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Fire Ecology

REVIEW

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The scientific value of fire in wilderness

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Abstract

Background Wilderness areas are important natural laboratories for scientists and managers working to understand fire. In the last half-century, shifts in the culture and policy of land management agencies have facilitated the management practice of letting some naturally ignited fires burn, allowing fire to fulfill its ecological role and increasing the extent of fire-related research opportunities. With the goal of identifying the global scientific advances enabled by this paradigm shift in wilderness fire management, we conducted a systematic review of publications that either (1) selected protected areas for investigation because of an active fire regime enabled by wilderness fire management, (2) studied modern fires or fire regimes deliberately located in a wilderness area, or (3) conducted applied research to support wilderness fire management.

Results Our systematic review returned a sample of 222 publications that met these criteria, with an increase in wilderness fire science over time. Studies largely occurred in the USA and were concentrated in a relatively small number of protected areas, particularly in the Northern Rocky Mountains. As a result, this sample of wilderness fire science is highly skewed toward areas of temperate mixed-conifer forests and historical mixed-severity fire regimes. Common principal subjects of publications included fire effects (44%), wilderness fire management (18%), or fire regimes (17%), and studies tended to focus on vegetation, disturbance, or wilderness management as response variables.

Conclusions This work identifies major scientific contributions facilitated by fire in wilderness, including self-limitation of fire, the effects of active fire regimes on forest and aquatic systems, barriers and potential solutions to wilderness fire management, and the effect of fire on wilderness recreation and visitor experiences. Our work reveals geographic and bioclimatic areas where more research attention is needed and highlights under-represented wilderness areas that could serve to fill these gaps. Finally, we identify priorities for future wilderness fire research, including the past and potential role of Indigenous and prescribed burning, the effects of changing climate and fire regimes on ecosystem processes, and how to overcome barriers to wilderness fire management.

Keywords Climate change, Prescribed burning, Resource objective fire, Wilderness, Wilderness for science, Wilderness fire management, Wildland fire use

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Resumen

Antecedentes Las áreas silvestres son laboratorios naturales importantes para científicos y gestores que trabajan para entender el fuego. En los pasados 50 años, cambios en la cultura y en políticas de manejo del fuego promovidas por las agencias de manejo de tierras, han facilitado la práctica de dejar que algunos fuegos iniciados naturalmente (i.e. por rayos) puedan quemar diferentes superficies, permitiendo que el fuego cumpla con su rol ecológico e incrementar asimismo las oportunidades de extender las investigaciones relacionadas con el fuego. Con el objetivo de identificar los avances científicos globales alcanzados por este cambio de paradigma en el manejo del fuego en áreas silvestres, condujimos una revisión sistemática de publicaciones que: (1) eligieron áreas protegidas para la investigación pues tenían un régimen activo de fuegos permitido por el manejo del fuego en esas áreas silvestres, (2) estudiaban fuegos modernos o actuales o regímenes de fuego ubicados deliberadamente en un área silvestre, o (3) condujeran investigación aplicada para apoyar el manejo del fuego en esas áreas silvestres.

Resultados Nuestra investigación sistemática condujo a una muestra de 222 publicaciones que cumplía con esos criterios, con un incremento paulatino, en el tiempo, de investigaciones sobre la ciencia del fuego en áreas silvestres. Los estudios fueron en su mayoría originados en los EEUU y estuvieron concentrados en un número reducido áreas protegidas, y particularmente en las montañas rocallosas del norte. Como resultado, esta muestra de la ciencia del fuego en áreas silvestres está totalmente sesgada hacia bosques templados mixtos de coníferas que tenían históricamente regímenes de fuego de severidad mixta. Los sujetos principales de publicación incluían efectos del fuego (44%), manejo del fuego en áreas silvestres (18%) o regímenes de fuego (17%), y los estudios tendían a enfocarse en la vegetación, los disturbios, o en el manejo de áreas silvestres como variable de respuesta.

Conclusiones Este trabajo identifica contribuciones científicas importantes facilitadas por los incendios en áreas silvestres, incluyendo la autolimitación del fuego, los efectos de los regímenes activos del fuego en el bosque o en los sistemas acuáticos, las barreras y soluciones potenciales al manejo del fuego en áreas silvestres, y los efectos del fuego en la recreación y experiencias de los visitantes de estas áreas. Nuestro trabajo revela áreas geográficas y bioclimáticas donde mayor atención debe ser puesta en relación a la necesidad de realizar investigaciones en fuegos, y destaca áreas silvestres que podrían servir para llenar esos vacíos. Finalmente, identificamos prioridades para futuras Investigaciones en fuego en áreas silvestres, incluyendo el rol pasado y potencial de los indígenas y de las quemas prescriptas, los efectos del cambio climático y regímenes de fuego en procesos ecosistémicos, y como superar barreras en el manejo del fuego en áreas silvestres.

Background

Wilderness and other protected areas provide value to society as places for scientific research and knowledge production. This is true in a strict sense for congressionally designated Wilderness Areas in the United States of America (USA), where the Wilderness Act of 1964 explicitly identifies scientific use as one of the six public purposes of wilderness ("Wilderness Act 16 U.S. Code § 1131," 1964). More generally, scientific study of ecosystems in wilderness and protected areas provides the basis for developing natural models of ecosystem structure and dynamics, including the role of natural disturbances (Franklin et al. 2002; Berkey et al. 2021a). This knowledge informs ecosystem restoration and conservation (Hopkins et al. 2014), including the development of ecologically based management systems used outside of formal reserves (Kuuluvainen et al. 2021).

A profound contribution of wilderness and protected area management has been to catalyze a paradigm shift from fire suppression to fire management for resource benefit (Van Wagtendonk 2007). This is especially true in the USA, where, for much of the 20th century, there was very little fire activity due to the 10 AM Policy—a national policy enacted in 1935 to suppress all wildfire ignitions—as well as earlier depopulation and displacement of Native Americans and their use of fire (Fisher 1997; Kimmerer and Lake 2001; Ostlund et al. 2005; Roos et al. 2021). However, the Leopold report (Leopold et al. 1963), which stimulated the National Park Service to recognize fire as an ecological process (Rothman 2007), along with the Wilderness Act ("Wilderness Act 16 U.S. Code § 1131," 1964), which prompted Forest Service managers in the US Northern Rocky Mountains to manage some natural ignitions (Smith 2014; Berkey et al. 2021b), began to restore fire as an ecological process and management tool in some parks and wilderness areas starting in the late 1960s and early 1970s. At this same time, a shift was also occurring in the scientific literature, acknowledging the important role of fire in ecosystems (Habeck and Mutch 1973; Heinselman 1973; Kilgore 1973; Wright 1974).Together, these changes created opportunities to study fire as an socioecological process and required development of new knowledge to support fire management decision making (Agee 2000; Kilgore 1987; Miller and Aplet 2016; Smith 2014).

We assessed the scientific contributions and knowledge production enabled by the shift toward recognizing fire as an integral ecosystem process, and the accompanying development of wilderness fire management in some places. Our review is partially motivated by the Wilderness Act's explicit identification of scientific use as one of the purposes of wilderness. Wilderness has, in the past, been criticized as not delivering on the promise and potential as a place for research (Franklin 1987); we question if that holds in the case of wilderness fire science in the present. While wilderness is largely a legal and philosophical construct originating from the early and middle 20th century environmental protection movement in the USA, many protected areas globally have active fire regimes. To include scientific contributions from those regions, we defined the geographic scope of our study to be global. Our specific objectives were to:

1. Summarize the scientific contributions made possible by wilderness fires and wilderness fire management in terms of their distribution in time and space, principal subject and environmental resource, and type of study and publication.
2. Assess the representativeness of studies in our sample in climate and fire regime space.
3. Synthesize major areas of scientific advancement and discovery made possible by wilderness fire management and identify future research priorities.

Methods

To establish the scope of our review, we defined wilderness as protected areas globally where natural disturbance processes such as fire are allowed to proceed under some cases. We thus used International Union for Conservation of Nature (IUCN) protected area management categories Ia (strict nature reserve), Ib (wilderness), and II (national park) (Dudley 2013). Though most naturally-ignited fires in wilderness are suppressed to some extent (Miller 2012), these areas nonetheless tend to have less suppression than outside of wilderness (Haire et al. 2013; Morgan et al. 2014), and are not subject to intensive management such as salvage logging.

Database search**:** We conducted a database search to identify a global sample of studies where fire in wilderness created either the opportunity or the need for research. Initially, we tested several search strings, including ["Wilderness" AND "fire"], ["National Park" AND "fire"], ["National Wildlife Refuge" AND "fire"], ["National Preserve" AND "fire"], and ["National Monument" AND "fire"], as well as searches for individual wilderness areas, national parks, or regions [e.g., "Denali National Park" AND "fire"]. Preliminary analysis of these search strings revealed that searches other than ["Wilderness" AND "fire"] were overly sensitive, returning many studies that did not meet our inclusion criteria. Thus, we ultimately compiled our dataset from a sample of the literature using the single search string ["Wilderness" AND "fire"]. These preliminary and final searches took place during May 2019 using the ISI Web of Science (https://webofknowledge.com) and U.S. Forest Service Treesearch (https://www.fs.usda.gov/treesearch/) databases.

We screened all publications, retaining those that met at least one of the following criteria: 1) studies that had selected a wilderness or other protected area for investigation because of the modern (post-mid-20th century) active fire regime enabled by wilderness fire management; 2) studies of modern fires or fire regimes deliberately located in wilderness or other protected areas; 3) applied research undertaken to support implementation or continuation of wilderness fire management. We used systematic literature review methods (Pullin and Stewart 2006) and placed no disciplinary or subject matter constraints on our review—our objective was to document the full range of scientific contributions made possible by wilderness fire management. However, we did exclude studies conducted in wilderness but with a pre-historical or historical focus prior to the mid-20th century. We also excluded large scale (e.g., regional to subcontinental scale) studies where the inclusion of protected areas was incidental to the core focus or study area. We retained reviews, syntheses, and meta-analyses when the scope, inference, or conclusions of these publications depended significantly on the contribution of one or more qualifying (as described above) wilderness fire studies. Four of the authors (MRK, MRJ, SAP, AJL) assessed publications for inclusion. We automatically included publications when three or more reviewers independently recommended inclusion in the final dataset, with ties reassessed and decided by the senior author.

To identify the scientific advances within this final dataset, we collected information on each study's research subject, themes, and location. The same four authors each assessed every publication in the final dataset to collect information on publication type, study type, principal subject, environmental resource, country, and protected area (Appendix 1). We initially used the Joint Fire Science Program (JFSP) *Findings Data Dictionary* (https://www.firescience.gov/PSR/documents/Findings_Data_Dictionary.pdf) to define possible categories for the study type, principal subject, and environmental resource attributes. However, preliminary review of qualifying studies in our sample showed a greater breadth of environmental resources and study types than those listed in the JFSP data dictionary. Thus, we ultimately adopted the value definitions described in Appendix 2 for definitions of possible publication type, study type, principal subject, and environmental resource categories.

Representativeness: To assess how representative our sample was of broader climate and fire activity, we compared patterns of climate and historical fire regimes represented in sampled wilderness areas to those of 1) wilderness areas in general and 2) all land designations. Because most studies focused on protected areas in the contiguous United States, we restricted our representativeness analyses to this area.

To assess the climatic representativeness of sampled areas, we constructed climate envelopes using annual climate water deficit and actual evapotranspiration data (aggregated to 1981–2010 averages) from gridded TerraClimate datasets (Abatzoglou et al. 2018). We compared the climate envelope for sampled wilderness areas to 1) a climate envelope of all wilderness areas in the contiguous USA and to 2) a climate envelope of the entire contiguous USA. To assess the historical fire regime representativeness of sampled areas, we constructed fire regime envelopes using Mean Fire Return Interval (MFRI) and Percent of Replacement-Severity Fire (PRS) from gridded LANDFIRE datasets (Rollins 2009). We converted these binned categorical values to their average value (e.g., the Replacement-Severity Fire category of 41-45% was converted to 43%). As before, we compared the fire regime envelope for sampled areas to that of all wilderness areas in the contiguous USA, as well as to that of the entire contiguous USA. We accessed TerraClimate and LANDFIRE datasets via Google Earth Engine (Gorelick et al. 2017), and extracted the values of all pixels at 4-km scale that fell within sampled wilderness areas, contiguous USA wilderness areas, and the entire contiguous USA respectively.

Results

Our initial keyword search returned 608 publications. Following the screening process, 222 publications were retained in our final sample and analyzed (Appendix 3). Code and data to reproduce all results and figures from this paper can be accessed through the Zenodo open-access repository at https://doi.org/10.5281/zenodo.6326355.

Summary statistics

Most studies in our sample reported on research conducted in the USA (90%). Australia (6%) and Canada (5%) were the only other countries with more than one publication, with a handful of additional countries—Dominican Republic, Mongolia, Russian Federation, South Africa, Spain, Zambia, and Zimbabwe—each the subject of a single publication (Fig. 1). Percentages sum to greater than 100 because nine publications focused on more than one country. Publications in our sample were published from 1970–2019, with an increasing trend in publications per year through time (Fig. 2).

Most publications in our final sample were journal articles (68%), with proceedings papers another common avenue for wilderness fire science (18%). The remaining publications were from books or book chapters (5%), General Technical Reports (3%), datasets (2%), management documents (2%), or other (2%) (Fig. 3A). Publications spanned many study types (Fig. 3B), with most reporting on new data in the form of observational studies (62%) or synthesizing information through reviews/meta-analyses (25%). The remainder of publications were modeling studies (7%), methods papers (3%), datasets (2%), or field experiments (1%).

Publications in our sample focused on a variety of principal subjects (Fig. 3C). The most common were publications primarily dealing with fire effects (44%), with additional representation from incident management (18%), fire regimes (17%), and fire ecology (12%). Remaining publications focused on fuel treatments (5%), monitoring (2%), fire behavior (1%), tool assessment (<1%), smoke management (<1%), and fuel characterization (<1%). Beyond their primary focus, publications dealt with an even more varied suite of environmental resources, or response variables. Over half of publications explored fire effects on vegetation (64%), patterns of fire (57%), or wilderness management in the context of active fire management (51%). Publications also reported, in lower numbers, on a wide variety of other response variables (Fig. 3D). Because publications could have more than one response variable, percentages sum to more than 100.

Publications in our sample that focused on fire ecology and fire effects were more likely to be published in peer-reviewed journals, while publications that focused on fire regimes, incident management, and fuel treatments were more likely to be published in proceedings papers (Fig. 4). Principal subjects of publications also tended to be linked to specific types of environmental resources. For example, fire ecology, fire effects, and fire regime publications focused more often on physical variables such as soil, water, vegetation, and biota, while publications with principal subjects of fuel treatment or incident management focused on more abstract variables such as economics or law/policy (Fig. 5).

Representativeness

All the publications from the United States of America (n = 199) occurred in the contiguous USA (Fig. 1), and we conducted further analysis of representativeness on this sub-sample. Within the USA, studies were largely concentrated in the Northern Rocky Mountains, several southwestern wilderness areas, the Sierra Nevada, and the Boundary Waters Canoe Area Wilderness (Fig. 1).

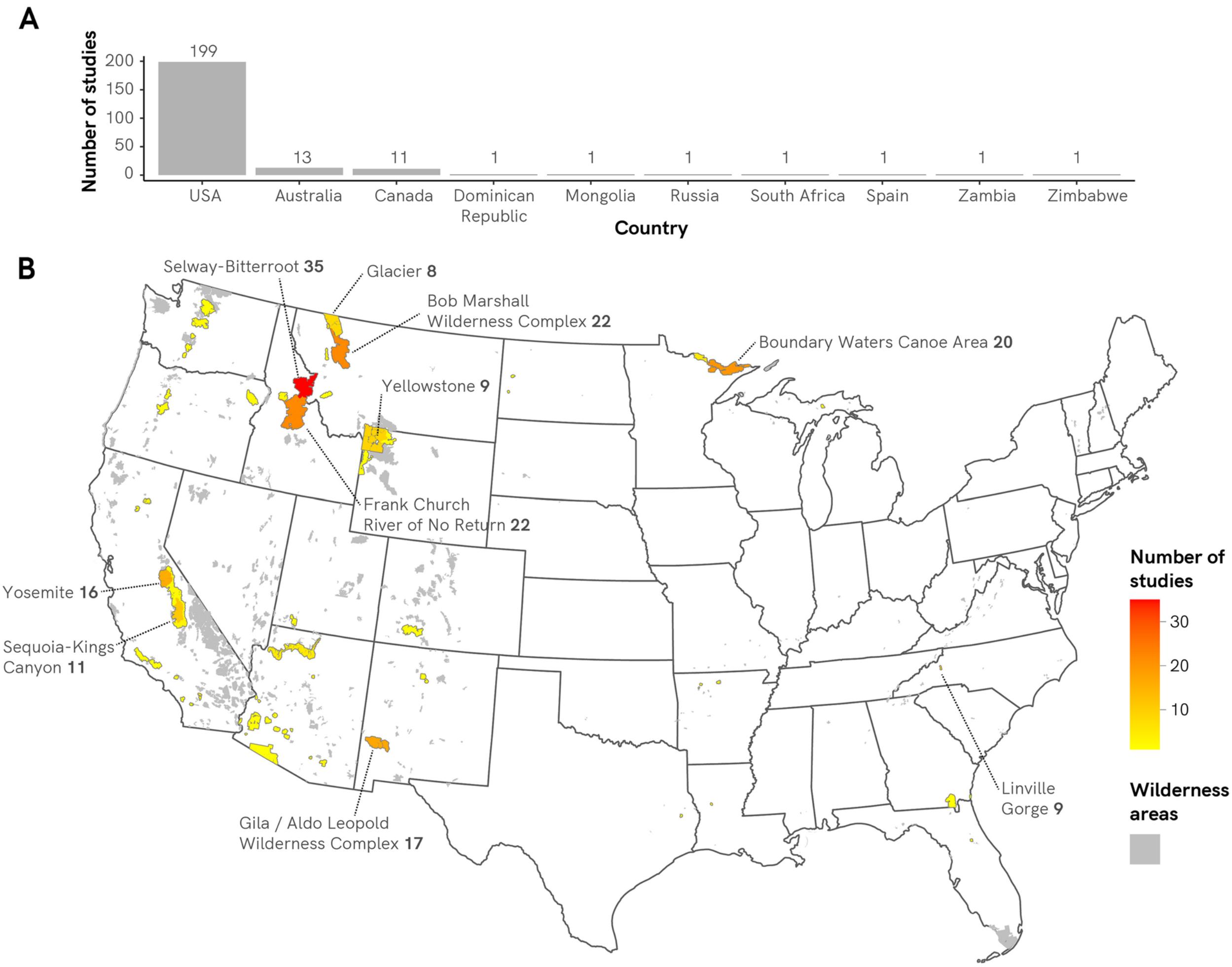

Fig. 1 **A** Number of studies taking place in each country. Note that some studies ($n = 9$) reported on research in more than one country. **B** Frequency of studies by wilderness area (USA only). Of the 199 studies from the USA in our sample, none documented research outside of the contiguous USA. Labels shown for the 10 wilderness areas with the most studies (Bob Marshall Wilderness, Scapegoat Wilderness, and Great Bear Wilderness were combined into "Bob Marshall Wilderness Complex"; Gila Wilderness and Aldo Leopold Wilderness were combined into "Gila / Aldo Leopold Wilderness Complex"). Note that many studies occurred in multiple wilderness areas

Climate of wilderness areas represented in our sub-sample occupied a reduced climate envelope (Fig. 6E) compared both to wilderness areas in the contiguous USA (Fig. 6C) and especially the contiguous USA at large (Fig. 6A). Research from this sub-sample has predominately occurred in areas with climate characterizing mixed-conifer forests.

In a similar manner, historical fire regimes of studied wilderness areas (Fig. 6F) represent a reduced fire regime envelope relative to wilderness areas in the contiguous USA (Fig. 6D) and the contiguous USA overall (Fig. 6B). Historical fire regimes of studied wilderness areas were clustered in mixed-severity regime space (i.e., stand-replacing proportion ~0.5 and mean return intervals of 30–100 years). There were few studied wilderness areas with historical frequent low-severity fire regimes, and virtually none with frequent stand-replacing fire regimes (i.e., grassland and shrubland ecosystems).

In the contiguous USA, every wilderness area with extensive fire in the last several decades (i.e., cumulative area >200,000 ha burned 1984–2019) is represented by at least one study in our sample (Fig. 7A). However, many of the wilderness areas with little or no representation in our sample have, in fact, experienced a relatively high amount of fire since 1984 (Fig. 7B).

Synthesis

Beyond the quantifiable metrics of research described above, we identified major conceptual areas in which scientific advancements have been facilitated by fire in

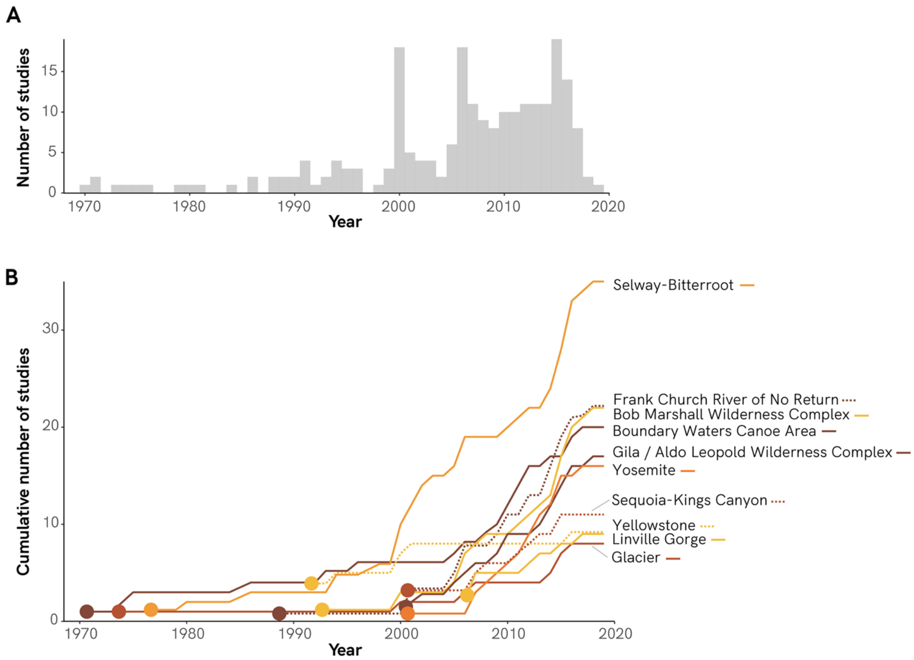

Fig. 2 **A** Frequency of studies by year. **B** Cumulative frequency of the 10 wilderness areas with the most studies. Circles indicate the first year the wilderness area occurs in our sample. Bob Marshall Wilderness, Scapegoat Wilderness, and Great Bear Wilderness were combined into "Bob Marshall Wilderness Complex"; Gila Wilderness and Aldo Leopold Wilderness were combined into "Gila / Aldo Leopold Wilderness Complex"

wilderness. We do not imply that research from outside of wilderness areas has nothing to offer, but rather that the following advancements have depended, in significant part, on research opportunities afforded by wilderness fires and wilderness fire management. We also propose high-priority research questions which future wilderness fire science is well-suited to address.

Self-limitation

A primary scientific advancement enabled by wilderness fire management is the extent to which fire limits the spread and intensity of subsequent fire. Ecological theory of this pattern-process relationship between fire and vegetation (Agee 1999; Peterson 2002; Turner 1989) has been demonstrated with field data largely arising from studies in wilderness areas (e.g., Collins et al. 2009; Parks et al. 2016, 2015, 2014; Teske et al. 2012). Areas with a management history of wildland fire use are essential for this research (Miller and Aplet 2016), because locations with heavy suppression provide few instances of interactions between fire perimeters through time. Wilderness fire science has also revealed that the self-limiting effects of fire vary by ecosystem, diminish over time, and are reduced by extreme fire weather (Collins et al. 2009; Parks et al. 2015). This body of research underscores how the decision to suppress a fire is a lost opportunity to create natural fuel breaks and restore ecosystem resilience (Miller 2012; Parks et al. 2015). Wilderness areas with active fire regimes can serve as excellent places for future research that tests how changing climate and fire regimes will impact the strength and longevity of self-limitation effects following fire.

Forest ecosystem dynamics under active fire regimes

With high levels of fire suppression in nearly all non-wilderness areas (Calkin et al. 2005; Quadrennial Fire Review 2014), wilderness areas with active fire management offer some of the only contemporary insights into how active fire regimes (i.e., where fires are allowed to burn under a wider range of conditions) shape forest ecosystems. Research in wilderness areas has highlighted fire as a driver of heterogeneity, both by increasing structural complexity in forest ecosystems (e.g., Holden et al. 2006; Kane et al. 2013; Robinson et al. 2005) as well as by catalyzing shifts in composition that maintain dynamic landscape mosaics (e.g., Jackson and Sullivan 2009; Kleindl et al. 2015; Reilly et al. 2006; van Wagtendonk et al. 2012). Additionally, wilderness fire research has assessed the ability of wildfires to restore target ranges of structure and composition, showing that wildfires, especially when allowed to burn under less extreme conditions, can be a successful restoration treatment in ecosystems with low- and moderate-severity fire regimes (Fulé and Laughlin 2007; Larson et al. 2013; Pawlikowski et al. 2019; Taylor

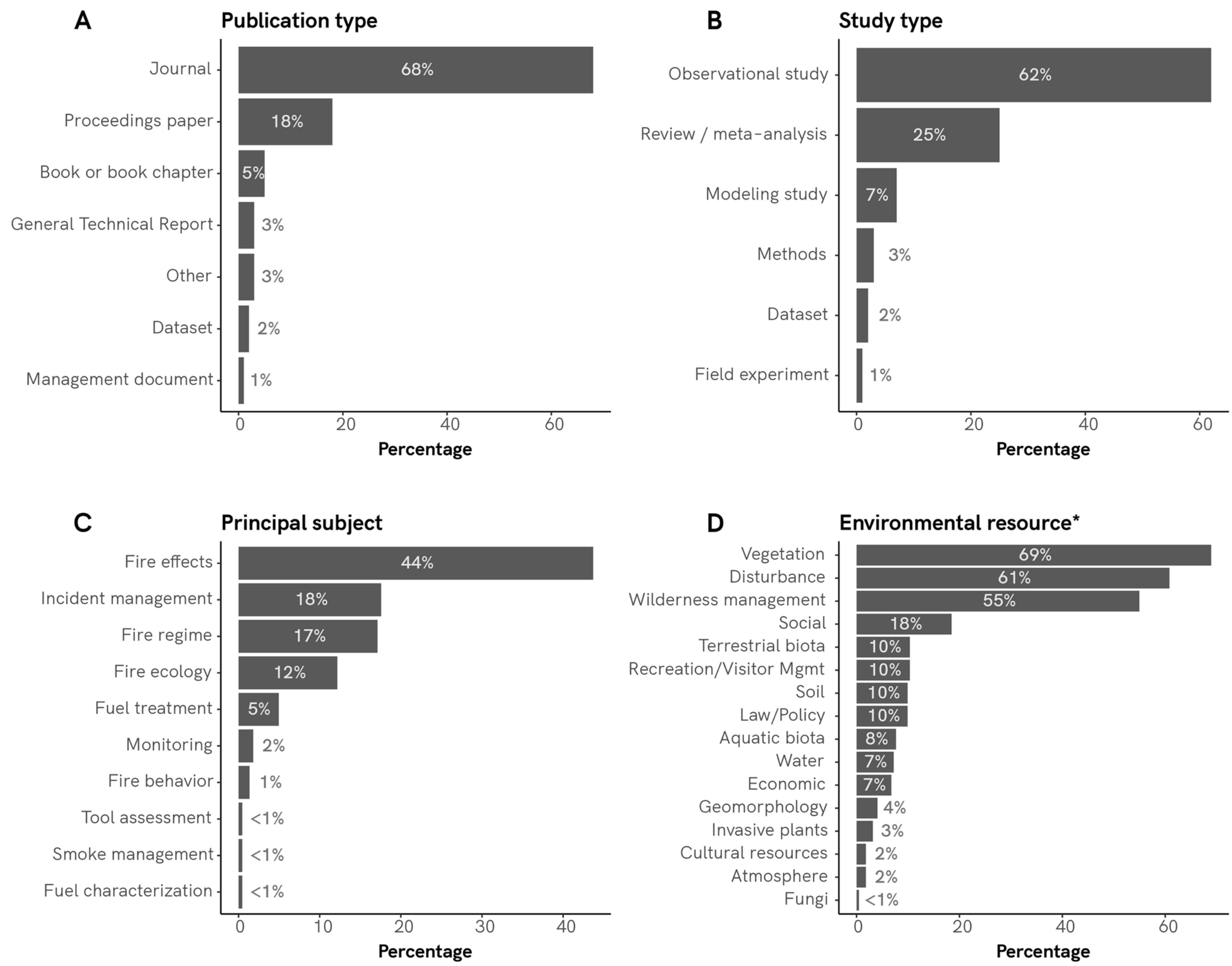

Fig. 3 Percentage of studies by **A** publication type, **B** study type, **C** principal subject, and **D** environmental resource. *Because studies could have more than one Environmental resource, values sum to greater than 100%

2010). As fire activity increases in many areas (e.g., Schoennagel et al. 2017; Jain et al. 2022), research from wilderness areas provides an important ecological baseline (Belote et al. 2015; Frelich 2017), helping us to create mechanistic predictions of how ecosystems may respond to changing climate and fire regimes. Furthermore, wilderness areas provide an excellent opportunity to test whether locations with active fire regimes—which tend to have reduced fuels, more structurally-diverse forests, and greater landscape heterogeneity—exhibit greater resiliency or smoother transitions to ecological change than areas where fire continues to be suppressed (Coop et al. 2020).

Aquatic ecosystem dynamics under active fire regimes

Though representing a much smaller proportion of our sample relative to publications dealing with vegetation, an important body of wilderness fire science has advanced understandings of the effects of fire on fluvial geomorphology and aquatic processes and biota. Wildfires strongly influence the routing of wood and sediment from upland and riparian areas to the channel network (Robinson et al. 2005; Marcus et al. 2011; Kleindl et al. 2015), which can increase spatial complexity (Arkle et al. 2010; Robinson et al. 2005), shift species composition of macroinvertebrates (Arkle et al. 2010; Jackson et al. 2012; Jackson and Sullivan 2009; Malison and Baxter 2010), and provide salmonid spawning habitat (Jacobs et al. 2021). Physical changes associated with increased flows following wildfires may also have negative effects such as increased nutrient loadings (Spencer et al. 2003) and decreased abundance of macroinvertebrates and fish (Bozek and Young 1994; Minshall et al. 2001; Rugenski and Minshall 2014). However, restoring natural wildfire regimes can provide numerous benefits, including increasing snowpack and reducing forest water stress (Boisramé et al. 2019). Wilderness fire management provides many research opportunities to explore how

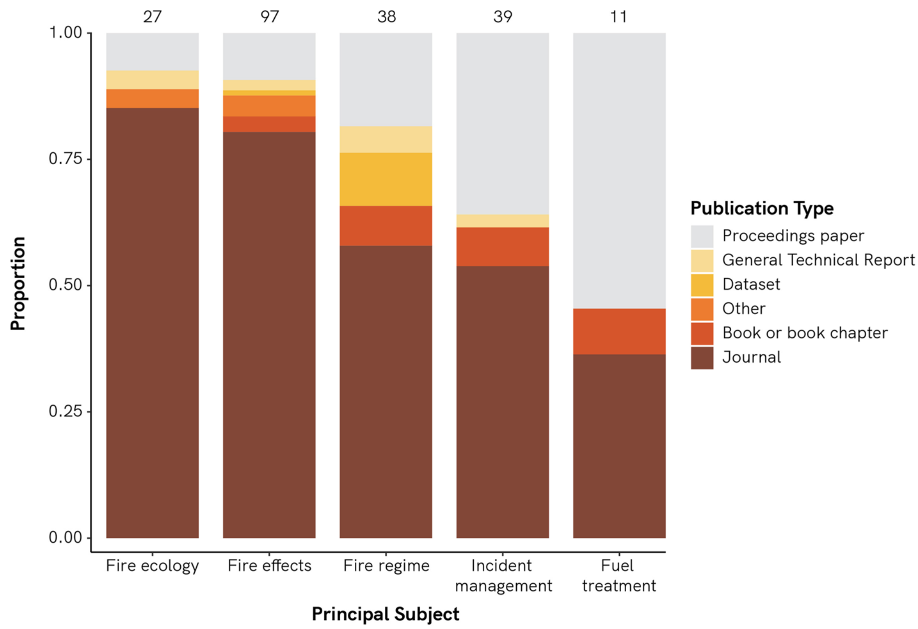

Fig. 4 Proportion of publication type by principal subject. Only the five principal subjects with the most publications are shown ($n = 212$; 95% of studies). Numbers on top of each column indicate the number of studies in that category

changing climate and fire regimes will impact aquatic systems, and whether aquatic systems within an active fire regime are better able to adapt to these changes.

Wilderness fire management decision making

Advancements in our understanding of self-limitation have equipped wilderness managers with improved tools for predicting when wildfires can be safely managed within wilderness boundaries (e.g., Barnett et al. 2016; Scott et al. 2012; Suffling et al. 2008). A sizeable body of publications in our sample have also identified the social and institutional challenges to restoring natural fire regimes to wilderness areas, such as a poor public perception of fire, negative smoke impacts, and a lack of institutional support (e.g., Miller 2003; Miller et al. 2011; Parsons 2000; Parsons et al. 2003; Williamson 2007). As a result of these barriers, the majority of fires continue to be suppressed in all but a handful of wilderness areas, where historical precedents exist for allowing wilderness fire (Seielstad 2015; Berkey et al. 2021b). To incentivize the wider implementation of active fire management, it is vital to increase public understanding of the inevitability of fire events and the importance of fire to ecosystem processes, build cooperation across administrative boundaries, and create a culture within land management agencies that equips, supports, and expects managers to manage fires for resource benefit when possible (Berkey et al. 2021b; Miller et al. 2011). Fifty years of training and experience might be expected to have made it easier to manage wilderness fires for resource benefit, but instead, social and institutional barriers continue to discourage the practice on a widescale basis (Seielstad 2015). Future wilderness fire science can investigate how to reverse this trend.

Fire impacts on recreation

Many of the qualities that draw recreationalists to wilderness areas—remoteness and ruggedness—are also what promote wildfires that burn with minimal, or no, suppression. As such, wilderness fire management often provides the opportunity for social science research exploring the effects of fire on recreation and recreationists' experiences and attitudes. Wilderness fire science has shown that fires and resulting trail closures can negatively impact experiences of wilderness recreationalists (Boxall et al. 1996; Brown et al. 2008; Tanner et al. 2022), although not all wildfires have this adverse effect (e.g., Love and Watson 1992). In fact, visual evidence of disturbances can increase wilderness character and public interest (Schroeder and Schneider 2010), leading recreationalists to seek out recently burned areas (Englin et al. 2008; Dvorak and Small 2011; Sánchez et al. 2016; but see Tanner et al. 2022). Studies in wilderness have shown that recreationalists often support natural and prescribed fires in wilderness (Borrie et al. 2006; Knotek et al. 2008; McCool and Stankey 1986; Watson et al. 2015), although this support may drop during high fire-activity years (Borrie et al. 2006). Public support is crucial

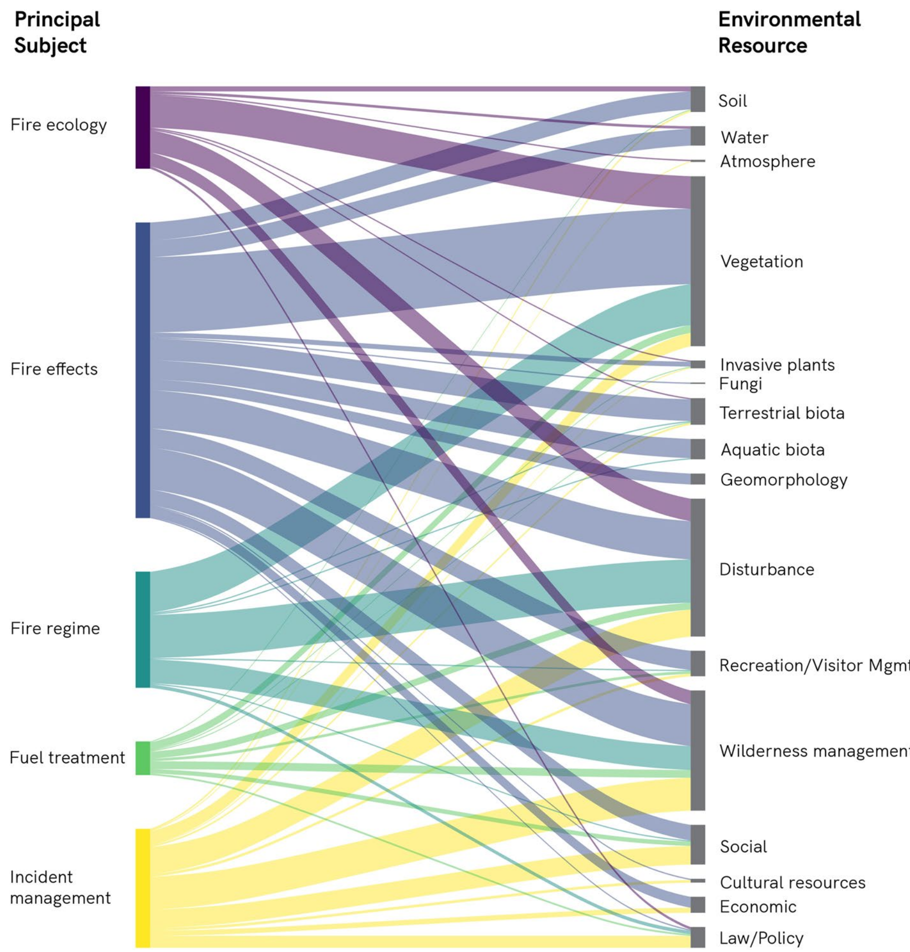

Fig. 5 Connections between the principal subjects and environmental resources of publications

to the feasibility of wilderness fire management, and an important future role of wilderness fire science will be to understand how the increasing size and severity of wildfires (Schoennagel et al. 2017) is impacting patterns of recreation and recreationalists' perceptions of wilderness fire management.

Discussion

This systematic review illustrates how fire in wilderness has created opportunities for research—and therefore the production of knowledge—related to patterns, processes, and effects of wildfire, as well as management of wildfire. While we present a diversity of research topics and advancements that have originated from wilderness fire science, our analysis also reveals areas—geographic, bioclimatic, and conceptual—where more research attention is needed.

Our sample of wilderness fire science is heavily skewed towards studies from the contiguous USA. Less than 10% of studies in our sample reported on findings from outside of North America, even though many other regions of the world have experienced more fire over the last several decades (Robinne et al. 2019). We only searched for publications in English, and our search string of ["Wilderness" AND "Fire"] may have contributed to the observed bias by identifying fewer studies from countries with protected areas named with other descriptors (e.g., "Reserve", "National Park", "Provincial Park", "Strictly Protected Area", etc.). However, given that the USA had among the earliest adoption of wilderness fire management and provided an early model of wilderness areas as a construct, it is perhaps not surprising that many of these publications come from landscapes in the USA.

Within the USA, studies were also heavily concentrated in a relatively small number of wilderness areas, particularly in the northern Rockies. This pattern is largely driven by where wilderness managers have allowed fire to burn (Miller and Aplet 2016). For example, the Selway-Bitterroot Wilderness had the most studies in our sample

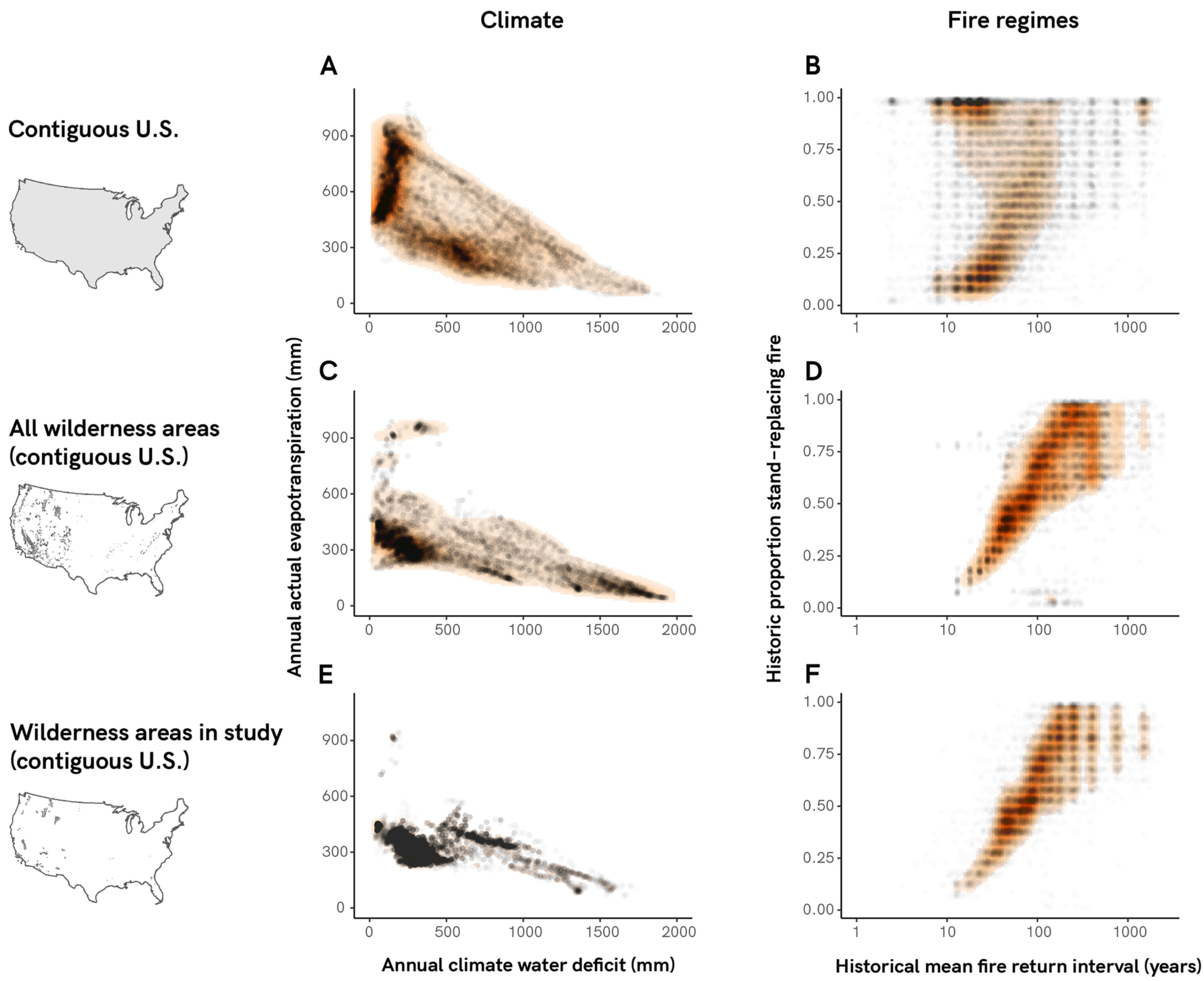

Fig. 6 Climate and fire regime envelopes for the contiguous USA **A**, **B**; all wilderness areas in the contiguous USA **C**, **D**; and only wilderness areas in our sample **E**, **F**. Grey shading in the lefthand maps show the spatial extent of pixels contributing to each row. Envelopes are approximated by 2D density plots (orange) with actual values shown by black dots. Data in E and F are proportional to the number of times a wilderness area was included in the sample (i.e., if a wilderness area was included 10 times in the sample, each pixel value from that wilderness area is also included 10 times)

by far, likely because it was the first US Forest Service-managed area to allow for scientific observation of fire (Smith 2014), as well as the first Forest Service area to adopt wilderness fire management (Berkey et al. 2021b). Furthermore, fires are almost always suppressed in small wilderness areas (Zimmerman et al. 2006) because unplanned ignitions are more likely to spread outside of wilderness boundaries (Barnett et al. 2016). For this reason, large wild areas (e.g., Selway-Bitterroot Wilderness, Frank Church River of No Return Wilderness, Bob Marshall Wilderness Complex, Yellowstone National Park, and Gila/Aldo Leopold Wilderness Complex) have allowed for greater use of wilderness fire management, resulting in increased research attention.

Our study is a sample of a broader body of research, and thus does not capture every wilderness fire science study. For example, there are some wilderness areas which did not appear in our sample, but where research has occurred: e.g., Kalmiopsis Wilderness in Oregon (Thompson and Spies 2009; Donaghy Cannon 2013) and Ventana Wilderness in California (Talley and Griffin 1980). Furthermore, our search strings may have not detected studies in designated wilderness areas where the location is better known by another name (e.g., a study conducted in Marjory Stoneman Douglas Wilderness in Florida, but using “Everglades National Park” to describe the study location; Beckage et al. 2003; Ruiz et al. 2013). However,

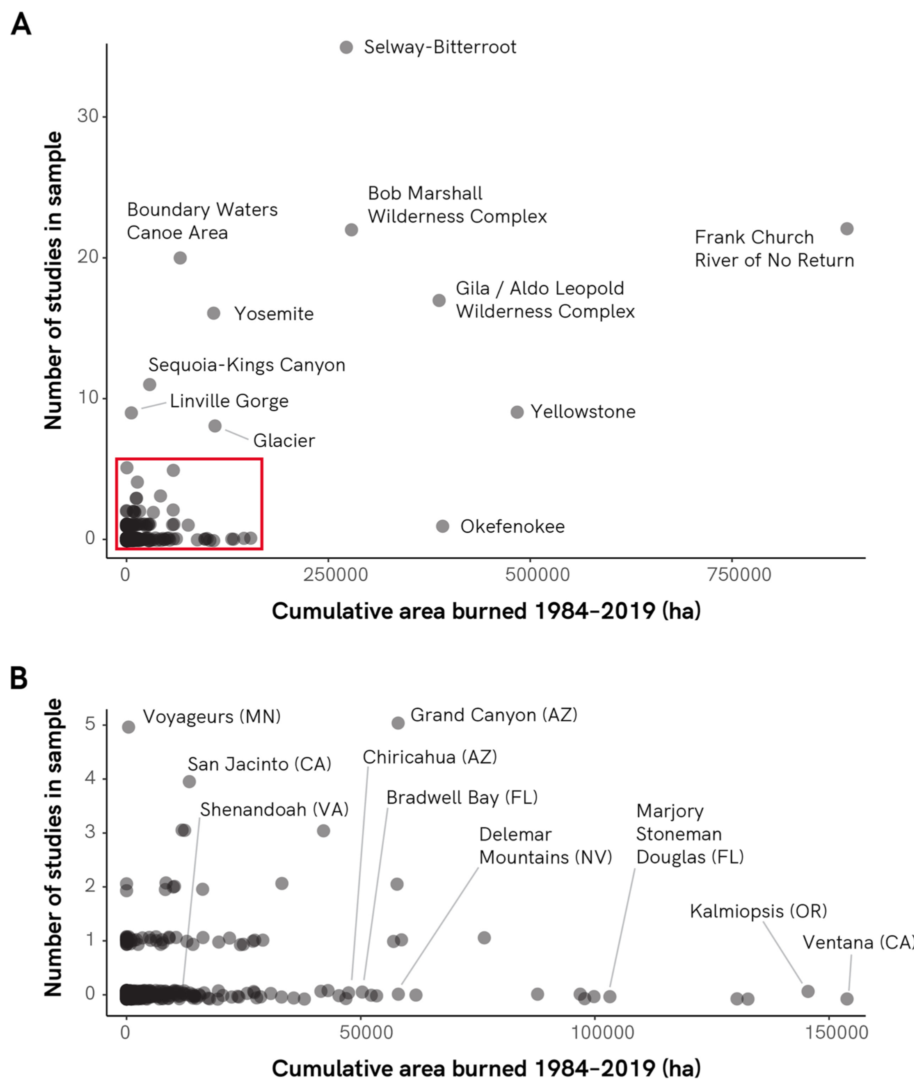

Fig. 7 **A** Relationship between total amount of fire burned (1984–2019) in each wilderness area in the contiguous USA and the number of times that wilderness area was studied in our sample. **B** Inset of wilderness areas falling within the red box in panel **A**

despite the imperfect detection of all wilderness fire science, we expect that the frequency with which wilderness areas appear in our sample is a useful proxy for the relative amounts of fire research attention, at least in the USA.

This sample of wilderness fire science is not fully representative of climate or fire regimes in the USA, and certainly not globally (Robinne et al. 2019). Rather, the sample is highly skewed toward the climate space of temperate mixed-conifer forests and the fire regime space of mixed-severity fire—largely due to where designated wilderness areas occur. Even if all current wilderness areas in the contiguous USA had active fire regimes, knowledge derived from these areas would still represent a reduced climate and fire regime space relative to the whole country (Fig. 6). Nevertheless, even when only considering available wilderness areas, there is potential to broaden the scope of fire science to better include under-represented climates and historical fire regimes. We identify many wilderness areas that have experienced significant wildfire but where our database search detected little or no research (e.g., many of the labeled wilderness areas in Fig. 7B). These under-represented areas offer the possibility for studies that would expand the geographic, climate, and fire regime spaces of wilderness fire science, thereby helping to address knowledge gaps. Additionally, allowing more fire to burn in wilderness areas with little to no contemporary fire can create additional research opportunities, especially in wilderness areas that might help to expand the representativeness of the current body of wilderness fire research.

While the body of research documented here covers a diversity of research areas and questions, there are several notable conceptual gaps. First, wilderness fire science has largely focused on fire effects on vegetation. Notwithstanding the valuable advances in other categories described in the synthesis section above, we urge the continued increase of research that explore how fire impacts other domains such as wildlife, fungi, the pyrodiversity-biodiversity hypothesis, soil, aquatic systems, and human dimensions in a wilderness context. Secondly, very few publications in our sample explicitly addressed the impacts of climate change on fire dynamics in wilderness (e.g., Frelich and Reich 2009; Rugenski and Minshall 2014). Many of the high-priority future research areas identified in the synthesis section relate to climate change, and we urge the greater use of wilderness areas as a natural laboratory to explore impacts of climate change on fire regimes and fire-prone ecosystems (Belote et al. 2015). Finally, while there is a growing appreciation that most wilderness areas were historically managed and impacted by Indigenous groups and their use of fire (Fisher 1997; Kimmerer and Lake 2001; Watson et al. 2011), our sampled detected very few publications that focused on the past or present role of cultural or Indigenous burning in wilderness (e.g., Kay 2000; Trauernicht et al. 2013). Despite the fact that Indigenous burning was identified as a research focus already forty years ago at a large North American symposium on wilderness fire (Kilgore 1987; Lotan et al. 1985), we found that this emphasis has largely diminished in our sample in more recent years. Research published since our analysis has begun to address this gap (e.g., Kipfmueller et al. 2021; Larson et al. 2021), however we believe that wilderness areas provide an excellent opportunity to expand on this vital research area.

Another critical issue that remains unresolved is the role of prescribed fire in wilderness settings. Prescribed fire is legally allowed in virtually all wilderness areas, with varying goals of reducing fire hazard, restoring historical structure and habitat, or allowing natural fire regimes to return (e.g., Bureau of Land Management, 2012; National Park Service, 2006; U.S. Fish and Wildlife Service 2008; U.S. Forest Service 2007). Furthermore, many backcountry recreationalists support the use of prescribed fire in wilderness (Knotek et al. 2008; McCool and Stankey 1986). However, prescribed fire is rarely implemented and is subject to many of the same challenges inherent in managing wildfire (Jaffe et al. 2020; Parsons 2000; Schultz et al. 2018) in addition to philosophical questions as to the appropriate level of human influence in wilderness (Lawhon 2011; Lotan et al. 1985; Parsons et al. 2003). Several publications identified by our review have attempted to overcome these hurdles: e.g., by making an ecological case for prescribed fire (Heinselman 1970), showing the important role that prescribed fire can play in restoring degraded habitats (Keane et al. 2006; Vequist 2007), or demonstrating that prescribed fire can often meet many of the management objectives of wildfires (Nesmith et al. 2011). However, the limited application of prescribed fire in wilderness areas today shows that additional work is needed, including applied research to help understand perceived policy barriers to using prescribed fire in wilderness and develop strategies to overcome these barriers. Future wilderness fire science can explore the extent to which prescribed fire emulates natural patterns of wildfire (e.g., seasonality, severity, duration, patch size), especially under changing climate and fire regimes.

Unlike previous reviews of wilderness fire science (Agee 2000; Kilgore 1987; Miller and Aplet 2016), we used systematic methods, allowing for quantitative analysis of research patterns. Additionally, our study differs from previous reviews in that we maintained a global scope. The previous reviews explicitly acknowledge their general emphasis on fire science from the western USA (e.g., Kilgore 1987; Miller and Aplet 2016), and while our study clearly bears witness to and quantifies this bias, it also highlights important research from other parts of the USA and globally. In the nearly four decades spanning these reviews, wilderness fire science has helped to identify and address many important research questions (Table 1). For example, fire as a landscape process and as a driver of complexity have remained active topics of wilderness fire science for several decades, as knowledge of these areas is continually deepened and expanded. Improved data and models were key areas featured by both Agee (2000) and Miller and Aplet (2016)—however, because these advances developed from and apply to fire science broadly, they were largely outside the defined scope of our wilderness-specific study and search strings.

Identifying and overcoming barriers to wilderness fire management has been a focus in every wilderness fire science review (Table 1), highlighting the complex and persistent hurdles faced by wilderness fire managers and calling into question whether this problem will be solely solved by additional research (Miller and Aplet 2016). Successful implementation of wilderness fire management depends both on managers with a deep commitment to fire as a fundamental ecological process, as well as strong support from institutional leaders to deal with the short-term risk incurred by allowing fire (Berkey et al. 2021b). It is important to support initiatives that

Table 1 Comparisons of wilderness fire science reviews through time

Paper	Identified areas of progress	Identified priority research areas
Kilgore 1987	• Fire regimes & fire history • Fire effects (on wildlife, insects/disease, nutrient cycling, diversity/stability) • Fire behavior	• What is "natural"? • Role of Indigenous fire in wilderness • Role of prescribed fire in wilderness • How has suppression impacted forest structure/composition? • Fire effects on habitats of endangered species • Barriers to wilderness fire management
Agee 2000	• Drivers of wilderness fire • Fire regimes • Models, data	• Improve fire weather models and data inputs • Incorporate more complexity into fire models • Consider fires in landscape context • Barriers to wilderness fire management
Miller and Aplet 2016	• Models, tools, and data • Fire as a driver of complexity • Fire as a landscape process • Barriers to wilderness fire management	• Identify opportunities for fire at the landscape scale • Effects of fire when allowed to burn in moderate weather conditions • Better accounting of risks and benefits of wilderness fire • Perceptions and responses of people to fire risk
This study	• Self-limitation • Forest and aquatic ecosystem dynamics under active fire regimes • Wilderness fire management • Impacts of fire on recreation	• Fire effects beyond vegetation • Climate change and fire • Role of Indigenous burning in wilderness • Role of prescribed fire in wilderness • Barriers to wilderness fire management

cultivate and deepen managers' professional wilderness fire ethic and encourage leaders to provide a supportive environment where this ethic can be expressed instead of being at odds with institutional leadership.

Some topics featured in wilderness fire science reviews have experienced a resurgence in recent years (Table 1). The roles of Indigenous and prescribed fire in wilderness were a major focus of the field at the time of Kilgore's review (1987), however they are absent from the priority research areas of later reviews (Agee 2000; Miller and Aplet 2016). Today, Indigenous and prescribed fire will likely play an important role in addressing the impacts of changing climate and fire regimes in protected areas, and increased research and discussion is vital (Larson et al. 2021).

Our review identified over 220 scientific studies enabled by fire in wilderness. Given that we were focused on the relatively narrow topic of fire, our sample of scientific literature is a conservative estimate of the total scientific contribution of wilderness. Research and scientific use of wilderness is often questioned and challenged by managers (Landres 2010), and the policies of some agencies force researchers to demonstrate that the work cannot be accomplished outside of wilderness. This distinction is not mandated by law or required of other wilderness uses or user groups (e.g., a recreational visitor does not need to demonstrate that their recreational activity can only be accomplished in wilderness before they are allowed to visit). Greater effort to quantify the scope, impact, and societal benefits of scientific research and monitoring conducted in wilderness, or in support of wilderness management, could help wilderness managers better understand the role of wilderness in larger socioecological systems (Parsons 2007; Smith and Gray 2021), potentially leading to greater support from managers for scientific activities in wilderness. At the same time, researchers have a responsibility to familiarize themselves with wilderness law and policy—especially section 4c of the Wilderness Act ("Wilderness Act 16 U.S. Code § 1131," 1964) which describes prohibited uses—as well as important wilderness management decision support tools, such as minimum requirements analysis. This will help to ensure that researchers propose appropriate methods, reducing conflicts with wilderness managers.

Conclusions

Wilderness fire science has increased in pace and scope over the last five decades, helping to advance knowledge in a variety of conceptual areas, including self-limitation of fire, forest and aquatic ecosystem dynamics under active fire regimes, fire management and decision-making, and fire effects on recreation and visitor experiences. Systematic methods enabled us to detect a wide range of disciplines; however, we show that our sample of wilderness fire science was heavily skewed towards studies from a handful of wilderness areas in the northern Rocky Mountains of the USA. As a result, the climate and fire regime spaces of this sample of studies are not entirely representative of wilderness areas in general, and certainly not of broader geographic areas. We identify several wilderness areas that have experienced wildfire but few or no studies—under-represented areas that offer the possibility for future research to help expand the geographic, climate, and fire spaces of wilderness fire science. Finally, we urge continued research in wilderness areas that deepens our understanding of the past and potential role of cultural and Indigenous burning, the impacts of changing climate and fire regimes on ecosystems and landscape processes, and how to increase support for wilderness fire management and prescribed fire.

Supplementary Information

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Additional file 1.

Additional file 2.

Additional file 3.

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Authors' contributions

Mark R. Kreider: Investigation, Formal analysis, Data curation, Writing—original draft, Writing – review & editing, Visualization. Melissa R. Jaffe: Investigation, Writing – review & editing. Julia K. Berkey: Methodology, Writing – review & editing. Sean A. Parks: Investigation, Writing – review & editing. Andrew J. Larson: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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Availability of data and materials

The datasets and scripts generated and analyzed during the current study are available in the Zenodo repository, https://doi.org/10.5281/zenodo.6326355.

Declarations

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The authors declare that they have no competing interests.

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