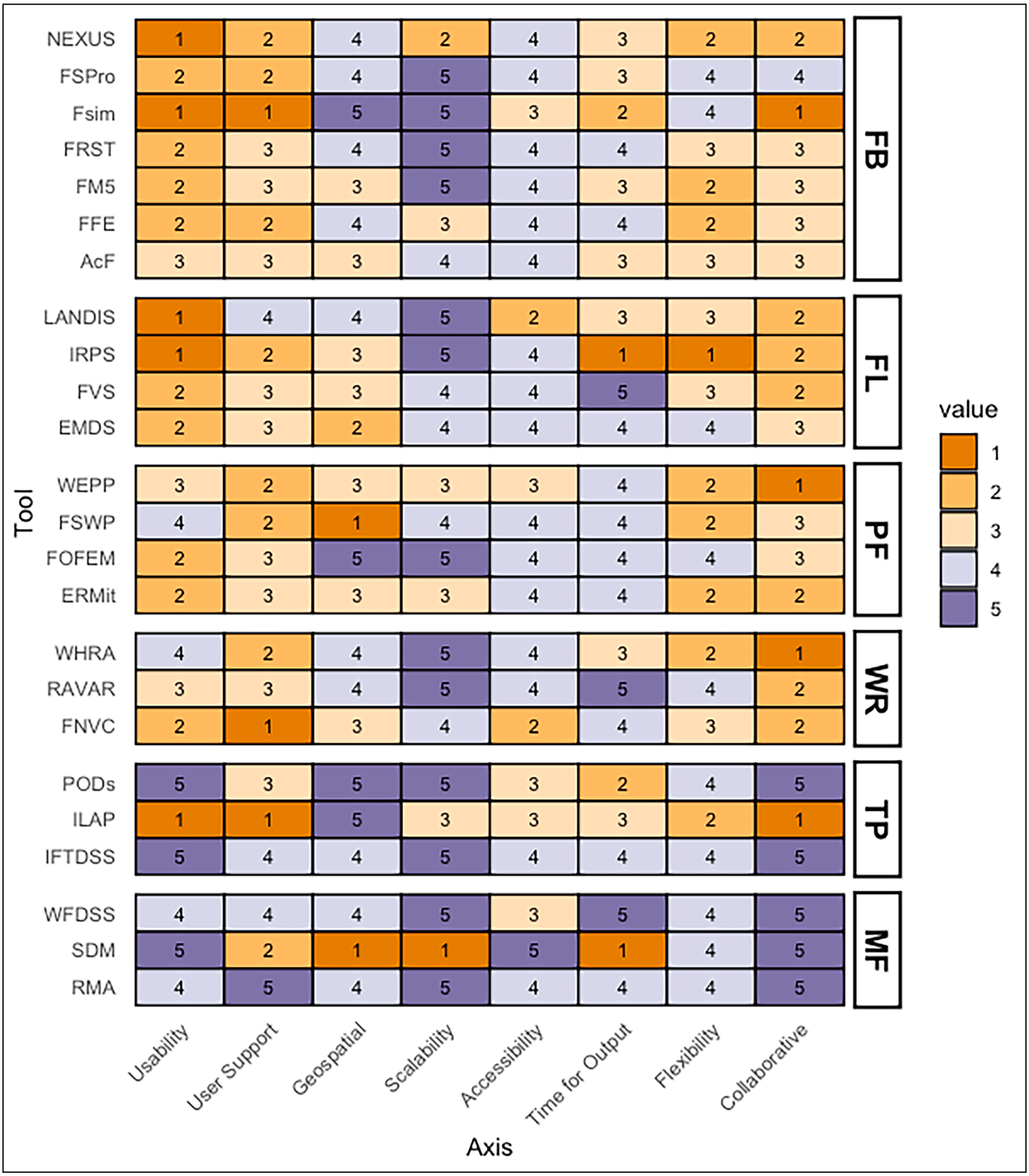

Fig. 3. Rankings of each DST (organized by DST category) for the eight classifying axes in the ordination. A higher score indicates that tool has more capabilities to meet broader applications while a lower score indicates specificity or lesser capability to address the corresponding class barriers. Reference Table 2 for specific value information. Tool categories are as followed: FB – Fire Behavior, FL – Forest Landscape, PF – Post Fire, WR – Wildfire Risk, TP – Treatment Prioritization, MF – Management Framework.

3.4. NMDS Ordination

We further investigated the tools found in the literature to compare their applications and functionalities. We found great tool variability when summarizing how each tool can address these objectives and questions (Fig. 3). The diverse range of decision support tools (DSTs) reflects the multi-faceted challenges of wildfire management. While tools like WFDSS, EMDS, and Fsim are prevalent in literature, specialized tools, although less common, play pivotal roles in addressing specific management questions and challenges. We assessed how our DST categories, developed from the systematic review, would align with functionality using NMDS ordination. Our NMDS ordination (Fig. 4) highlights potential gaps in post-fire tools, pointing to areas ripe for development, such as integrating burned area emergency response (BAER) and adaptive management strategies into decision support tools, as well as improving the effectiveness of real-time post-fire monitoring for flooding and erosion control (Fig. 5).

Our NMDS ordination had a stress value of 0.04, indicating that our ordination was trustworthy and not due to random chance. Our NMDS ordination illustrates how each category of DSTs interacts with each other and the different classification axes in space. Our ordination shows significant overlap between most categories, especially Fire Behavior, Treatment Prioritization, and Wildfire Risk, following the depiction displayed in our conceptual framework (Fig. 1). Our ordination results suggest that the Fire Behavior category encompasses the largest decision-making space and shows a diverse range of variability among the tools in this category, as these tools often lay the framework for other decision-support tools to build off. Post Fire tools fail to capture most classifications as a category, while individual post fire tools fall close to *Time Investment for Output* and *Accessibility* (classes 4 and 5). The largest decision space identified in the ordination corresponds to DSTs within the Wildfire Risk and Management Framework category, emphasizing their central role in wildfire decision-making processes. No individual tools or categories represented *Usability* and *Collaboration* (classes 1 and 8). Tools in the Management Framework category are the closest to *Collaborative Potential* (class 8). In contrast, individual tools such as IFTDSS, RMA, and PODs are close to this axis, indicating that these tools have more collaborative features than other categories.

Our ordination also calls to light tools that are very specialized in their design and function, as well as generalist tools with multiple overlapping functionalities. For example, Fsim and ILAP are both tools that are highly specialized in their capabilities and designed for specific analyses and functions. These tools fall very far away from the rest of the tools in the landscape, closest to the *Geospatia*l and *Scalability* axes (classes 3 and 4) and the furthest away from *Collaborative Potential* and *Usability* (classes 1 and 8). Tools such as LANDIS-II and FOFEM, while having different categories, functions, and intentional designs, are more generalist tools that fill similar spaces due to their ability to meet multiple managerial objectives and similar usability metrics scoring. As noted in their rankings, these tools vary in scope, function, design, and execution. This ordination can be used to understand better how these tools move through this space and the complexity of the wildfire management decision support space. It can also aid managers as they need to plan for the ongoing wildfire crisis efficiently and effectively.

3.5. DST Management applications

Most tools can address several different steps and iterations in the management process. Nonetheless, other tools such as WEPP and FireNVC provide more narrowed support for specialized objectives that pertain to their specific design as a decision support tool and their overall tool categories, such as post-fire monitoring and wildfire risk (Fig. 5). This additional exploration further depicts the vast space of decision support tools suited for particular functions to target broad outcomes. It allows managers to glance at the decision support tool application capabilities for the individual and category levels.

4. Discussion

The diverse range of decision support tools (DSTs) reflects the multi-

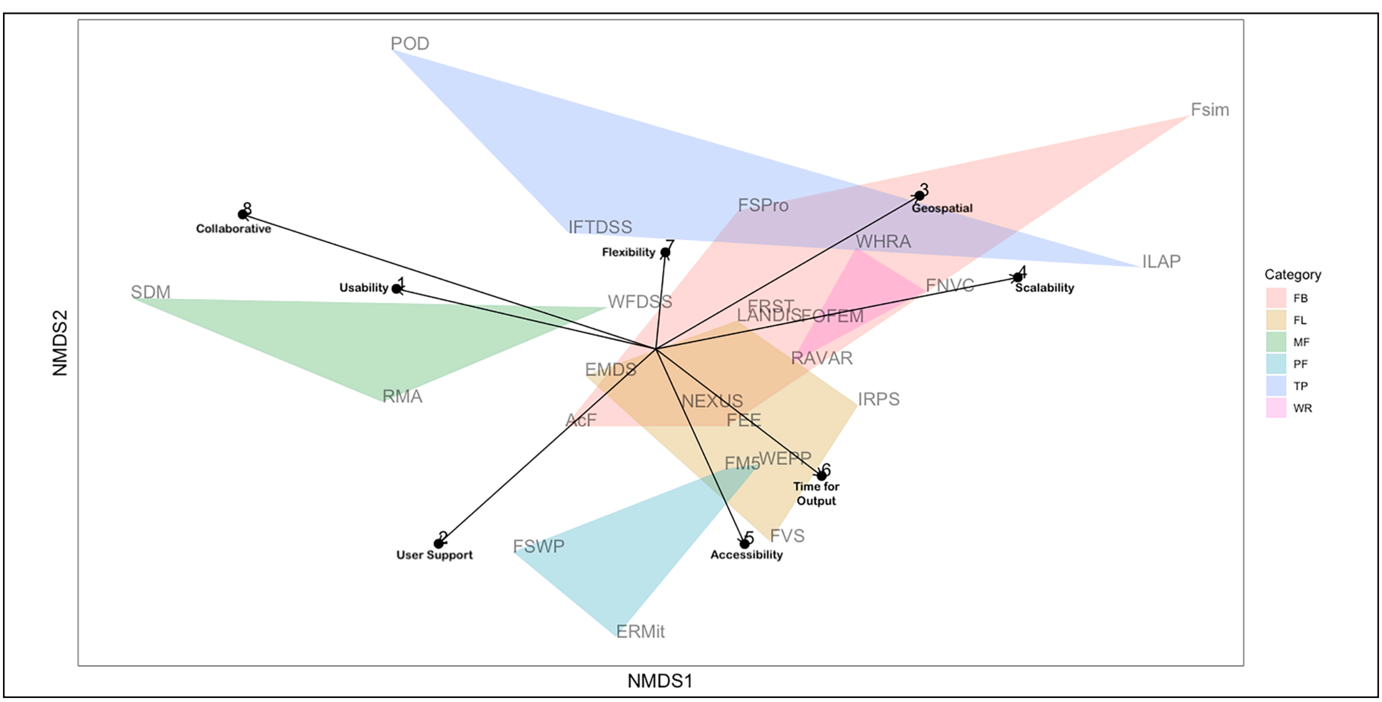

Fig. 4. Non-metric Multidimensional Scaling (NMDS) ordination of the decision support tools found in the peer-reviewed systematic literature. Colors represent DST categories (Fig. 1). Polygons represent how each category interacts in the decision-making space. Classifications and rankings are expanded upon in the Table 2 and Fig. 3. Tool categories are as followed: FB – Fire Behavior, FL – Forest Landscape, PF – Post Fire, WR – Wildfire Risk, TP – Treatment Prioritization, MF – Management Framework.

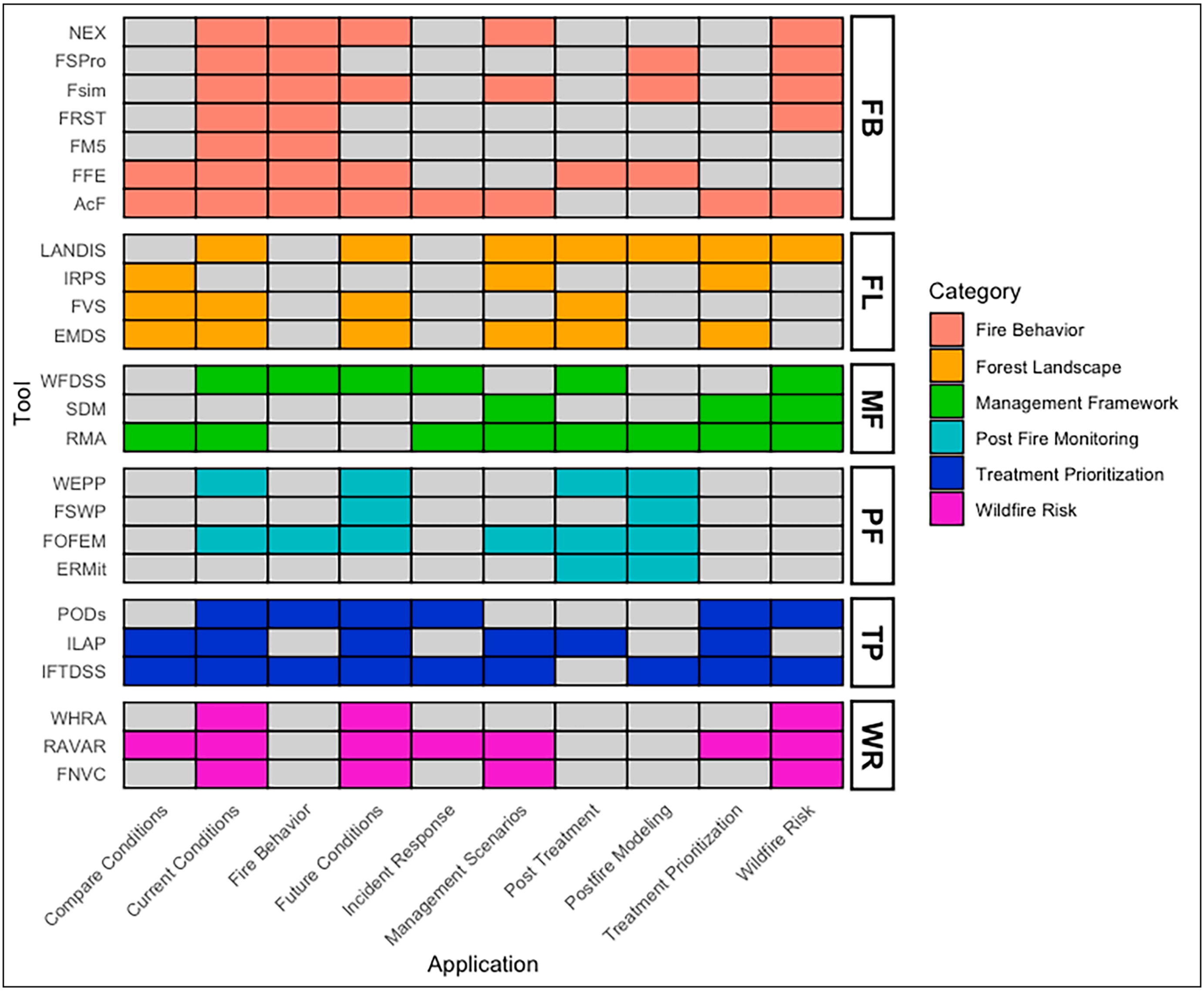

Fig. 5. Tile plot of DSTs found in the review and what common objectives, questions, and applications they can answer. A filled in tile represents that tool has the ability to achieve that application to some capacity. The color of each tile refers to what DST category it belongs to.

faceted challenges of wildfire management. While tools like WFDSS, EMDS, and Fsim are prevalent in the literature, specialized tools, although less common, also play pivotal roles in addressing specific challenges. A noted challenge among managers is the complexity of sophisticated tools, underscoring the need for user-friendly yet comprehensive platforms (Thompson et al., 2020). Many managers also desire unified tools to streamline decision-making processes, especially in multi-jurisdictional contexts (Colavito, 2021; Finney, 2021).

Furthermore, our study underscores the vital role of accurate and real-time data in fire management, as seen in our review's emphasis on fuel and fire behavior models. It also identifies a gap in post-fire tools, particularly those for post-restoration, which currently focus mainly on mitigating flooding and erosion. This suggests a need for tools that enhance Burned Area Emergency Response (BAER) by incorporating climate and fire data (Robichaud et al., 2013; Robinne et al., 2019). Despite frequently mentioned tools like Fsim, WFDSS, and EMDS in scholarly articles, there's a discrepancy with their actual usage, highlighting a critical gap in how decision-support tools are represented in academic versus practical contexts. Our findings reveal a significant gap in decision-making tools that effectively combine usability and collaboration, underscoring the need for continued development. As wildfire crises intensify, the demand for tools supporting real-time decision-making and adaptive post-fire management becomes increasingly crucial (Hyde et al., 2013; Noble et al., 2020; Povak et al., 2022).

Our research has identified significant gaps in the current decision-making framework that could inadvertently affect professionals' choice of tools. These gaps may lead to biased preferences, potentially resulting in suboptimal choices for certain situations. We observe that academic literature tends to overstate the use of tools in the Fire Behavior category. Advanced tools in this category, like Fsim, require substantial expertise for sophisticated fire behavior modeling. However, the literature fails to reflect the practical usage in real-world applications. For instance, while tools such as IFTDSS and WFDSS are mandated for specific incidents, their representation in academic citations suggests less frequent use. This discrepancy underscores the need for improved documentation of tool usage in scholarly studies and reducing barriers to accessing more advanced wildfire decision support tools, thereby streamlining the decision-making process.

Our review indicates a notable misalignment between DSTs commonly used in practice and those highlighted in academic literature. This gap underscores the critical need to bridge theoretical discussions with practical applications of DSTs. This misalignment calls for more indepth social science research to understand better the real-world use of DSTs in the western United States, as the academic literature does not comprehensively represent all tools historically or currently in use (Colavito, 2021; Noble et al. 2020). Further research is essential to detail these tools' usage, frequency, and user demographics. Though some DSTs are established, they may not completely satisfy the needs of forest and wildfire management practitioners (Finney, 2021). Consequently, we advocate for a multi-faceted strategy to bridge these gaps and enhance DST utility in forest and wildfire management, enabling a more robust and integrated approach to wildfire management that fully utilizes the capabilities of the wildfire decision support space.

4.1. Limitations of our systematic review

As mentioned in our introduction, the nature of a systematic review will create a cap on what literature is included in the review and to what extent to provide a very targeted replicable assessment of existing peer-reviewed literature. Owing to the structured nature, our study encountered limitations that prevented a comprehensive capture of all existing wildfire decision support tools in the current landscape. Keeping pace with the rapidly evolving field is daunting, underscoring the necessity for enhanced communication and thorough documentation during the creation, updating, and utilization of these tools. Additionally, our review could not accurately determine the real-world frequency of tool utilization. We highlight the need for subsequent social science research to delve deeper into the gap between the representation of tool usage in academic literature and actual application in-field practices. In some of the preliminary filtering in the literature searches, several articles met most of the criteria for tools. Still, they emphasized efforts outside the forest and fire management framework. This limitation also applies to the literature regarding general forest and watersheds management tools and some frameworks and recent advances for wildfire decision support systems (e.g., Firesheds, Forsys, Land Tender). Preliminary searches and filters based on inclusion and exclusion criteria removed a fair amount of decision-support tools and studies that emphasized post-fire restoration efforts in watersheds.

While our review provides information on various common decision-support tools, little information is presented in most articles about the barriers to implementing decision-support tools in management. Most studies mentioned uncertainty as a limitation for decision support systems. Like all models, decision support tools and systems will have some uncertainty that is irremovable from them. Limitations regarding uncertainties mentioned in older studies from 2005 to 2012 emphasized the spatial and temporal limitation on obtaining up-to-date spatial data input layers and the limitations with model accuracy due to the precision and resolution of input layers into the models (Calkin et al., 2011; McRoberts et al., 2007; Reynolds and Hessburg, 2005). As advances in remote sensing, climate modeling, and fire simulators have occurred over the past several years, fire models' spatial and temporal limitations are less relevant today. The increased accuracy of weather reports and access to current conditions have made real-time risk assessment tools feasible and effective in fire management. While now, it can be distinguished that geospatial and temporal data and knowledge uncertainty have improved greatly, decision support tools still have room for further improvement. Additional investment into pre-fire planning can help mitigate some of these uncertainties and the need for an accelerated pace of management response (Calkin et al., 2021).

4.2. Potential directions for DST development

Given the dynamic nature of wildfire management and ongoing advancements in decision support tools (DSTs), it is crucial to keep stakeholders updated with the latest developments. In light of this, we advocate for establishing a "living document" that dynamically updates to reflect the latest inclusions and modifications to DSTs as they emerge in the literature. Such a real-time repository will ensure practitioners and academic researchers are equipped with the latest and most pertinent tools, facilitating more informed decision-making.

As the complexities of wildfire management grow, so does the need for enhanced collaboration across varied jurisdictions and departments. The present gaps in DSTs, as identified through our research, underscore the urgency for a unified platform designed to nurture seamless interaction and collaboration. Envisioned as an integrative platform, it would offer stakeholders a consolidated view of the forest landscape. By merging fine-grained structural data with extensive landscape-scale datasets and predictive fire behavior models, this platform would stand poised to bring about a paradigm shift in wildfire risk assessment and strategic planning. This envisioned platform's holistic nature promises to redefine how stakeholders approach and manage wildfires, fostering a comprehensive strategy rooted in collaboration and informed decision-making.

One of the more profound revelations from our research was the discernible disconnect between the theoretical frameworks presented in academic literature and the practical application of DSTs in real-world scenarios. To reconcile this divide, we emphasize a renewed focus on social science research that delves deeper into understanding the practical application and preferences surrounding DSTs in the western United States. By juxtaposing this against their representation in academic discourses, such research endeavors can unearth valuable insights. The ultimate goal is to foster the development and refinement of DSTs that strike a harmonious balance between theoretical robustness and practical relevance, ensuring that tools are academically sound and aligned with the needs of practitioners in the field.

In conclusion, further investigation is essential to overcome obstacles and integrate decision support tools and systems more effectively into public and private land management practices. Although these tools offer significant aid in mitigating the pressures associated with intense decision-making in forest and fire management, their limitations must be acknowledged and rectified. Wildfire risk assessment is a complex, multi-dimensional process that involves diverse stakeholder engagement, variable weather conditions, and the evaluation of different values at risk. To be truly effective, decision support tools must be capable of managing this complexity and evolve towards offering more comprehensive, holistic decision-making frameworks.

5. Conclusions

In practice, IFTDSS, PODs, and WFDSS have been identified as pivotal tools, with a marked frequency of usage in real-world applications. The extent of these tools' use suggests an intrinsic utility in addressing the nuanced challenges of wildfires. However, an examination of academic literature paints a somewhat contrasting picture. Fsim, WFDSS, and EMDS emerge as the most frequently cited Decision Support Tools (DSTs). This discrepancy between scholarly mentions and practical application accentuates a potential disconnect between theoretical discussions and real-world tool utility, emphasizing the need to bridge this gap. Our review also highlights the gap between the amount of usage in the literature and the field. No reviews or tools have captured how specific tools are used in conjunction with one another and what frequency. While adding multiple tools can be beneficial to meet and complement managerial needs that other tools cannot, it can create a more cumbersome task for managers. Using multiple tools requires competency and more time investment into multiple tools, creates more points for uncertainty between tool comparison and predictions, and can slow down the overall decision-making process. Striving to create one platform or one singular wildfire decision support tool or framework, to streamline decision support would be ideal instead of the current systems that sometimes require the use of six or seven at once to answer managers' questions.

Furthermore, a salient takeaway from our study is the lack of tools that effectively combine ease of use with collaborative functionality. This finding underscores a pressing need for tools that strike a balance between user-friendliness and fostering collaboration across various jurisdictions and departments. Among the findings, we observed that some of the most advanced tools, like Fsim, necessitating specialized expertise, are infrequently utilized due to their complexity. Fsim is combined with other decision support tools but is not a universally applicable solution suitable for use in all forests or at any time. DSTs within the Wildfire Risk and Management Framework stand out when appraising the breadth of decision-making. Our research indicates that these tools command the most extensive decision space, signifying their adaptability and pivotal role in holistically addressing wildfire management's multifaceted challenges.

Our research delved into the intricate landscape of decision support tools (DSTs) for wildfire management, shedding light on their practical utility and academic representation. Our research has revealed key gaps in tool capabilities and their representation, highlighting a crucial yet unfulfilled demand for tools that expertly blend ease of use with collaborative strength. As we face the growing threats posed by wildfires, pursuing DSTs that are comprehensive and conducive to teamwork emerges as a critical and inspiring mission. The conspicuous absence of tools merging usability with collaboration underscores an unmet need in wildfire management. As wildfires continue to pose escalating challenges, the quest for comprehensive, intuitive, simple, and collaborative tools has become paramount. This journey into the realm of DSTs is but a starting point, hinting at the vast, uncharted territories awaiting exploration.

CRediT authorship contribution statement

Tristan O'Mara: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andrew Sánchez Meador:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Melanie Colavito:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Amy Waltz:** Writing – review & editing, Funding acquisition. **Elvy Barton:** Writing – review & editing, Resources, Funding acquisition.

Declaration of competing interest

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

Tristan O'Mara reports financial support was provided by US Department of Agriculture Forest Service. A. Sanchez Meador, Amy Waltz, and Melanie Colavito reports financial support was provided by US Department of Agriculture Forest Service. Tristan O'Mara reports financial support was provided by Salt River Project. A. Sanchez Meador, Amy Waltz, and Melanie Colavito reports financial support was provided by Salt River Project. E. Barton is employed by Salt River Project 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.

Data availability

Data will be made available on request.

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Appendix

Table A1

Category	Description	Inputs	Outputs
Fire Behavior Models (FB)	Fire behavior model fire behavior under various conditions. These tools utilize input data such as weather, fuel characteristics, and topography to predict the spread and intensity of wildfires.	Canopy height Canopy bulk density Canopy base height Forest canopy cover Weather (wind and weather) Topography	Flame length Rate of spread Fuel moisture Wind speed Crown fire potential
Forest Landscape Models (FL)	Forest landscape models simulate changes in forest ecosystems over time, incorporating factors such as vegetation growth, succession, and disturbances on a variety of scales. These models are typically used in silviculture and enable the assessment of the temporal changes on forest landscapes, evaluate the effectiveness of different management strategies, and identify areas in need of treatment.	Forest canopy metrics Stand dynamic metrics Harvesting and biomass data Topography	Silvicultural scenarios Current conditions Treatment scenarios Biomass Outputs
Management Frameworks (MF)	Management frameworks provide an overarching structured approach to wildfire management decision making. These tools offer guidelines for various aspects of fire management, including preparedness, response, and recovery. These frameworks may host dashboards that hold tools that often include risk assessment, collaboration, and other modeling.	Fire behavior outputs Firefighting resources Topography and weather Real time information updates Risk communication strategies	Resource allocation plans Incident response planning Scenario analyses Communication planning Long term assessments
Post Fire Models (PF)	Post-fire monitoring tools assist in assessing the ecological and environmental impacts of wildfires after they have occurred. These tools enable collecting and analyzing data related to vegetation recovery, soil erosion, water quality, flood risk, and wildlife habitat.	Fire behavior outputs Burned area erosion response (BAER) Topographic and hydrologic information Geological data	Fire severity maps Burn severity assessments Vegetation recovery Hydrological functions Flood risk Erosion risk

(*continued on next page*)

Table A1 (*continued*)

Category	Description	Inputs	Outputs
Wildfire Risk Models (WR)	Wildfire risk models assess the potential risk of wildfires in specific areas and the impacts on the wildland-urban interface (WUI) and other high-valued assets (HVRAs). These models consider various factors such as historical treatment and fire data, fuel characteristics, weather patterns, and proximity to values at risk.	Fire behavior outputs Values (social, ecological, economic) Fire probability	Wildfire risk maps Fire spread High values assets at risk rankings Fire hazards
Treatment Prioritization Tools (TP)	Treatment prioritization tools assist in identifying areas where fuel treatments (e.g., prescribed burns, thinning) should be implemented to reduce high severity wildfire risks. These tools consider factors such as fuel loads, vegetation types, ecosystem resilience, cross-boundary collaboration, and values at risk.	Fire behavior outputs Stakeholder preferences Climate and vegetative data Wildfire risk Economic and management policies	Economic cost components Pre-fire planning Quantitative Wildfire Risk Assessments (QWRAs)

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