frontiers in Forests and Global Change

TYPE Review
PUBLISHED 18 August 2026
DOI 10.3389/ffgc.2026.1870338

Check for updates

OPEN ACCESS

EDITED BY
Himanshu Bargali,
Gurukul Kangri University, India

REVIEWED BY
Dhruba Sharma,
Assam Down Town University, India
Zongrong Li,
Texas A&M University, United States

*CORRESPONDENCE
Lacour M. Ayompe
✉ mlacour@uci.edu

RECEIVED 01 May 2026
REVISED 23 June 2026
ACCEPTED 31 July 2026
PUBLISHED 18 August 2026

CITATION
Ayompe LM and Elias M (2026) Navigating the dual nature of wildfire in the Anthropocene: a framework for assessing impacts on nature's contributions to people and pathways to adaptive management.
Front. For. Glob. Change 9:1870338.
doi: 10.3389/ffgc.2026.1870338

COPYRIGHT
© 2026 Ayompe and Elias. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Navigating the dual nature of wildfire in the Anthropocene: a framework for assessing impacts on nature's contributions to people and pathways to adaptive management

Lacour M. Ayompe[1]* and Micah Elias[2]

[1]Department of Earth System Science, University of California Irvine, Irvine, CA, United States, [2]Blue Forest, Sacramento, CA, United States

Wildfires historically shaped and sustained global biomes, but climate change, strict fire exclusion policies, and rapid expansion into the wildland–urban interface have fueled an era of unprecedented, high-severity "megafires." This review synthesizes current literature on the dual nature of wildland fires, categorizing their impacts on material, non-material, and regulating Nature's Contributions to People (NCP) using the IPBES framework. Grounded in case studies from regions experiencing acute megafires including California, Australia, Canada, Chile, Siberia, Maui, and Los Angeles, we present a conceptual framework illustrating fire's transition from an ecological regulator to a driver of severe NCP degradation. High-severity fires frequently cross ecological thresholds, causing acute detriments like massive timber loss, water quality degradation, disrupted soil microbiomes, and eroded recreational landscapes. Conversely, low-to-moderate severity fires, particularly Indigenous cultural burning practices, remain vital for sustaining these ecosystem contributions. We identify critical research gaps regarding multi-decadal post-fire recovery and sector-specific economic valuations, which are essential for improving decision support. Furthermore, we argue that risk-based NCP accounting must be paired with innovative conservation finance models to fund proactive, landscape-scale fire management. This synthesis underscores the urgent need to shift global land management from absolute fire suppression toward adaptive resilience and co-management, utilizing the NCP framework to evaluate complex trade-offs, target fuel treatments, quantify costs, and drive necessary policy reforms in increasingly fire-prone landscapes.

KEYWORDS
adaptive co-management, conservation finance, cultural burning, IPBES framework, megafires, nature-based solutions, nature's contributions to people, wildland–urban interface

1 Introduction

The past and future of wildfires are deeply intertwined with Nature's Contributions to People (NCP), a framework that captures the duality of fire as both a vital ecological regulator and a catastrophic hazard. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) NCP framework, which supersedes the Millennium Ecosystem Assessment by encompassing material, non-material, and regulating contributions, provides a coherent lens for assessing wildfire impacts across both ecological and social systems (Depietri and Orenstein, 2019; Horvat and Karleuša, 2024). The NCP paradigm offers distinct conceptual advantages over traditional ecosystem services (ES) frameworks by explicitly incorporating relational values, fluid nature-culture boundaries, and Indigenous and Local Knowledge (ILK; Gillson et al., 2019; Palacios-Abrantes et al., 2022). Rather than treating human governance merely as an external management input or positioning societies as passive economic beneficiaries, the NCP lens conceptualizes human stewardship such as cultural burning as an intrinsic, reciprocal component of ecosystem health and fire-regime maintenance (Fisk et al., 2024; Nikolakis et al., 2022).

Historically, in fire-adapted biomes such as Mediterranean, boreal, and savanna ecosystems, fire has acted as a vital natural disturbance and soil-forming agent (McLauchlan et al., 2020; Pausas and Bond, 2020). Under historical regimes of low-to-moderate severity fires, where 'fire severity' serves as a distinct, standardized metric quantifying the degree of organic matter consumption, vegetation mortality, and soil alteration rather than mere physical energy output (Bargali et al., 2024; Schmidt et al., 2024; Yackulic et al., 2025), regular fire sustained landscape heterogeneity, biodiversity, and nutrient cycling (Kelly et al., 2020; Shen et al., 2025). This specific distribution of low-to-moderate fire effects acts as a vital structural anchor for ecosystem equilibrium. These processes ultimately contributed to long-term ecosystem health and the resilient delivery of NCP, including carbon storage (regulating), water quality regulation (regulating), timber resources (material), and culturally meaningful landscapes (non-material; Jenerette et al., 2022; Thomas et al., 2022).

However, contemporary wildfire regimes are undergoing rapid, climate- and human-driven transformations. A century of strict fire exclusion policies has created a massive "fire deficit," an ecological debt characterized by excessive fuel accumulations and the absence of natural, regulatory disturbance cycles. This deficit, compounded by climate warming and prolonged multi-year droughts, has shifted many regions toward increasingly high-severity fires. These modern "megafires" increasingly exceed historical severities and burn capacities (Prichard et al., 2021; Schoennagel et al., 2017). These ecological shifts are severely compounded by rapid human population growth and development within the wildland–urban interface (WUI). Recent Earth Observation data quantitatively demonstrates the unprecedented global scale of this WUI expansion, where communities, infrastructure, and economies directly intersect with fire-prone ecosystems (Schug et al., 2023). In these zones, fires threaten lives and essential resources, intensifying socio-economic costs and undermining the very NCP that WUI communities rely upon (Hessburg et al., 2019; McGranahan and Wonkka, 2025). The WUI thus represents a critical locus where wildfire transitions from an essential ecological process to a catastrophic hazard, demanding management strategies that balance risk mitigation with NCP maintenance (Christ et al., 2022).

The dual nature of wildfire is therefore both contextual and heavily contested. On one hand, as a fundamental regulator of fuel loads, nutrient cycling, and habitat dynamics, fire supports positive NCP under specific management conditions, such as prescribed burning or naturally ignited, low-severity fires (Depietri and Orenstein, 2019). On the other hand, when fires burn large, severe, or out of alignment with natural ecosystem structures, they cross critical ecological thresholds. This results in profound negative impacts on NCP, such as degraded water quality, eroded carbon storage, reduced timber productivity, and the destruction of culturally significant landscapes, that severely impair societal wellbeing (González and Ghermandi, 2024).

The literature converges on several core claims that frame this review. First, human health and resilience in the WUI are deeply tied to these fire-altered NCP, requiring integrated ecological and social science insights to properly assess vulnerability (Anderson et al., 2013; Greenberg et al., 2024; Thomas et al., 2022). Second, the synergistic interactions between climate change, fuel accumulations, and urban expansion are challenging traditional suppression paradigms, prompting an urgent shift toward adaptive resilience and fire-informed planning (McGranahan and Wonkka, 2025; Moya et al., 2019; Prichard et al., 2021). Third, while some fire-related NCP are enhanced in specific contexts (e.g., habitat renewal), these same processes can trigger detrimental impacts when thresholds are crossed or when fire regimes are mismatched with human needs (González and Ghermandi, 2024; Horvat and Karleuša, 2024).

This review synthesizes current evidence on the dual nature of wildfire through the NCP framework, focusing on Mediterranean, boreal, and savanna biomes alongside the rapidly evolving WUI. Our case studies specifically target regions experiencing the most acute megafire impacts today, notably California, Australia, Canada, Chile, Siberia, and Maui. Integrating recent extreme events like the 2023 Maui wildfire and the 2025 Los Angeles wildfire allows for an updated, multi-environmental evaluation of disaster dynamics. These cases elucidate how contemporary fires cross severe socio-ecological thresholds, ranging from isolated island ecosystem vulnerabilities to complex structural and economic losses in heavily populated municipal boundaries where advanced Earth Observation tracking is required. While we acknowledge the exclusion of other highly fire-prone regions (such as Southern Europe and sub-Saharan Africa) as a minor limitation, constraining our scope to these specific hotspots allows for a deeper examination of contemporary megafire consequences and the frontiers of adaptive management.

Furthermore, while we utilize the human-centric focus of the NCP framework to address societal impacts, we explicitly discuss the inherent limitations this framework poses for non-utilitarian, marginalized species and broader nature-to-nature coexistence in later sections. To guide this synthesis, we present a conceptual framework (Figure 1) illustrating the threshold where fire transitions from an ecological regulator to a driver of negative impacts on NCP. By evaluating how megafires disrupt ecosystem functions versus how managed fires sustain them, this review clarifies the

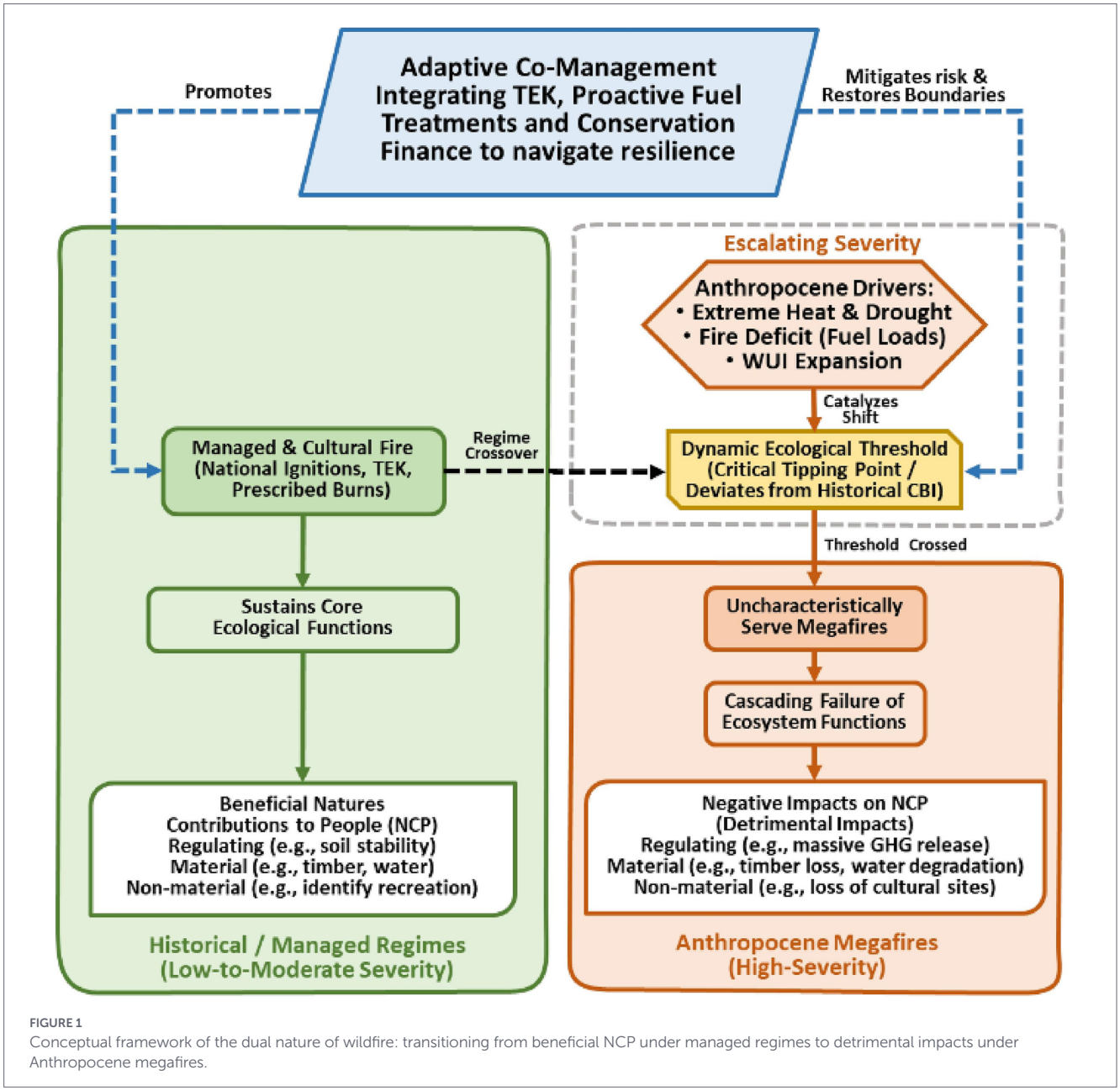


FIGURE 1
Conceptual framework of the dual nature of wildfire: transitioning from beneficial NCP under managed regimes to detrimental impacts under Anthropocene megafires.

conditions dictating wildfire's role as a beneficial contribution or a detrimental impact. Finally, we outline critical implications for environmental management, spatial planning, and climate adaptation to safeguard NCP delivery in increasingly fire-prone landscapes.

2 Methodology

To comprehensively assess the current state of knowledge regarding the impacts of wildland fire on NCP, this review employed a structured literature search and integrative synthesis approach.

2.1 Literature search strategy

A comprehensive search was conducted across three primary academic databases: Web of Science (Core Collection), Scopus, and Google Scholar. The search targeted peer-reviewed journal articles, book chapters, and synthesis reports published between January 2000 and March 2026, capturing a period of significant expansion in both megafire occurrences and NCP/ecosystem services research. The exact Boolean search string deployed across these databases was: ("wildfire*" OR "megafire*" OR "prescribed burn*" OR "cultural burn*" OR "fire severity" OR "fire regime*") AND ("Nature's Contributions to People" OR "NCP" OR "ecosystem service*" OR "water provisioning" OR "carbon sequestration" OR "wildland–urban interface" OR "WUI").

Legacy "ecosystem services" terms were retained in the search string as much of the literature published prior to 2018 relies on this terminology. Because Google Scholar employs dynamic, automated relevance-ranking algorithms rather than strict Boolean indexing, our screening within this database was systematically capped at the first 300 results sorted by relevance to ensure a reproducible boundary for the search protocol. These 300 targeted records were directly integrated into our primary literature pool alongside the outputs from the indexed databases to form the baseline of our PRISMA tracking system.

2.2 Inclusion and exclusion criteria

To ensure a robust and highly relevant synthesis, this review applied strict inclusion and exclusion criteria. Articles were included if they explicitly applied an NCP or ecosystem services framework to evaluate wildland fire impacts or trade-offs, encompassing empirical field studies, hydrological and spatial modeling simulations, and regional or global meta-analyses. Additionally, we actively included research integrating Indigenous Ecological Knowledge (IEK) or cultural burning practices within an NCP context, provided the articles were published in peer-reviewed, English-language journals. Conversely, studies were excluded from the analysis if they focused solely on fire behavior, combustion physics, or suppression logistics without clearly connecting these physical factors to ecological functions or human benefits. Finally, to maintain the scientific rigor of the review, all non-peer-reviewed grey literature, opinion pieces, and unverified preprints were excluded.

2.3 Data extraction and synthesis

In alignment with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, the step-by-step study selection process is detailed in Figure 2. To maintain complete transparency regarding our data management workflow, the initial screening and evaluation phases were executed exclusively by the first author. To safeguard against selection drift and maximize internal consistency, a rigid, predefined binary decision checklist derived from our Section 2.2 criteria was utilized. The second author subsequently audited the final extracted data matrix to cross-verify the conceptual classification of the selected papers.

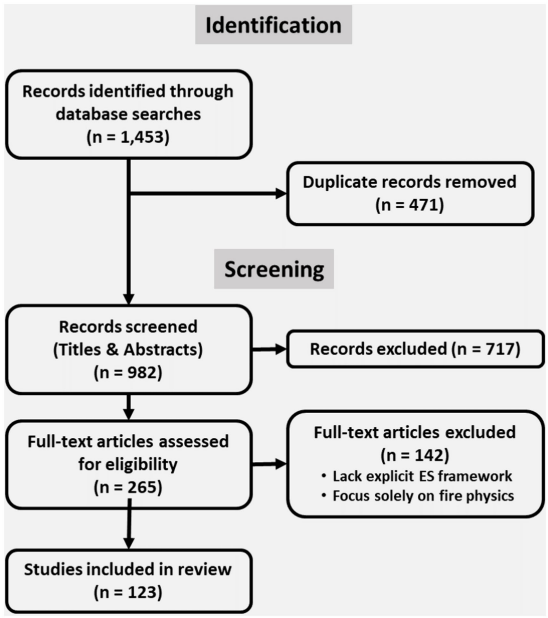


FIGURE 2
PRISMA flow diagram detailing the literature search, screening, and study selection process.

The initial database search yielded a combined total of 1,453 potentially relevant records. This total consists of 1,153 records retrieved via the structured indexes of Web of Science and Scopus, combined with the top 300 relevance-ranked records extracted from Google Scholar. Following the removal of 471 duplicates across these aggregated sources, an initial screening of titles and abstracts for relevance excluded 717 articles that did not meet the thematic criteria. The remaining 265 selected core studies were evaluated for full-text inclusion. During this rigorous full-text screening, 142 articles were excluded (primarily for lacking an explicit NCP or ecosystem services framework or focusing solely on fire physics), resulting in a final total of 123 articles retained for data extraction and synthesis.

A standardized data-extraction spreadsheet was utilized to systematically collect and organize data from the final 123 studies. The specific criteria and variables compiled from each paper included:

- Geographic and Spatial Metrics: Specific geographic coordinates, regional jurisdiction, and biome type (e.g., Mediterranean, boreal, savanna, island ecosystems) and the integration of Earth Observation data. Remote sensing and satellite data indicators were specifically extracted to provide a macro-level context for mapping global WUI expansion, fire risks, and human settlement patterns (e.g., Schug et al., 2023).
- Fire Dynamics: Fire regime characteristics, specific fire events captured (including recent benchmarks like the 2023 Maui and 2025 Los Angeles fires), and evaluated fire severity metrics.
- Socio-Ecological Framework Variables: Target IPBES NCP categories affected (Material, Non-material, Regulating) and the explicit human beneficiary groups impacted (e.g., wildland–urban interface communities, downstream municipalities, Indigenous groups).
- Analytical Outcomes: Quantitative or qualitative recovery indicators, temporal trajectories of post-fire ecosystem recovery, and sector-specific economic disaster valuations.

The extracted findings were transitioned from legacy ecosystem service models and categorized according to the IPBES NCP framework. This updated classification supersedes the Millennium Ecosystem Assessment (MEA) by grouping contributions into Material, Non-material, and Regulating categories. Furthermore, while legacy frameworks like the MEA had historical limitations regarding non-material benefits that frequently required supplementary models like Indigenous Cultural Ecosystem Services (ICES), the IPBES NCP framework inherently integrates Traditional Ecological Knowledge (TEK) and Indigenous perspectives (e.g., through NCP 17: Supporting identities). Utilizing this broader, more flexible structure allowed us to accurately capture the nuances of cultural burning, traditional knowledge, and co-management paradigms without relying on disjointed sub-frameworks.

Furthermore, during the synthesis process, it became evident that the most robust empirical data and prominent examples of modern megafire impacts are geographically concentrated in specific

fire-prone regions; consequently, our core case studies heavily feature evidence from California, Australia, Canada, Chile, Siberia, and Maui.

3 Impacts on nature's contributions to people

Following the IPBES framework, this review categorizes impacts into three broad, interconnected domains: Regulating, Material, and Non-material contributions. However, to fully capture the complexities of contemporary fire-prone landscapes, we evaluate these domains through this modernized lens, which integrates Traditional Ecological Knowledge (TEK), particularly through specific categories like NCP 17 (Supporting identities), and better addresses the unique socio-ecological vulnerabilities at the WUI.

The synthesized literature consistently demonstrates that wildland fires function along a dynamic spectrum. Rather than existing as a strict binary of "service" or "disservice," fire events frequently produce multidirectional, time-dependent, and stakeholder-contingent trade-offs. A single fire can simultaneously act as a vital beneficial contribution for one beneficiary group, such as through resource renewal or post-fire water yield increases for downstream users, while manifesting as an acute negative impact on NCP for another, such as through slope destabilization, catastrophic timber loss, or severe smoke impacts. The ultimate trajectory of these impacts depends heavily on fire severity, recurrence intervals, historical disturbance regimes, and the underlying resilience of the specific ecosystem in question (Thom and Seidl, 2016).

To conceptualize these divergent trajectories, Figure 1 illustrates the complex trade-offs of wildfire. A central tenet of this framework is the concept of ecological thresholds, the critical tipping points at which a fire ceases to function as a beneficial contribution and instead drives cascading detrimental impacts. In this review, we define these thresholds empirically as the point where fire effects significantly deviate from pre-colonial or historical reference conditions, measurable through metrics such as the Composite Burn Index (CBI). Crucially, these thresholds are not static; they vary substantially by ecosystem type, historical fire regime, and current forest condition. Furthermore, different NCP categories and stakeholder groups will experience these thresholds differently; the severity threshold at which a fire degrades regulating contributions (like carbon storage) may differ entirely from the threshold at which it compromises material and non-material contributions.

By defining and integrating these dynamic thresholds, our framework acknowledges that while historical and managed fire regimes sustain core ecological functions and non-material contributions, the shift toward Anthropocene megafires triggers a "regime crossover." In this altered state, extreme heat, drought conditions, and the previously defined "fire deficit" catalyze a cascading failure of ecosystem functions. By visualizing these trade-offs, the diagram highlights the critical role of adaptive co-management in navigating the transition from catastrophic suppression-based models toward landscape resilience. The following subsections directly detail the substantive evidence of these highly contextual impacts across the three core NCP domains, bypassing generalized framing to focus on specific ecological and socio-economic outcomes.

3.1 Regulating contributions

Regulating contributions (NCP 1–10) encompass the ecosystem processes that moderate environmental conditions, including climate regulation, hydrology, soil stability, and air quality. Wildfires perturb these contributions through immediate atmospheric emissions and long-term alterations to carbon dynamics, hydrological responses, and microclimate feedbacks. To provide a clear overview of these divergent impacts, Table 1 summarizes how fire intensity and management strategies dictate the transition between beneficial NCP and negative impacts across key regulating categories.

3.1.1 Regulation of climate (NCP 4)

Severe wildfires rapidly release large pools of stored carbon and other greenhouse gases (GHGs) from soils and vegetation, temporarily weakening the climate-regulating function of both forested and savanna ecosystems (Hurteau et al., 2012; Morecroft et al., 2019). In these extreme scenarios, the net climate-regulating role of the ecosystem is compromised by rapid carbon release and severely altered post-fire recovery trajectories. In contrast, managed fire regimes, such as prescribed burning or natural fire intervals, can act as safety valves that sustain or even enhance long-term carbon sequestration. By reducing excessive fuel loads, forests and rangelands can re-establish robust carbon sinks over decadal timescales (Keith et al., 2019; Russell-Smith et al., 2013).

This dynamic directly impacts climate regulation policies and carbon markets. For example, Australia's savanna-burning programs demonstrate how strategic early-dry-season prescribed fires can successfully abate GHG emissions and generate carbon credits (Rodriguez-Franco et al., 2024; Russell-Smith et al., 2024). Conversely, in the United State, particularly in California's compliance market, escalating wildfire severity poses a severe threat to forest carbon offset permanence, resulting in significant buffer pool depletion and high reversal risk (Badgley et al., 2022). This contribution/detriment trade-off is highly evident here: carbon markets structured around active resilience treatments (such as the Climate Action Reserve's REM protocol or upcoming Verra methodologies) can function as a contribution by aligning financial incentives with wildfire mitigation (Elias et al., 2025). In contrast, extended-rotation protocols that fail to account for escalating fire risks can amplify ecological impacts by allowing overstocked forests to burn catastrophically (Elias et al., 2025; Herbert et al., 2022). Policy frameworks must carefully account for local ecological memory, fuel loads, and the risk of carbon store reversal (Hyde et al., 2017).

3.1.2 Regulation of freshwater quantity, location, timing, and quality (NCP 6 and 7)

High-intensity wildfires severely disrupt hydrological regulation by removing canopy interception, burning organic soil layers, and increasing soil water repellency. This leads to higher surface runoff, enhanced erosion, and the subsequent transport of sediment and ash into streams and reservoirs (Russell-Smith et al., 2013). Consequently, the regulatory burden on water-treatment infrastructure increases significantly due to degraded water quality and pollutant loading in drinking water sources (Hurteau et al., 2012).

TABLE 1 Comparative analysis of wildfire impacts on key regulating contributions.

Regulating contribution (NCP category)	Impact of high-severity fire (negative impact)	Impact of managed/low-severity fire (beneficial contribution)	Key reference citations
Regulation of climate (NCP 4)	Rapid release of stored CO_2 and GHGs; weakens long-term climate regulation and alters recovery trajectories.	Acts as a "safety valve"; reduces fuel to protect long-term sinks. Savanna burning can generate carbon credits.	Hurteau et al. (2012); Keith et al. (2019); Russell-Smith et al. (2024)
Regulation of freshwater quantity and quality (NCP 6 and 7)	Removes canopy; creates soil water repellency; increases runoff, sedimentation, and pollutant loading in reservoirs.	Mitigates catastrophic fire risk; maintains soil organic matter and stabilizes infiltration pathways.	Hurteau et al. (2012); Russell-Smith et al. (2013); Hyde et al. (2017)
Formation, protection and decontamination of soils (NCP 8)	Consumes organic layers; reduces nutrient pools and alters soil structure, leading to high erosion rates.	Stabilizes soils by maintaining ground cover and promoting rapid post-fire vegetation re-establishment.	Morecroft et al. (2019); Rodriguez-Franco et al. (2024); Beard et al. (2010)
Regulation of air quality (NCP 2)	Severe degradation via particulate matter and ozone precursors; causes macro-scale health and visibility issues.	Controlled, short-term emissions used strategically to prevent larger, unmanaged, and more toxic smoke events.	Ghosh et al. (2024); Rodriguez-Franco et al. (2024)
Habitat creation and maintenance (NCP 1)/maintenance of options (NCP 18)	Crosses thresholds that can lead to permanent loss of carbon sinks or habitat type conversion.	Maintains "ecological memory" and aligns management with biome-specific historical fire intervals.	Dass et al. (2018); Hyde et al. (2017); OECD (2023)

Conversely, low-severity prescribed burning can mitigate the likelihood of catastrophic fires that cause severe hydrological disruption. Managed fire regimes help maintain soil organic matter and stabilize infiltration pathways, supporting more consistent water regulation over time. However, if prescribed burns are mis-timed or exceed ecological thresholds, they risk dampening hydrological resilience, highlighting the need for adaptive scheduling and rigorous watershed monitoring (Hyde et al., 2017; Russell-Smith et al., 2013).

3.1.3 Formation, protection and decontamination of soils (NCP 8)

Intense fires rapidly consume soil organic layers, reducing vital nutrient pools and altering the soil structure properties that resist erosion. Over time, the recovery of soil organic matter is heavily modulated by post-fire vegetation regrowth and active management interventions, such as mulching and reforestation (Morecroft et al., 2019). Strategic fuel-load management via early-season or prescribed fires stabilizes soils by maintaining adequate ground cover, promoting rapid vegetation re-establishment, and preventing the extreme soil disturbances characteristic of megafires (Rodriguez-Franco et al., 2024). Furthermore, while aboveground carbon stocks are highly vulnerable to fire, belowground dark carbon pools show relative resilience to certain disturbance patterns, a distinction critical for effective carbon accounting and soil-management strategies (Beard et al., 2010; Dass et al., 2018).

3.1.4 Regulation of air quality (NCP 2)

Wildfire smoke severely degrades regional and macro-scale air quality by releasing heavy particulate matter, ozone precursors, and harmful gases, directly impacting public health, visibility, and ecosystem function. The public health literature increasingly highlights that these impacts are not distributed equally; smoke events impose disproportionate burdens on outdoor and agricultural workers, lower-income communities lacking adequate indoor air filtration, and individuals with pre-existing respiratory and cardiovascular conditions (D'Evelyn et al., 2022; Vargo et al., 2023). Managing this regulating contribution involves complex trade-offs: while prescribed burns intentionally introduce regulated emissions in the short term, they reduce the risk of larger, drastically more polluting megafires in the future. Balancing these dynamics requires transparent accounting, integrated smoke-management protocols, and air-quality standards that are closely aligned with current scientific evidence (Ghosh et al., 2024).

3.1.5 Synthesis and policy-relevant implications for regulating contributions

The literature consistently reveals the dual nature of wildfire: it acts as an immediate disruptor of regulating contributions, but, when properly managed, serves as a necessary mechanism for long-term resource renewal (Hurteau et al., 2012; Hyde et al., 2017). Effective policy must embrace a context-dependent approach that leverages prescribed fire to protect soil and water (NCP 6, 7, and 8), aligns carbon accounting (NCP 4) with biome-specific risks (to avoid overreliance on vulnerable forest offsets), and reconciles strict air-quality constraints (NCP 2) with essential NCP-sustaining fire practices (Morecroft et al., 2019; Rodriguez-Franco et al., 2024). Importantly, carbon markets and regulatory inventories must account for reversal risk and recognize that cross-system differences, spanning savannas, grasslands, and varied forest types, demand locally calibrated assessments rather than universal management prescriptions (Dass et al., 2018; Ghosh et al., 2024; Keith et al., 2019).

TABLE 2 Wildfire impacts and trade-offs in material contributions.

Material contribution (NCP category)	Primary impact of fire (negative impact)	Potential secondary effect/opportunity	Key reference citations
Materials, companionship and labor (NCP 13)	Immediate destruction of merchantable timber; disruption of wood supply chains and massive economic shocks.	*Salvage Logging:* Recovers economic value but may impair long-term erosion control and biodiversity.	Krofcheck et al. (2019); Leverkus et al. (2020); Pereira et al. (2021)
Freshwater as a material resource (reliant on NCP 6 and 7)	Removal of mature vegetation reduces evapotranspiration (ET), leading to sharp, often unmanaged runoff spikes. Massive mobilization of ash elevates treatment costs.	*Hydrological Paradox:* Decreased ET can increase groundwater recharge and baseflow for up to two decades.	Ma et al. (2020); Roche et al. (2020); Saksa et al. (2020b); Ebel et al. (2023); Penna et al. (2021); Wine et al. (2018)
Energy (NCP 11) and Food and feed (NCP 12)	Short-term loss of grazing land and biomass energy sources during the immediate post-fire window.	*Regeneration:* Fire can stimulate new growth for forage in specific savanna and grassland biomes.	Pausas and Keeley (2019); Roces-Díaz et al. (2021)

3.2 Material contributions

Material contributions (NCP 11–14) from forested and wildland ecosystems encompass the tangible, extractive goods that directly support human livelihoods, including timber, fuelwood, grazing forage, and municipal water supplies. Across the literature, the most consistent patterns observed are substantial direct economic losses to the forestry sector from timber destruction, and complex, often counter-intuitive effects on catchment hydrology driven by altered vegetation structure and soil properties (Ma et al., 2020; Pausas and Keeley, 2019; Roces-Díaz et al., 2021). To navigate these competing dynamics, Table 2 summarizes the primary material impacts and the specific trade-offs inherent in post-fire resource recovery.

3.2.1 Materials (NCP 13): timber destruction and the salvage logging trade-off

The most immediate and visible impact of severe wildfire is the destruction of merchantable timber and wood fiber, translating into massive economic shocks for the forestry sector. Large-area megafires can eliminate vast portions of standing timber, severely reducing future yields and disrupting regional wood supply chains in the near term (Krofcheck et al., 2019; Pausas and Keeley, 2019; Pereira et al., 2021). While post-fire recovery interventions, such as salvage logging, are frequently employed to recover lost economic value and reduce future fuel loads, these practices introduce pervasive trade-offs. Meta-analyses indicate that while salvage operations provide short-term material benefits, they can negatively impact long-term regulating services (e.g., natural erosion control) and must be carefully timed and managed to maintain broader ecological integrity (Leverkus et al., 2020).

3.2.2 Freshwater as a material resource: the hydrological paradox

Beyond timber, the effects of fire on water provisioning present a nuanced hydrological paradox driven largely by evapotranspiration (ET) dynamics. In many watersheds, the extensive destruction of mature, high-biomass vegetation significantly reduces canopy interception and pre-fire ET demand. Consequently, groundwater recharge, baseflow, and overall streamflow can increase in the years following a fire. For example, in California's Sierra Nevada, Ma et al. (2020) demonstrated that ET declined by approximately 265 mm/yr in the first year post-fire, and by roughly 169 mm/yr over the subsequent 15 years, with the strongest reductions occurring in dense, mid-elevation evergreen forests. These post-fire ET reductions can be remarkably long-lived; spatial mapping by Roche et al. (2020) indicates that ET suppression can persist for more than two decades, translating to sustained changes in water yield and drought resilience. However, hydrologic responses are not uniform across landscapes. Using RHESSys-based assessments, Saksa et al. (2020b) found that while wildfires cause large runoff increases in the wetter central Sierra Nevada, the responses are much more muted in the drier southern Sierra catchments, illustrating the high sensitivity of water yield to pre-fire climate and moisture regimes.

Crucially, this potential short-term enhancement in water yield is almost universally offset by severe degradation in water quality and elevated downstream hazards. The mobilization of ash, char, and sediment sharply elevates turbidity, nutrient loads, and contaminant concentrations in drinking water reservoirs, directly constraining raw water usability and overwhelming physical filtration infrastructure (Ebel et al., 2023; Penna et al., 2021). The financial burden of these well-documented post-fire treatment costs falls directly on municipal water utilities and, ultimately, their rate-paying customers. Furthermore, the same studies consistently warn of hazard amplification: increased water yields in burned, hydrophobic catchments elevate the risks of flash floods and destructive debris flows, imposing severe downstream environmental disruptions and immediate safety risks for communities and infrastructure (Kettridge et al., 2017; Wine et al., 2018). Connecting these downstream impacts to avoided cost frameworks provides a powerful mechanism for policy intervention; demonstrating the avoided costs of intensive post-fire water treatment can catalyze conservation finance models, such as Water Funds and Forest Resilience Bonds (FRBs). The cascading economic burdens triggered by these biophysical hazards, and the financial frameworks required to mitigate them, are explored in Section 3.2.3.

3.2.3 Management and policy implications for material contributions

Ultimately, managing these complex trade-offs requires integrating material contribution considerations directly into climate adaptation and fire-smart planning frameworks. To effectively

translate these ecological impacts into actionable policy, it is increasingly critical to incorporate the economic valuation of both market and non-market NCP. While the direct financial impacts of mega fires, such as marketable timber loss and infrastructure destruction, are readily quantifiable, policymakers must also account for the massive monetary costs of subsequent negative impacts on these contributions. Comprehensive valuations must monetize the "hidden" burdens, including the aforementioned increased costs of municipal water treatment resulting from post-fire sedimentation borne by utilities and ratepayers, the social cost of carbon emissions from burned biomass, and the regional economic shocks caused by diminished ecotourism and recreational access.

Policy and management implications arise around several key strategies: (a) utilizing proactive forest thinning and fuel reduction as tools to calibrate future ET and runoff responses, thereby preventing catastrophic, unmanageable water yield spikes (Ma et al., 2020; Saksa et al., 2020a); (b) implementing integrated water resource planning that explicitly accounts for post-fire hydrologic changes and leverages the avoided-cost frameworks mentioned above to fund proactive treatments; (c) leveraging advanced machine learning and remote sensing tools (e.g., SSEBop) to actively monitor post-fire ET trajectories and adapt municipal water supply forecasts (Poon and Kinoshita, 2018); and (d) incorporating varied post-fire recovery trajectories into comprehensive hazard mitigation plans to safely sustain material contributions under a changing climate (Abdollahi et al., 2023; Kettridge et al., 2017; Roche et al., 2020). By assigning robust economic value to these contributions, landscape managers can more effectively justify the upfront financial investment required for adaptive co-management, demonstrating that the cost of prevention is vastly outweighed by the economic toll of megafires.

3.3 Non-material contributions

Non-material contributions (NCP 15–17) encompass the non-material, often non-consumptive benefits that people derive from landscapes, including recreation, aesthetic enjoyment, education, spiritual enrichment, and the preservation of cultural heritage. The available evidence reveals a nuanced picture: while high-severity megafires can degrade recreational experiences and undermine Indigenous knowledge linked to intact landscapes, fire also serves as a critical, culturally salient tool in many Indigenous traditions (Christianson et al., 2022; Pereira et al., 2023). To contrast these impacts, Table 3 highlights how the management of fire regimes directly influences the preservation or erosion of cultural value.

3.3.1 Physical and psychological experiences (NCP 16): recreational, aesthetic, and ecotourism value

Severe, uncontrolled wildfires typically inflict immediate reductions on a landscape's aesthetic value and recreational accessibility. This results in significant downstream economic consequences for ecotourism, hiking, and camping-dependent communities. Across multiple studies, post-fire landscapes exhibit sharply diminished visitation in the short term due to safety hazards, degraded scenery, and the destruction of recreational infrastructure (Hessburg et al., 2021; Kelly et al., 2020). Conversely, where fire is used deliberately and skillfully to create a mosaic of habitats, there can be highly positive cultural and recreational outcomes. Maintaining heterogeneous, open landscapes supports species diversity that attracts nature-based tourism, such as birdwatching and photography, and fosters a broader cultural appreciation for the dynamic, natural role of fire regimes in shaping the environment (Talmage et al., 2022).

3.3.2 Supporting identities and learning (NCP 17 and 15): indigenous knowledge and stewardship

A substantial and growing body of work emphasizes that Indigenous fire stewardship, specifically low-intensity, culturally oriented burning, functions as a central practice that upholds language, ritual, subsistence gathering, and deep spiritual connections to place. Cultural burning is not merely a mechanical fuel-reduction technique; it is a profound act of cultural expression and landscape governance that sustains intergenerational knowledge systems and livelihoods (Regos et al., 2023; Sample et al., 2022; Walker et al., 2022).

Unlike previous models that relied on supplementary frameworks like Indigenous Cultural Ecosystem Services (ICES), the IPES framework inherently illustrates how cultural burning

TABLE 3 Wildfire impacts on non-material contributions and indigenous stewardship.

Non-material contribution (NCP category)	Impact of high-severity fire (negative impact)	Impact of managed/cultural fire (beneficial contribution)	Key reference citations
Physical and psychological experience (NCP 16)	Immediate loss of aesthetic value; destruction of infrastructure; long-term visitation declines.	Creates habitat mosaics; supports biodiversity for nature-based tourism (e.g., birdwatching).	Hessburg et al. (2021); Kelly et al. (2020); Talmage et al. (2022)
Supporting identities (NCP 17) & Learning and inspiration (NCP 15)	Disrupts plant cycles and subsistence gathering; erodes spiritual connections to specific sites; catastrophic loss of sacred landscapes.	Acts as a "cultural technology"; sustains language, ritual, and intergenerational knowledge transfer.	Mucioki et al. (2021); Walker et al. (2022); Regos et al. (2023); Christianson et al. (2022); Franklin and MacDonald (2024)
Learning and inspiration (NCP 15)	Opportunities limited to studying disaster response and "cascading failures."	Provides a living laboratory for co-management, IEK integration, and adaptive resilience.	Sample et al. (2022); Dewi et al. (2024)

contributes to a comprehensive suite of NCP. These include material contributions (cultivating plants for food, medicine, and fiber), regulating contributions (pest control and habitat health), underlying ecological functions (maintaining forage for culturally important species), and core non-material contributions (educational and ceremonial practices). The historical exclusion and proscription of cultural fire management have demonstrably reduced these integrated contributions, underscoring that these cultural services are inextricably linked to Indigenous fire practices and autonomous governance arrangements (Mucioki et al., 2021).

Specific regional contexts highlight how restrictive policy barriers continue to constrain Indigenous fire regimes. For example, in the Klamath River Basin, climate-driven changes to culturally significant plant cycles intersect with rigid governance structures that restrict low-intensity cultural fires, resulting in severe negative impacts on non-material contributions (Mucioki et al., 2021). Similar dynamics are evident in boreal and temperate rainforests, where historical Indigenous fire knowledge shaped vibrant vegetation mosaics, but contemporary, colonial land-management restrictions hinder the restoration of these culturally aligned practices (Dewi et al., 2024; Franklin and MacDonald, 2024).

3.3.3 Synthesis and implications for non-material contributions

The literature consistently advocates for the integration of Indigenous voices and fire practices into formal planning, governance, and restoration initiatives as the primary pathway to strengthen non-material contributions, specifically supporting identities and learning (NCP 15 and 17). Place-based fire regimes that align with Indigenous knowledge systems act as a cultural technology, reinforcing a sense of place and stewardship while maintaining landscape heterogeneity (Christianson et al., 2022; Sample et al., 2022; Talmage et al., 2022).

To optimize these non-material contributions, modern fire management must transition toward co-management models that treat Traditional Ecological Knowledge (TEK) as a foundational asset rather than a supplemental practice. This requires: (a) elevating Indigenous leadership in fire governance to restore traditional burning; (b) designing fire management strategies that deliberately create habitat mosaics to support ecotourism (physical and psychological experiences, NCP 16) while fiercely protecting sacred sites; and (c) explicitly valuing non-material contributions within broader NCP accounting frameworks (Balantic et al., 2021; Kelly et al., 2020).

3.4 Underlying ecological functions and habitat maintenance (NCP 1 and 18)

Underlying ecological functions, including soil formation, nutrient cycling, and the maintenance of biodiversity, underpin the delivery of NCP. Because they form the ecological foundation of a landscape, these services are particularly susceptible to shifts in fire regimes, including alterations in fire intensity, frequency, and spatial patterning. To illustrate the foundational impact of fire on these processes, Table 4 contrasts how varying fire severities dictate the long-term health of the soil–plant–microbe interface.

3.4.1 Soil formation, nutrient cycling, and fertility

The impact of fire on soil-based ecological functions (NCP 8) is highly dependent on burn severity. Low-to-moderate severity fires can accelerate nutrient turnover and stimulate soil formation by rapidly decomposing organic matter. The subsequent deposition of ash returns readily available mineral nutrients to the soil, creating a nutrient pulse that enhances short-term fertility and supports the microbial activity necessary for post-fire vegetative regeneration (Roces-Díaz, 2023).

Conversely, the extreme heat associated with megafires can severely disrupt these vital underlying functions. High-severity fires volatilize essential soil nutrients, most notably nitrogen, and devastate resident soil microbiomes. Post-fire soils often exhibit reduced bacterial and fungal richness, with pyrophilous (fire-adapted) taxa only transiently dominating the altered landscape

TABLE 4 Impact of fire severity and recurrence on underlying ecological functions and habitat maintenance.

Underlying function (NCP category)	Impact of high-severity fire (negative impact)	Impact of managed/low-severity fire (beneficial contribution)	Key reference citations
Formation, protection, and decontamination of soils (NCP 8)	Volatilizes essential nutrients (e.g., nitrogen); devastates resident soil microbiomes and reduces fungal richness.	Accelerates nutrient turnover via organic matter decomposition; creates a "nutrient pulse" through ash deposition.	Godfree et al. (2021); Roces-Díaz (2023); Crandall et al. (2021)
Formation, protection and decontamination of soils (NCP 8)	Extreme heat alters pH and cation exchange capacity (CEC); high recurrence leads to long-lasting fertility loss.	Stimulates microbial activity necessary for regeneration; maintains soil moisture and texture profiles.	Hoyland et al. (2024); Raeofy et al. (2023); Oliveira et al. (2020)
Habitat creation and maintenance (NCP 1)	Homogenizes the landscape; erases microhabitats and suppresses natural regeneration pathways.	Promotes complex habitat mosaics and structural variety; provides niches for fire-adapted species.	Kang et al. (2023); Oliveira et al. (2020); Godfree et al. (2021)
Maintenance of options (NCP 18)	Triggers biogeographic shifts in vegetation; disrupts plant–soil feedbacks that underpin multifunctionality.	Maintains successional trajectories; supports "ecological memory" and biome-specific resilience.	Enright et al. (2022); Saunders et al. (2024); Goffin et al. (2024)

(Godfree et al., 2021). The recovery of these microbial communities is not uniform; persistent alterations in microbial composition can modify nutrient cycling pathways for years, fundamentally altering successional trajectories (Crandall et al., 2021). Furthermore, soil properties such as moisture, texture, pH, and cation exchange capacity (CEC) heavily modulate heat transfer during a fire and dictate the resilience of soil-based nutrient cycling in its aftermath (Hoyland et al., 2024; Raeofy et al., 2023).

Importantly, the relationship between burn severity and soil function is compounded by fire recurrence. Scenarios combining high fire recurrence with high severity result in marked, long-lasting reductions in soil-quality and soil-fertility indicators, illustrating how compounded disturbances threaten soil-based contributions far more than isolated fire events.

3.4.2 Biodiversity, habitat mosaics, and regeneration pathways

Disturbance regimes strongly mediate habitat heterogeneity, which is a core component of habitat creation and maintenance (NCP 1) through its role in biodiversity maintenance. Natural, heterogeneous fire regimes, characterized by patches of varying burn severity, promote complex landscape mosaics. This structural variety provides vital microhabitats and regeneration niches, enabling the germination, recruitment, and persistence of fire-adapted plant species, which in turn sustains broader biodiversity (Godfree et al., 2021; Oliveira et al., 2020).

Crucially, discussions of biodiversity maintenance must explicitly distinguish between fire-sensitive and fire-adapted ecosystems (He et al., 2019). In fire-adapted biomes, the "negative impact" framing of wildfire breaks down entirely for a vast array of organisms. A substantial body of literature regarding rebound ecology highlights that fire-obligate and fire-adapted species, such as serotinous conifers that require heat to release seeds, pyrophilous insects that breed exclusively in recently burned timber, and fire-following annuals, depend entirely on periodic fire for their life history strategies (Gill et al., 2022; Mason et al., 2023). For these species, fire functions as an irreplaceable ecological process sustaining NCP (He et al., 2019). This dynamic perfectly illustrates the necessity of the threshold and trade-off framework: biodiversity is only maintained when fire severity and frequency remain within the evolutionary tolerances of these adapted organisms (Gill et al., 2022).

In stark contrast, when these ecological thresholds are crossed, catastrophic megafires tend to homogenize landscapes by uniformly erasing key microhabitats and suppressing regeneration pathways. These high-severity events can drastically alter plant assemblages and early-successional species distributions, sometimes triggering broader biogeographic shifts in vegetation (Kang et al., 2023). These changes in habitat structure generate cascading negative effects on other underlying ecological processes, including soil stabilization and the plant–soil feedbacks that underpin overall ecosystem resilience (Enright et al., 2022).

3.4.3 Ecosystem multifunctionality and context-dependent nuances

When evaluating the footprint of large burn events, it is essential to look at ecosystem multifunctionality. The literature cautions against simply equating the vast physical size of a megafire with uniform ecological devastation; rather, it is the underlying heterogeneity in burn severity that ultimately mediates the impacts on soil processes and biodiversity (Hoyland et al., 2024; Saunders et al., 2024). The apparent tension in the literature, where some studies emphasize an immediate positive nutrient flush while others warn of long-term soil degradation, reflects this deep context-dependence. The ultimate balance between the beneficial and detrimental effects of fire on these underlying functions and contributions hinges entirely on the specific disturbance context (severity and recurrence) and the intrinsic resilience of local soil and biotic communities (Goffin et al., 2024).

3.5 Case studies of megafire impacts on NCP

To ground the theoretical NCP framework in empirical reality, this section examines several unprecedented modern megafire events across diverse global biomes, including the Australian Black summer, the Siberian peatland fires, and the Canadian boreal megafires. While historical, low-to-moderate severity fires once sustained these landscapes, these contemporary case studies illustrate the rapid transition from natural regulation to acute negative impacts on nature's contributions. By examining these extreme, climate-driven fire regimes, we can observe the cascading failure of critical material, non-material, and regulating contributions.

Furthermore, these events highlight the profound socio-ecological vulnerabilities at the rapidly expanding WUI. Crucially, rather than serving merely as a catalog of disasters, these case studies provide the direct empirical evidence for our subsequent management recommendations. They highlight critical, region-specific vulnerabilities, from carbon market structures in California to the plantation-heavy landscapes of Chile, and demonstrate precisely why localized, adaptive co-management and innovative funding mechanisms are essential.

3.5.1 The 2019–2020 Australian "Black Summer"

The 2019–2020 Australian bushfire season was globally unprecedented. Fueled by record-breaking temperatures and prolonged drought, the fires consumed upwards of 19 million hectares of land (van Eeden et al., 2020). These fires caused catastrophic losses to underlying ecological functions and habitat maintenance (NCP 1), with an estimated three billion native vertebrates killed or displaced as the blazes permanently altered traditionally fire-resistant ecosystems. The event also generated massive negative impacts on regulating contributions, particularly air quality regulation (NCP 2); widespread smoke resulted in a significant spike in asthma-related hospitalizations and emergency department presentations across eastern Australia (Borchers Arriagada et al., 2020). Furthermore, the destruction of landscapes holding deep spiritual significance severely impacted non-material contributions (supporting identities and experiences, NCP 16 and 17), sparking a national conversation about the necessity of reinstating Indigenous "cultural burning" to manage fuel loads and restore ecological balance (Fletcher et al., 2021). Consequently, this case specifically underscores the urgent management need for expanded "right-to-burn" legislative frameworks. Overcoming the entrenched liability barriers that currently restrict prescribed fire is critical to empowering Indigenous and local communities to apply this NCP-sustaining practice at scale.

3.5.2 The 2020–2021 California megafires

In 2020, California experienced its worst fire season on record at the time, with over 4.2 million acres burned (Keeley and Syphard, 2021). High-severity fires decimated rangelands and merchantable timber, severely impacting material contributions (NCP 12 and 13), particularly regional timber and agricultural yields. Densely packed, evenly spaced industrial timber plantations experienced nearly 50% higher odds of high-severity megafires than varied public lands (Zald and Dunn, 2018). The agricultural sector also suffered acute negative impacts on material contributions as heavy smoke caused significant "smoke taint" in unharvested wine grapes, resulting in massive crop losses (Kropp, 2022). In terms of regulating contributions (specifically climate regulation, NCP 4), the 2020 fires wiped out years of state GHG reduction progress, temporarily turning California's historically vital forest carbon sinks into massive carbon sources (Jerrett et al., 2022). This catastrophic reversal exposes the extreme vulnerability of forest carbon markets under changing fire regimes. The massive, wildfire-driven depletion of California's compliance market buffer pools demonstrates that current carbon offset permanence protocols are dangerously inadequate. This season provided stark empirical evidence for the structural necessity of designing carbon markets that financially incentivize active, resilience-based forest treatments rather than passive, extended-rotation storage with high reversal risk.

3.5.3 The 2023 Canadian boreal megafires

The 2023 Canadian wildfire season shattered historical records, burning over 18 million hectares of predominantly boreal forest. This event had profound, trans-continental impacts on regulating contributions (climate regulation, NCP 4, and air quality, NCP 2). The Canadian boreal forest is traditionally one of the world's most vital terrestrial carbon sinks; however, the 2023 fires released an estimated 570 to 727 million metric tons of carbon dioxide, severely undermining global climate regulation efforts (Byrne et al., 2024). Additionally, the fires generated a massive negative impact via transboundary smoke pollution, exposing over 350 million people across North America and Europe to hazardous daily PM2.5 levels (Zhang et al., 2025). The fires also disrupted non-material and material contributions for Indigenous First Nations. This functioned as an acute socio-ecological detriment, as widespread evacuations severed cultural ties to ancestral lands and hindered subsistence hunting, trapping, and foraging. The vast geographic reach of these impacts emphasizes the structural need for cross-jurisdictional smoke-management protocols and international collaboration in managing the planetary-scale negative impacts of extreme fire events.

3.5.4 The 2017 Chilean megafires

In early 2017, central-south Chile experienced a catastrophic fire event burning over 500,000 ha, driven by a decade-long megadrought. This event perfectly illustrates the trade-offs between material contributions and underlying ecological functions (commercial timber production, NCP 13, versus native habitat resilience, NCP 1). Historically, the region's land use was converted to support a booming timber economy, resulting in vast plantations of exotic, fire-prone species like *Pinus radiata*. When the megafires ignited, these dense plantations acted as continuous fuel beds, amplifying fire severity and resulting in massive economic losses for the forestry sector, an acute loss of material contributions. Simultaneously, the fires severely degraded habitat maintenance and soil formation (NCP 1 and 8) by spilling over into endangered native forest fragments. This triggered a positive feedback loop for biological invasion, as fire-adapted exotic pines rapidly colonized the deeply burned native areas, fundamentally altering the soil microbiome and driving native ecosystems toward an irreversible state of degradation (González et al., 2023). Unlike the mixed federal-state-private land ownership of the western U.S., Chile's specific landscape matrix necessitates highly targeted regulatory reform for private industrial plantations. This case illustrates the critical need for spatial planning and enforced fuel-reduction buffer zones between commercial timber and fire-sensitive native forests.

3.5.5 The Siberian Arctic and peatland fires (2019–2021)

Between 2019 and 2021, the Russian Arctic and Siberian taiga experienced consecutive years of unprecedented megafires. Unlike typical forest fires, the Siberian fires burned deeply into ancient peatlands, severely impacting regulating contributions (climate regulation, NCP 4). The combustion of these organic soils released hundreds of millions of tons of ancient carbon, shifting the Arctic biome from a net carbon sink to a net carbon source (Khairoun et al., 2026). Furthermore, the burning of the insulating organic surface layer exposed the underlying permafrost to extreme summer heat. This rapid thawing released trapped methane, creating a vicious, self-sustaining climate feedback loop that further degraded global climate regulating contributions (Turetsky et al., 2020). This high-latitude ecosystem failure highlights an urgent need to incorporate deep-soil organic combustion and permafrost feedback loops more accurately into global climate mitigation accounting and long-term adaptation planning.

3.5.6 The 2023 Maui wildfire

In August 2023, catastrophic wildfires swept across the Hawaiian island of Maui, devastating the historic town of Lahaina. This event crossed critical socio-ecological thresholds in a fragile island ecosystem, highlighting the extreme vulnerabilities of isolated communities and exposing severe infrastructural challenges during rapid WUI fire spread (Kerber and Alkonis, 2024). The fire simultaneously devastated material and non-material contributions by disrupting sensitive ecological water filtration systems and heavily contaminating post-fire drinking water supplies (regulating, NCP 6; McLatchy et al., 2026), alongside heavily striking tourism-dependent regional economies (non-material, NCP 15 and 16). Evaluating this event through a multi-source tri-environmental conceptual framework for fire impact analysis reveals how compounding stressors such as invasive grass fuel loads, drought, and hurricane-force winds resulted in a cascading failure of natural and built environments (Kerber and Alkonis, 2024). This case underscores the necessity of multi-dimensional baseline assessments and community-driven disaster responses for island ecosystems recovering from megafires (McLatchy et al., 2026).

TABLE 5 Regional case studies of megafire impacts on NCP.

Case study/ region	Dominant drivers of megafire	Primary NCP impacted	Supporting citations
2019–2020 Australian "Black summer"	Record heat, prolonged multi-year drought	*Habitat maintenance (NCP 1):* Catastrophic biodiversity loss *Regulating (NCP 2):* Severe air quality degradation *Non-material (NCP 17):* Disruption of Indigenous heritage	van Eeden et al. (2020); Borchers Arriagada et al. (2020); Fletcher et al. (2021)
2020–2021 California megafires	Extreme aridity, historical fire suppression, dense fuel loads	*Material (NCP 12 and 13):* Timber/crop loss, smoke taint *Regulating (NCP 4):* Loss of carbon sequestration	Keeley and Syphard (2021); Zald and Dunn (2018); Kropp (2022); Jerrett et al. (2022)
2023 Canadian boreal megafires	Extreme heat, atmospheric blocking, drought	*Regulating (NCP 2 and 4):* Massive CO_2 emissions, transboundary smoke *Non-material and Material (NCP 11, 12, 17):* Evacuation of First Nations, loss of foraging	Byrne et al. (2024); Zhang et al. (2025)
2017 Chilean megafires	Megadrought, exotic timber plantations	*Material (NCP 13):* Devastation of commercial forestry *Habitat and Soil (NCP 1 and 8):* Native forest degradation, exotic pine invasion	González et al. (2023)
2019–2021 Siberian Arctic and peatland fires	Arctic warming, extreme summer heat	*Regulating (NCP 4):* Deep peat carbon combustion, permafrost thaw, methane release	Khairoun et al. (2026); Turetsky et al. (2020)
2023 Maui wildfire	Invasive grasses, drought, extreme hurricane-force winds	*Regulating (NCP):* Disruption of ecological water filtration	Kerber and Alkonis (2024); McLatchy et al. (2026)
2025 Los Angeles wildfire	Extreme WUI encroachment, climate-driven aridity	*Material and Regulating:* Cascading structural and economic losses, critical infrastructure degradation	Li et al. (2026)

3.5.7 The 2025 Los Angeles wildfire

The 2025 Los Angeles wildfire represents a critical inflection point for WUI exposure and economic cost modeling. As fires encroach further into densely populated municipalities, traditional damage assessments fall short of capturing the true socio-ecological toll. Integrating Earth Observation data into the tri-environmental evaluation of the economic cost of natural disasters for the LA wildfire allowed for a comprehensive multi-environmental evaluation of disaster costs. This approach captured cascading socio-economic losses, critical infrastructure degradation, and heightened social vulnerability across natural-built boundaries (Li et al., 2026). This event emphasizes how advanced satellite tracking and multi-environmental frameworks are essential for accurately quantifying the loss of material and regulating NCP, ultimately guiding more resilient urban spatial planning.

3.5.8 Summary of megafire case studies

To contextualize the regional events discussed above, Table 5 synthesizes the diverse impacts of recent global megafires. This summary highlights how extreme fire events, driven by compounding climatic factors, systematically degrade specific NCP across vastly different global biomes, serving as a comparative reference for the catastrophic failure of these natural systems.

However, while the ecological and economic tolls documented in these global cases are staggering, they concurrently construct a compelling economic argument for proactive intervention. The persistent barrier to implementing the management solutions derived from these case studies, such as buffer creation, cultural burning, and resilience treatments, is the sheer scale of required funding. Crucially, as the spatial extent of necessary treatments grows, it is increasingly evident that public dollars alone will never be sufficient to fill this massive funding gap. To ground this paper's economic valuation argument in practical action, policy must increasingly turn to conservation finance mechanisms as a necessary, additive lens to traditional public budgeting. Payment for Ecosystem Services (PES) schemes, FRBs, Water Funds, and outcome-based payment structures are increasingly being developed and deployed to bridge this public funding gap. By explicitly monetizing the avoided negative impacts documented in these case studies (e.g., avoided water treatment costs, protected infrastructure, stabilized carbon offset markets), these financial models allow downstream beneficiaries and private investors to provide the upfront capital necessary to scale upstream forest treatments alongside public agencies. Scaling these finance mechanisms is the vital next step to translate the NCP frameworks discussed herein into robust, landscape-level resilience.

4 Discussion

4.1 Summary of main findings and policy implications

The historical paradigm of absolute fire suppression has proven not only physically unsustainable in a warming climate but ecologically detrimental, inadvertently fostering dense,

homogenous landscapes that fuel contemporary megafires. Viewed through the NCP framework, it is clear that attempting to eliminate fire entirely results in severe, long-term negative impacts on ecological functions. Consequently, modern wildfire management must urgently transition from a reactive "war on fire" toward a paradigm of active coexistence and adaptive resilience. As demonstrated by the regional case studies in Section 4, this structural shift demands the implementation of robust, proactive strategies, including the deployment of Nature-based Solutions (NbS), the systemic reintegration of Indigenous eco-cultural burning, and rigorous spatial planning within the WUI. Ultimately, unmanaged megafires erode the planetary safety net, while adaptive, community-led fire governance restores it.

4.1.1 Shifting paradigms: from suppression to coexistence

The prevailing historical paradigm of wildfire management has long centered on a strategy of absolute suppression, often characterized as a "war on fire." While this approach aimed to protect human lives, infrastructure, and commercial timber resources in the short term, it has inadvertently produced severe long-term vulnerabilities. Decades of aggressive suppression have altered natural fire regimes, created a significant "fire deficit" (an ecological debt that now manifests as catastrophic fire risk), and allowed dangerous fuel loads to accumulate across historically fire-adapted landscapes (DellaSala et al., 2004; Prichard et al., 2021). Today, there is a clear consensus within the contemporary literature that a suppression-only approach is physically untenable in a warming, increasingly fire-prone world, and ecologically detrimental to the maintenance of vital nature's contributions. Consequently, researchers and practitioners alike are urging a definitive paradigm shift away from a dichotomous suppression-versus-wildfire narrative and toward a continuum of adaptive resilience and active coexistence (Roos et al., 2016; Srinivasan et al., 2025).

Central to this paradigm shift is the conceptual reframing of wildland fire from a purely mechanical hazard to a complex socio-ecological process. This broader perspective is essential to justify deliberate fire use, such as safely managed natural ignitions and prescribed burning, as legitimate, necessary landscape management tools. Rather than enforcing universal suppression mandates, management interventions can be aligned with local fire regimes to restore landscape heterogeneity, disrupt fuel continuity, and mitigate the negative impacts on NCP associated with extreme megafires (Depietri and Orenstein, 2019; Smith et al., 2016). When conducted under strict safety thresholds and with comprehensive stakeholder engagement, intentional fire use not only stabilizes fire regimes but also enhances overall ecological integrity, habitat quality, and long-term biodiversity (Prichard et al., 2021).

To operationalize this coexistence, the integration of NbS is increasingly identified as a critical pathway to harmonize human safety with the preservation of NCP. NbS approaches, such as the deployment of green firebreaks and close-to-nature forest management, complement traditional suppression by creating resilient, multifunctional landscapes that can better absorb fire disturbances (Taccaliti et al., 2023). Furthermore, these solutions deliver substantial co-benefits, including carbon storage (regulating) and enhanced recreational values (non-material). This perspective situates NbS within a broader governance framework that emphasizes the co-management of fire risk alongside local communities, land managers, and policymakers, ensuring that risk reduction strategies align closely with both social and ecological objectives (Depietri and Orenstein, 2019; Johnston et al., 2024).

Finally, transitioning to adaptive fire management requires bridging persistent disciplinary silos. Successfully coexisting with fire demands the integration of fire science with urban planning, landscape design, and risk governance to overcome jurisdictional fragmentation and scale mismatches (Roos et al., 2016). Actionable policies must institutionalize cross-jurisdictional collaboration and promote region-specific interventions, particularly within the WUI (Taccaliti et al., 2023).

However, even with integrated planning, this transition is frequently stalled by a massive "scale gap" between policy endorsement and on-the-ground delivery. For instance, while jurisdictions like California have set ambitious targets of treating 400,000 acres per year with beneficial fire, actual delivery remains a fraction of that goal. This scale gap cannot be treated merely as a tractable policy hurdle; rather, it is driven by entrenched, structural barriers. These include severe workforce shortages, strict liability frameworks, complex air quality permitting processes, and pervasive interagency coordination challenges (Williams et al., 2023). To overcome these deeply rooted barriers, policy frameworks must decouple wildfire budgets from emergency-only response funds, creating dedicated, multi-year funding streams for'pre-suppression' activities such as controlled burning and green infrastructure. Furthermore, air quality regulations must be modernized to recognize the critical trade-off between the short-term, regulated smoke of prescribed fires and the catastrophic, high-toxicity emissions of unmanaged megafires. While the necessity of adaptive resilience is broadly accepted, researchers acknowledge remaining uncertainties surrounding social acceptance, economic costs, and the predictability of climate-driven outcomes. Addressing these tensions requires robust evaluation frameworks and highly inclusive stakeholder processes to effectively balance safety, ecological integrity, and diverse social values (Smith et al., 2016).

4.1.2 Adaptive management strategies

Effective adaptation to the dual nature of wildfire requires a paradigm shift from purely reactive fire suppression toward proactive, Integrated Fire Management (IFM). Operating across multiple spatial scales and social-ecological contexts, IFM frameworks emphasize moving beyond "one-size-fits-all" policies toward flexible governance arrangements that can absorb climate-driven uncertainties and learn from near-real-time outcomes (Stephens et al., 2020). Central to this adaptive approach is the deployment of NbS, such as fire-smart forestry and strategic mechanical fuel treatments coupled with prescribed or managed burning (Keenan et al., 2021; Nolan et al., 2021). These interventions effectively reduce surface and ladder fuels while preserving the structural diversity and landscape heterogeneity necessary for long-term ecosystem resilience (Hessburg et al., 2021; Stephens and Ruth, 2005). Importantly, managers must design these treatments with explicit attention to future climate projections; relying solely on historical fire regimes may no longer represent feasible or desirable targets under contemporary climate and land-use conditions (Prichard et al., 2021; Schoennagel et al., 2017).

However, it must be explicitly acknowledged that management prescriptions are not universally interchangeable across global biomes. The western U.S. context, for instance, is highly distinctive due to a century of active suppression, mixed federal/state/private land ownership, a heavily regulated prescribed burn environment, and the

proximity of fire to large urban populations (Schultz et al., 2019). By contrast, the savanna fire regimes of Australia or the heavily planted industrial matrices of Chile require fundamentally different policy interventions (Escobedo et al., 2024; Nikolakis et al., 2022). Acknowledging this geographic specificity is critical for translating broad frameworks into actionable policy.

A robust, rights-based adaptive strategy must fundamentally integrate Indigenous fire governance and eco-cultural burning. Reinvigorating traditional ecological knowledge (TEK) and IEK within formal risk-management frameworks is repeatedly linked to improved biodiversity, optimized fuel reduction, and the vital restoration of non-material contributions, particularly supporting identities and intergenerational learning (NCP 15 and 17; Dewi et al., 2024; Dickson-Hoyle et al., 2022). Establishing formal inter-agency and Indigenous-public-private partnerships that respect Indigenous communities as rights-holders is critical for co-producing knowledge and sharing decision-making power. However, successfully scaling these collaborative models requires policy reform to navigate and dismantle persistent jurisdictional barriers, resolve legal liability concerns, and create protective frameworks for cultural fire practitioners (McCormack et al., 2023; Williams et al., 2023).

In the U.S. context particularly, a critical policy lever for scaling adaptive management is the reform of liability laws for prescribed fire. In many jurisdictions, the'strict liability' standard, where a practitioner is held responsible for any fire escape regardless of negligence, acts as a primary deterrent for private landowners and certified burn bosses. Adopting a'gross negligence' standard, similar to recent legislative shifts in California and parts of the Southeastern United States, provides the legal protection necessary to significantly increase the pace and scale of proactive fuel treatments. Furthermore, drawing directly from the lessons of the Australian Black summer fires, international policy should institutionalize'right-to-burn' frameworks that recognize Indigenous cultural burning not merely as a fuel-reduction tactic, but as a protected exercise of sovereignty and cultural heritage.

Beyond wildland interventions, adaptive strategies demand stringent spatial planning within the expanding WUI to mitigate risks, protect infrastructure, and safeguard human health. This includes enforcing fire-resilient building codes, establishing community-wide defensible spaces, and proactively restricting new development in historically high-risk fire corridors to limit human-caused ignitions (Atkinson and Molina, 2023; Menor et al., 2025). Additionally, as vividly illustrated by the 2017 Chilean case study, in landscapes dominated by commercial forestry, proactive spatial planning necessitates targeted regulatory reform for private industrial plantations. This includes enforcing strict fuel-reduction buffer zones between exotic timber and fire-sensitive native forests. Furthermore, holistic spatial planning must explicitly address environmental justice by coordinating with public health agencies to protect vulnerable populations from severe smoke exposure during both managed burns and megafires (D'Evelyn et al., 2022; Gillespie and Lange, 2025). To protect material contributions like municipal water supplies and support subsequent forest regeneration, rapid-response post-fire remediation protocols, such as the deployment of erosion control mulching and log barriers, remain a critical component of WUI and watershed defense (Johnston et al., 2024; Sample et al., 2022).

Ultimately, the success of this multifaceted portfolio approach depends on institutionalizing adaptive learning loops, iterative cycles of implementation, monitoring, evaluation, and subsequent policy adjustment (Hessburg et al., 2021; Nolan et al., 2021). Sustaining these efforts requires overcoming structural barriers through new, multi-year funding models and enhanced post-fire data collection. Furthermore, as strategies are shared across regions, cross-jurisdictional learning must be pursued with careful attention to biome-specific ecological nuances and local socio-cultural contexts to ensure that adaptive management remains both effective and equitable (Nikolakis and Roberts, 2021; Smith et al., 2016).

4.2 Future directions and critical research gaps

The literature evaluating wildfire effects through the NCP framework reveals several persistent gaps that limit the integration of post-fire socio-ecological recovery into long-term restoration and modern wildfire management. Foremost among these is a pronounced research imbalance: while pre-fire mitigation and active-fire dynamics are heavily studied, the long-term trajectories of post-fire recovery remain underrepresented (Bowman et al., 2020; Shen et al., 2025).

Furthermore, there is a critical need for standardizing Earth Observation data with localized socio-economic metrics. Doing so is essential for tracking cascading impacts across the natural-built divide and calculating true disaster costs within the shifting WUI. Additionally, current wildfire literature exhibits severe geographic biases. There is a distinct over-representation of studies focused on North America and Australia compared to heavily fire-affected regions like African savannas, South American ecosystems, and tropical peatlands. Addressing these spatial blind spots is crucial for globalizing adaptive governance models.

To synthesize the path forward for the scientific community, Figure 3 maps the primary dimensions where knowledge remains fragmented across six critical gap categories: temporal imbalance, cascading disturbances, social equity and justice, methodological opacity, threshold dynamics, and sector-specific economic valuation. This framework visually highlights the transition required from current research limitations, such as the lack of multi-decadal post-fire data and modeling opacity, toward an integrated, multi-decadal, and equitable research agenda for incorporating NCP into wildfire management. To guide future scholarly efforts, Table 6 further details these deficiencies, highlighting a vital gap in applied economic valuation, and identifies the specific methodological and thematic advancements required to bridge them.

4.2.1 Post-fire recovery and the temporal scale

Elevating post-fire recovery to parity with fire suppression research requires multi-decadal monitoring designs capable of capturing baseline shifts under a warming climate. However, immediate post-fire threats, such as pests, disease, invasive species, and hydrological shifts, often dominate the short-term context. Consequently, recovery trajectories are rarely linear; they are highly contingent on localized pre-fire legacies, persistent refugia, and varying structural layers (e.g., canopy versus understory), underscoring the need for context-specific analyses rather than assuming uniform landscape regeneration (van Etten et al., 2022; Legge et al., 2022).

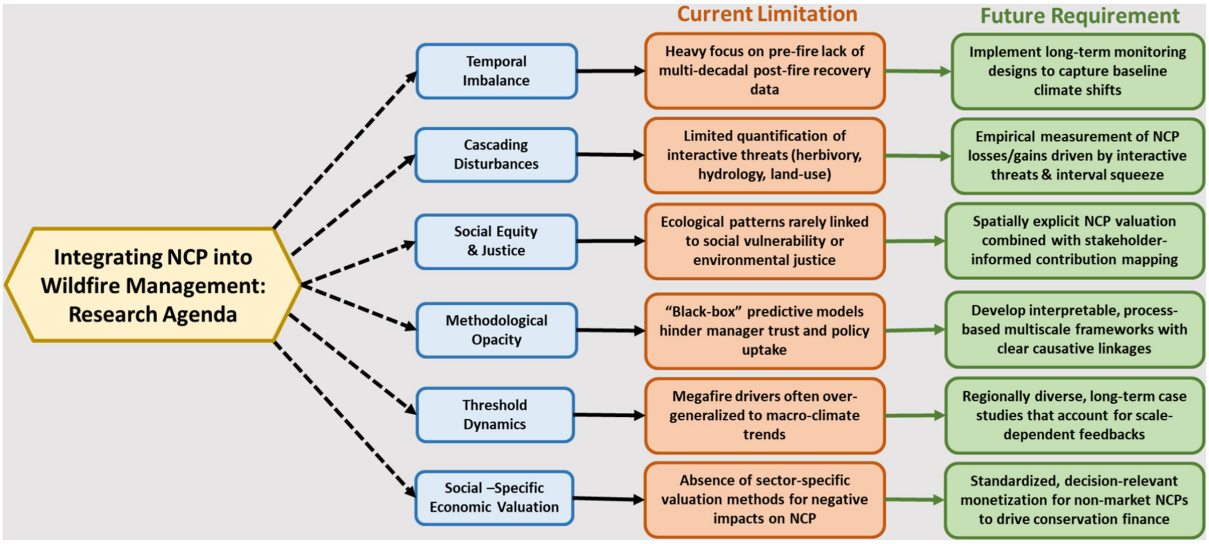


FIGURE 3
Multi-dimensional research gaps and future directions for integrating CP into wildfire management.

TABLE 6 Critical research gaps in wildfire-NCP literature and requirements for future integration.

Research gap category	Current limitation	Requirement for future research	Key reference citations
Temporal imbalance	Heavy focus on pre-fire mitigation; lack of multi-decadal post-fire recovery data.	Implement long-term monitoring designs to capture baseline shifts in a warming climate.	Bowman et al. (2020); Shen et al. (2025); van Etten et al. (2022)
Cascading disturbances	Limited quantification of how fire interacts with herbivory, altered hydrology, and land-use change.	Empirical measurement of NCP losses/gains driven by "interval squeeze" and interactive threats.	Geary et al. (2021); Gallagher et al. (2022); Breton et al. (2022)
Social equity and justice	Ecological patterns (refugia/habitat) are rarely linked to social vulnerability or environmental justice.	Spatially explicit NCP valuation combined with stakeholder-informed contribution mapping.	Keeley et al. (2024); Nolan et al. (2022); Six (2025)
Methodological opacity	"Black-box" predictive models hinder manager trust and policy uptake.	Development of interpretable, process-based multiscale frameworks with clear causative linkages.	Evers et al. (2022); Li et al. (2024); Coen et al. (2018)
Threshold dynamics	Mechanistic drivers of megafires are often over-generalized to macro-climate trends.	Regionally diverse, long-term case studies that account for localized, scale-dependent feedbacks.	Santos et al. (2022); Legge et al. (2022); Coen et al. (2018)
Sector specific economic valuation	Absence of industry- or sector-specific (e.g., utilities, corporates, local governments) standardized economic valuation methods for fire-related negative impacts on NCP.	Develop standardized, decision-relevant monetization methodologies for non-market NCP and their negative impacts tailored to specific stakeholder sectors to drive conservation finance.	Ebel et al. (2023); Johnston et al. (2024); Bladon et al. (2014); Depietri and Orenstein (2019); Gartner et al. (2017); Wlostowski et al. (2021)

4.2.2 Cascading disturbances and threshold dynamics

Post-fire ES recovery cannot be disentangled from co-occurring, competing threats like herbivory, altered hydrology, and land-use changes (Geary et al., 2021). While these interactive threats are broadly recognized, there remains limited empirical quantification of how they translate into measurable NCP losses or gains across regulating, material, and non-material contributions, as well as underlying ecological functions (Gallagher et al., 2022). Shifting fire intervals (e.g., "interval squeeze") and climate-driven regime shifts produce highly heterogeneous outcomes. While extreme fire behavior is often attributed broadly to macro-climate warming, mechanistic studies demonstrate that megafires frequently arise from localized, scale-dependent feedbacks. To understand these threshold dynamics and drivers of resilience, researchers must expand regionally diverse, long-term case studies that accommodate spatial heterogeneity (Breton et al., 2022; Coen et al., 2018; Santos et al., 2022).

4.2.3 Equity, valuation, and decision support

Another significant deficiency is the limited understanding of the distributional and equity dimensions of NCP losses. While post-fire studies frequently identify localized variations in biodiversity and habitat refugia, they rarely tie these ecological patterns systematically to social vulnerability, watershed governance, or environmental justice

concerns across disparate human communities (Keeley et al., 2024; Nolan et al., 2022). Addressing this requires the implementation of spatially explicit, ecologically grounded NCP valuation. By combining advanced remote sensing, field ecology, and stakeholder-informed contribution mapping, researchers can detect differential environmental responses and provide actionable, multi-contribution data to inform equitable restoration priorities (Shen et al., 2025; Six, 2025).

Finally, methodological gaps in forecasting and decision support continue to hinder policy uptake. While the predictive accuracy of fire models has improved, the opacity of "black-box" systems remains a challenge for managers. There is a pressing need to broaden the use of interpretable, process-based multiscale frameworks that reveal clear causative linkages among climate, fuels, human factors, and ultimate NCP outcomes (Evers et al., 2022; Li et al., 2024). Ultimately, an integrated NCP-post-fire research program must translate these complex ecological cascades into transparent resilience metrics and decision-relevant outputs for effective long-term policy design.

4.2.4 Applied economic valuation and conservation finance

Crucially, while this review strongly advocates for monetizing non-market NCP to drive policy action, there remains a pronounced absence of industry- and sector-specific standardized economic valuation methods for fire-related negative impacts on NCP. Pointing methodology development specifically toward decision-relevant actors, such as municipal water utilities, corporate stakeholders, and local governments, must become a top research priority.

For example, future research should develop targeted avoided-cost modeling frameworks for municipal water utilities to quantify the economic burden of negative impacts of post-fire sedimentation (Bladon et al., 2014; Gartner et al., 2017). By calculating the deferred costs of dredging reservoirs, upgrading water filtration infrastructure, or sourcing alternative water supplies, these models can translate biophysical hazards directly into explicit financial liabilities. This level of standardized, sector-specific valuation is essential to justify and scale upstream investments in forest resilience, such as through Forest Resilience Bonds (Depietri and Orenstein, 2019; Wlostowski et al., 2021). Developing these financial mechanisms ensures that the ecological knowledge synthesized in this review translates directly into sustainable landscape management and conservation finance.

4.3 Limitations of the study

A conceptual limitation of framing wildfire management purely through the IPES NCP lens is its inherent grounding in human-centric contributions. While the framework successfully captures diverse worldviews and relational values, prioritizing management actions based on quantified material or regulating benefits risks marginalizing ecosystem components and species that lack documented utilitarian value to human societies. In the context of nature's co-existence, an over-reliance on NCP metrics may skew fire management policies (such as targeted fuel treatments) toward protecting high-value human-built or human-utilized landscapes, potentially disrupting the evolutionary fire niches required by non-beneficial or isolated endemic species. Future firescape frameworks should balance NCP assessments with intrinsic biodiversity valuation paradigms to safeguard holistic ecosystem co-existence.

5 Conclusion

The narrative surrounding wildland fire is often dominated by destruction and disaster. However, as this review demonstrates, viewing fire strictly as an ecological catastrophe overlooks its profound, dual role as both a consumer and a provider of Nature's Contributions to People (NCP). For millennia, low-to-moderate severity fires have functioned as essential regulating contributions and drivers of underlying ecological functions, cycling vital nutrients back into the soil, creating complex habitat mosaics that sustain biodiversity, and naturally regulating hazardous fuel loads.

Yet, the unprecedented megafires of the Anthropocene, illustrated by catastrophic events from the Australian bush to the Siberian Arctic, and extending into the complex municipal and island boundaries of Los Angeles and Maui, represent a stark departure from historical fire regimes. Driven by a volatile combination of climate change, compounding droughts, and a century of misguided fire exclusion policies, these high-severity fire events are driving acute negative impacts on nature's contributions. They are converting long-term terrestrial carbon sinks into massive GHG sources, devastating water quality and provisioning systems for millions of people, and permanently altering fragile ecosystems.

As we look to the future, the NCP framework must be placed at the center of environmental planning. By explicitly identifying the complex trade-offs and regime shifts inherent in landscape management, policymakers can move away from the untenable goal of absolute fire suppression. To protect the vital material, non-material, and regulating contributions upon which human societies rely, we must embrace adaptive socio-ecological governance. This requires integrating IEK with Western science, actively utilizing prescribed and cultural burning, implementing proactive forest thinning, and enforcing smart development restrictions within the WUI. Furthermore, explicitly quantifying the economic value of non-market NCP will be essential for policymakers to financially justify these proactive interventions. As outlined in Section 4, systematically addressing current research gaps, particularly regarding compounding disturbances and the sector-specific economic valuation of these non-material and regulating contributions, will be crucial to supporting this transition.

Moving forward, the success of this 'Adaptive Socio-Ecological Governance' model hinges on three policy pillars: (1) Liability Reform, to empower local practitioners and reduce the risk of proactive management; (2) Equitable Governance, which moves beyond consulting Indigenous communities to granting them autonomous decision-making power over cultural fire; and (3) Risk-Based Accounting, which integrates the long-term value of NCP, such as water security and carbon stability, into the economic metrics used to justify fire management budgets. Crucially, because public dollars alone will likely never be sufficient to fill the massive funding gap required for landscape-scale treatments, this accounting must be coupled with the additive lens of innovative financing. By rigorously quantifying avoided negative impacts on these contributions, managers can leverage conservation finance models, drawing in private capital and incentivizing downstream beneficiaries to co-invest alongside public agencies. Ultimately, learning to proactively coexist with fire, rather than endlessly fighting it, is not merely an ecological ideal; it is an urgent necessity for global sustainability in a warming world.

Author contributions

LA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. ME: Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abdollahi, M., Vahedifard, F., and Tracy, F. (2023). Post-wildfire stability of unsaturated hillslopes against rainfall-triggered landslides. *Earth's Future* 11:e2022EF003213. doi: 10.1029/2022ef003213

Anderson, S., Hodges, H., and Anderson, T. (2013). Technical management in an age of openness: the political, public, and environmental forest ranger. *J. Policy Anal. Manag.* 32, 554–573. doi: 10.1002/pam.21697

Atkinson, A., and Molina, C. (2023). Reconnecting fire culture of Aboriginal communities with contemporary wildfire risk management. *Fire* 6:296. doi: 10.3390/fire6080296

Badgley, G., Chay, F., Chegwidden, O. S., Hamman, J. J., Freeman, J., and Cullenward, D. (2022). California's forest carbon offsets buffer pool is severely undercapitalized. *Front. For. Global Change* 5:930426. doi: 10.3389/ffgc.2022.930426

Balantic, C., Adams, A., Gross, S., Mazur, R., Sawyer, S., Tucker, J., et al. (2021). Toward climate change refugia conservation at an ecoregion scale. *Conserv. Sci. Pract.* 3:e497. doi: 10.1111/csp2.497

Bargali, H., Pandey, A., Bhatt, D., and Sundriyal, R. C. (2024). Loss of carbon stock in the forests of Uttarakhand due to unprecedented seasonal forest fires. *Front. For. Global Change* 7:1352265. doi: 10.3389/ffgc.2024.1352265

Beard, L., Cardell, J., Dobson, I., Galvan, F., Hawkins, D., Jewell, W., et al. (2010). Key technical challenges for the electric power industry and climate change. *IEEE Trans. Energy Convers.* 25, 465–473. doi: 10.1109/tec.2009.2032578

Bladon, K. D., Emelko, M. B., Silins, U., and Stone, M. (2014). Wildfire and the future of water supply. *Environ. Sci. Technol.* 48, 8936–8943. doi: 10.1021/es500130g

Borchers Arriagada, N., Palmer, A. J., Bowman, D. M., Morgan, G. G., Jalaludin, B. B., and Johnston, F. H. (2020). Unprecedented smoke-related health burden associated with the 2019–20 bushfires in eastern Australia. *Med. J. Aust.* 213, 282–283. doi: 10.5694/mja2.50545

Bowman, D., Williamson, G., Price, O., Ndalila, M., and Bradstock, R. (2020). Australian forests, megafires and the risk of dwindling carbon stocks. *Plant Cell Environ.* 44, 347–355. doi: 10.1111/pce.13916

Breton, T., Lyons, M., Nolan, R., Penman, T., Williamson, G., and Ooi, M. (2022). Megafire-induced interval squeeze threatens vegetation at landscape scales. *Front. Ecol. Environ.* 20, 327–334. doi: 10.1002/fee.2482

Byrne, B., Liu, J., Bowman, K. W., Pascolini-Campbell, M., Chatterjee, A., Pandey, S., et al. (2024). Carbon emissions from the 2023 Canadian wildfires. *Nature* 633, 835–839. doi: 10.1038/s41586-024-07878-z

Christ, S., Schwarz, N., and Sliuzas, R. (2022). Wildland urban interface of the City of Cape Town 1990–2019. *Geogr. Res.* 60, 395–413. doi: 10.1111/1745-5871.12535

Christianson, A., Sutherland, C., Moola, F., Bautista, N., Young, D., and MacDonald, H. (2022). Centering indigenous voices: the role of fire in the boreal forest of North America. *Curr. For. Rep.* 8, 257–276. doi: 10.1007/s40725-022-00168-9

Coen, J., Stavros, E., and Fites-Kaufman, J. (2018). Deconstructing the King megafire. *Ecol. Appl.* 28, 1565–1580. doi: 10.1002/eap.1752

Crandall, T., Jones, E., Greenhalgh, M., Frei, R., Griffin, N., Severe, E., et al. (2021). Megafire affects stream sediment flux and dissolved organic matter reactivity, but land use dominates nutrient dynamics in semiarid watersheds. *PLoS One* 16:e0257733. doi: 10.1371/journal.pone.0257733

D'Evelyn, S., Jung, J., Alvarado, E., Baumgartner, J., Caligiuri, P., Hagmann, R., et al. (2022). Wildfire, smoke exposure, human health, and environmental justice need to be integrated into forest restoration and management. *Curr. Environ. Health Rep.* 9, 366–385. doi: 10.1007/s40572-022-00355-7

Dass, P., Houlton, B., Wang, Y., and Wårlind, D. (2018). Grasslands may be more reliable carbon sinks than forests in California. *Environ. Res. Lett.* 13:074027. doi: 10.1088/1748-9326/aacb39

DellaSala, D., Williams, J., Williams, C., and Franklin, J. (2004). Beyond smoke and mirrors: a synthesis of fire policy and science. *Conserv. Biol.* 18, 976–986. doi: 10.1111/j.1523-1739.2004.00529.x

Depietri, Y., and Orenstein, D. (2019). Fire-regulating services and disservices with an application to the Haifa–Carmel region in Israel. *Front. Environ. Sci.* 7. doi: 10.3389/fenvs.2019.00107

Dewi, T., Herdiansyah, H., Soesilo, T., and Venus, A. (2024). Identifying and addressing the right to burn for indigenous-led fire stewardship practices. *Int. J. Environ. Imp. Manag. Mitig. Recov.* 7, 159–168. doi: 10.18280/ijei.070201

Dickson-Hoyle, S., Ignace, R., Ignace, M., Hagerman, S., Daniels, L., and Copes-Gerbitz, K. (2022). Walking on two legs: a pathway of Indigenous restoration and reconciliation in fire-adapted landscapes. *Restor. Ecol.* 30:e13566. doi: 10.1111/rec.13566

Ebel, B., Shephard, Z., Walvoord, M., Murphy, S., Partridge, T., and Perkins, K. (2023). Modeling post-wildfire hydrologic response: review and future directions for applications of physically based distributed simulation. *Earth's Future* 11:e2022EF003038. doi: 10.1029/2022ef003038

Elias, M., Yackulic, E., Duffy, K., Saksa, P., Sanchez, D. L., Pevzner, N., et al. (2025). Carbon finance for forest resilience in California. *Front. For. Global Change* 7:1507554. doi: 10.3389/ffgc.2024.1507554

Enright, D. J., Frangioso, K. M., Isobe, K., Rizzo, D. M., and Glassman, S. I. (2022). Megafire in redwood tanoak forest reduces bacterial and fungal richness and selects for pyrophilous taxa that are phylogenetically conserved. *Mol. Ecol.* 31, 2475–2493. doi: 10.1111/mec.16399

Escobedo, V. M., Gómez, P., Molina-Montenegro, M. A., and Acuña-Rodríguez, I. S. (2024). Post-fire negative relationship between a native tree and an invasive pine at the Coastal Maulino Forest in Central Chile. *Front. Ecol. Evol.* 12:1494548. doi: 10.3389/fevo.2024.1494548

van Etten, EJB., Brooks, ML., Greenville, AC., and Wardle, GM. (2022). Editorial: fire regimes in desert ecosystems: drivers, impacts and changes. *Front. Ecol. Evol.* 10:968031. doi: 10.3389/fevo.2022.968031

Evers, C., Holz, A., Busby, S., and Nielsen-Pincus, M. (2022). Extreme winds alter influence of fuels and topography on megafire burn severity in seasonal temperate rainforests under record fuel aridity. *Fire* 5:41. doi: 10.3390/fire5020041

Fisk, J., Leong, K. M., Berl, R. E. W., Long, J. W., Landon, A. C., Adams, M. M., et al. (2024). Evolving wildlife management cultures of governance through indigenous knowledges and perspectives. *J. Wildl. Manag.* 88:e22584. doi: 10.1002/jwmg.22584

Fletcher, M. S., Romano, A., Connor, S., Mariani, M., and Maezumi, S. Y. (2021). Catastrophic bushfires, indigenous fire knowledge and the reframing of science in Southeast Australia. *Fire* 4:61. doi: 10.3390/fire4030061

Franklin, J., and MacDonald, G. (2024). Climate change and California sustainability—challenges and solutions. *Proc. Natl. Acad. Sci.* 121:e2405458121. doi: 10.1073/pnas.2405458121

Gallagher, R., Allen, S., Mackenzie, B., Keith, D., Nolan, R., Rumpff, L., et al. (2022). An integrated approach to assessing abiotic and biotic threats to post-fire plant species recovery: lessons from the 2019–2020 Australian fire season. *Glob. Ecol. Biogeogr.* 31, 2056–2069. doi: 10.1111/geb.13478

Gartner, T., Francesco, K. D., Ozment, S., Huber-Stearns, H., Lichten, N., and Tognetti, S. (2017). Protecting drinking water at the source: lessons from US watershed investment programs. *J. Am. Water Works Assoc.* 109, 30–41. doi: 10.5942/jawwa.2017.109.0049

Geary, W., Buchan, A., Allen, T., Attard, D., Bruce, M., Collins, L., et al. (2021). Responding to the biodiversity impacts of a megafire: a case study from south-eastern Australia's Black Summer. *Divers. Distrib.* 28, 463–478. doi: 10.1111/ddi.13292

Ghosh, D., Page-Dumroese, D., Han, H., and Anderson, N. (2024). Role of biochar made from low-value woody forest residues in ecological sustainability and carbon neutrality. *Soil Sci. Soc. Am. J.* 89:e20793. doi: 10.1002/saj2.20793

Gill, N. S., Turner, M. G., Brown, C. D., Glassman, S. I., Haire, S. L., Hansen, W. D., et al. (2022). Limitations to propagule dispersal will constrain postfire recovery of plants and fungi in western coniferous forests. *Bioscience* 72, 347–364. doi: 10.1093/biosci/biab139

Gillespie, J., and Lange, J. (2025). Bushfire management, prescribed burning, and a right to fire?*Geogr. Res.* 63, 697–711. doi: 10.1111/1745-5871.70021

Gillson, L., Whitlock, C. L., and Humphrey, G. (2019). Resilience and fire management in the Anthropocene. *Ecol. Soc.* 24:14. doi: 10.5751/es-11022-240314

Godfree, R., Knerr, N., Encinas-Viso, F., Albrecht, D., Bush, D., Cargill, D., et al. (2021). Implications of the 2019–2020 megafires for the biogeography and conservation of Australian vegetation. *Nat. Commun.* 12:1023. doi: 10.1038/s41467-021-21266-5

Goffin, B., Aryal, A., Deppert, Q., Ross, K., and Lakshmi, V. (2024). Mapping extreme wildfires using a critical threshold in SMAP soil moisture. *Remote Sens. (Basel)* 16:2457. doi: 10.3390/rs16132457

Kropp, J. D., and De Andrade, M. A. (2022). Wildfires and Smoke Exposure Create Contracting and Crop Insurance Challenges for California's Wine Industry Choices. Quarter 2. Available online: https://www.choicesmagazine.org/choices-magazine/submitted-articles/wildfires-and-smoke-exposure-create-contracting-and-crop-insurance-challenges-for-californias-wine-industry

González, M. E., Galleguillos, M., Lopatin, J., Leal, C., Becerra-Rodas, C., Lara, A., et al. (2023). Surviving in a hostile landscape: *Nothofagus alessandrii* remnant forests threatened by mega-fires and exotic pine invasion in the coastal range of central Chile. *Oryx* 57, 228–238. doi: 10.1017/S0030605322000102

González, S., and Ghermandi, L. (2024). How to define the wildland–urban interface? Methods and limitations: towards a unified protocol. *Front. Environ. Sci.* 11:1284631. doi: 10.3389/fenvs.2023.1284631

Greenberg, M., Angelo, H., Losada, E., and Wilmers, C. (2024). Relational geographies of urban unsustainability: the entanglement of California's housing crisis with WUI growth and climate change. *Proc. Natl. Acad. Sci.* 121:e2310080121. doi: 10.1073/pnas.2310080121

He, T., Lamont, B. B., and Pausas, J. G. (2019). Fire as a key driver of Earth's biodiversity. *Biol. Rev.* 94, 1983–2010. doi: 10.1111/brv.12544

Herbert, C., Haya, B. K., Stephens, S. L., and Butsic, V. (2022). Managing nature-based solutions in fire-prone ecosystems: competing management objectives in California forests evaluated at a landscape scale. *Front. For. Global Change* 5:957189. doi: 10.3389/ffgc.2022.957189

Hessburg, P., Miller, C., Parks, S., Povak, N., Taylor, A., Higuera, P., et al. (2019). Climate, environment, and disturbance history govern resilience of Western North American forests. *Front. Ecol. Evol.* 7:239. doi: 10.3389/fevo.2019.00239

Hessburg, P., Prichard, S., Hagmann, R., Povak, N., and Lake, F. (2021). Wildfire and climate change adaptation of western North American forests: a case for intentional management. *Ecol. Appl.* 31:e02432. doi: 10.1002/eap.2432

Horvat, B., and Karleuša, B. (2024). Conceptual model for integrated meso-scale fire risk assessment in the coastal catchments in Croatia. *Remote Sens. (Basel)* 16:2118. doi: 10.3390/rs16122118

Hoyland, R., McHenry, M., and Foster, E. (2024). Fire and geodiversity. *Int. J. Wildland Fire* 33:WF23134. doi: 10.1071/wf23134

Hurteau, M., Hungate, B., Koch, G., North, M., and Smith, G. (2012). Aligning ecology and markets in the forest carbon cycle. *Front. Ecol. Environ.* 11, 37–42. doi: 10.1890/120039

Hyde, J., Yedinak, K., Talhelm, A., Smith, A., Bowman, D., Johnston, F., et al. (2017). Air quality policy and fire management responses addressing smoke from wildland fires in the United States and Australia. *Int. J. Wildland Fire* 26, 347–363. doi: 10.1071/wf16154

Jenerette, G., Anderson, K., Cadenasso, M., Fenn, M., Franklin, J., Goulden, M., et al. (2022). An expanded framework for wildland–urban interfaces and their management. *Front. Ecol. Environ.* 20, 516–523. doi: 10.1002/fee.2533

Jerrett, M., Jina, A. S., and Marlier, M. E. (2022). Up in smoke: California's greenhouse gas reductions could be wiped out by 2020 wildfires. *Environ. Pollut.* 310:119888. doi: 10.1016/j.envpol.2022.119888

Johnston, F., Jones, C., Li, F., Stehr, A., Torres-Vázquez, M., Turco, M., et al. (2024). Interdisciplinary solutions and collaborations for wildfire management. *iScience* 27:110438. doi: 10.1016/j.isci.2024.110438

Kang, Z., Quan, X., and Lai, G. (2023). Assessing the effects of fuel moisture content on the 2018 megafires in California. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* 16, 868–877. doi: 10.1109/jstars.2022.3232665

Keeley, J., Flannigan, M., Brown, T., Rolinski, T., Cayan, D., Syphard, A., et al. (2024). Climate and weather drivers in southern California Santa Ana Wind and non-Santa Wind fires. *Int. J. Wildland Fire* 33:WF23190. doi: 10.1071/wf23190

Keeley, J. E., and Syphard, A. D. (2021). Large California wildfires: 2020 fires in historical context. *Fire Ecol.* 17:22. doi: 10.1186/s42408-021-00110-7

Keenan, R., Weston, C., and Volkova, L. (2021). Potential for forest thinning to reduce risk and increase resilience to wildfire in Australian temperate Eucalyptus forests. *Curr. Opin. Environ. Sci. Health* 23:100280. doi: 10.1016/j.coesh.2021.100280

Keith, H., Vardon, M., Stein, J., and Lindenmayer, D. (2019). Contribution of native forests to climate change mitigation—a common approach to carbon accounting that aligns results from environmental-economic accounting with rules for emissions reduction. *Environ. Sci. Policy* 93, 189–199. doi: 10.1016/j.envsci.2018.11.001

Kelly, L., Giljohann, K., Duane, A., Aquilué, N., Archibald, S., Batllori, E., et al. (2020). Fire and biodiversity in the Anthropocene. *Science* 370. doi: 10.1126/science.abb0355

Kerber, S., and Alkonis, D. (2024). *Lahaina Fire Incident Analysis Report*. Columbia, Maryland: UL Research Institute.

Kettridge, N., Lukenbach, M., Hokanson, K., Hopkinson, C., Devito, K., Petrone, R., et al. (2017). Low evapotranspiration enhances the resilience of peatland carbon stocks to fire. *Geophys. Res. Lett.* 44, 9341–9349. doi: 10.1002/2017gl074186

Khairoun, A., Ciais, P., Nguyen, T. H., Qiu, C., Fang, C., Aires, F., et al. (2026). Peat fires contribute disproportionately to Siberian fire carbon emissions. *Sci. Adv.* 12:eadl2368. doi: 10.1126/sciadv.adl2368

Krofcheck, D., Remy, C., Keyser, A., and Hurteau, M. (2019). Optimizing forest management stabilizes carbon under projected climate and wildfires. *J. Geophys. Res. Biogeo.* 124, 3075–3087. doi: 10.1029/2019jg005206

Legge, S., Rumpff, L., Woinarski, J., Whiterod, N., Ward, M., Southwell, D., et al. (2022). The conservation impacts of ecological disturbance: time-bound estimates of population loss and recovery for fauna affected by the 2019–2020 Australian megafires. *Glob. Ecol. Biogeogr.* 31, 2085–2104. doi: 10.1111/geb.13473

Leverkus, A., Gustafsson, L., Lindenmayer, D., Castro, J., Beñayas, J., Ranius, T., et al. (2020). Salvage logging effects on regulating ecosystem services and fuel loads. *Front. Ecol. Environ.* 18, 391–400. doi: 10.1002/fee.2219

Li, C., Li, H., Yang, Y., Wang, S., and Zhu, Y. (2026). Integrating earth observation data into the tri environmental evaluation of the economic cost of natural disasters: a case study of the 2025 LA wildfire. *Int. J. Appl. Earth Obs. Geoinf.* 150:105342. doi: 10.1016/j.jag.2026.105342

Li, F., Zhu, Q., Yuan, K., Ji, F., Paul, A., Lee, P., et al. (2024). Projecting large fires in the Western US with an interpretable and accurate hybrid machine learning method. *Earth's Future* 12:e2024EF004588. doi: 10.1029/2024ef004588

Ma, Q., Bales, R., Rungee, J., Conklin, M., Collins, B., and Goulden, M. (2020). Wildfire controls on evapotranspiration in California's Sierra Nevada. *J. Hydrol.* 590:125364. doi: 10.1016/j.jhydrol.2020.125364

Mason, S. C., Shirey, V., Waite, E. S., Gallagher, M. R., and Skowronski, N. S. (2023). Exploring prescribed fire severity effects on ground beetle (Coleoptera: Carabidae) taxonomic and functional community composition. *Fire* 6:366. doi: 10.3390/fire6090366

McCormack, P., Miller, R., and McDonald, J. (2023). Prescribed burning on private land: reflections on recent law reform in Australia and California. *Int. J. Wildland Fire* 33. doi: 10.1071/wf22213

McGranahan, D., and Wonkka, C. (2025). Quantifying wildfire risk to the built environment in rural rangelands of the US Interior West. *Philos. Trans. R. Soc. B* 380:20230457. doi: 10.1098/rstb.2023.0457

McLatchy, L. A., Whelton, A. J., Rong, K. C., Cole, K. D. P., L'I, J., and Shuler, C. K. (2026). Community-driven water quality assessment following the 2023 Maui wildfires: insights into post-fire drinking water contamination and resilient disaster response. *ACS EST Water* 6, 793–804. doi: 10.1021/acsestwater.5c00896

McLauchlan, K., Higuera, P., Miesel, J., Rogers, B., Schweitzer, J., Shuman, J., et al. (2020). Fire as a fundamental ecological process: research advances and frontiers. *J. Ecol.* 108, 2047–2069. doi: 10.1111/1365-2745.13403

Menor, I., Prat-Guitart, N., Spadoni, G., Hsu, A., Fernandes, P., Puig-Gironès, R., et al. (2025). Integrated fire management as an adaptation and mitigation strategy to altered fire regimes. *Commun. Earth Environ.* 6. doi: 10.1038/s43247-025-02165-9

Morecroft, M., Duffield, S., Harley, M., Pearce-Higgins, J., Stevens, N., Watts, O., et al. (2019). Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. *Science* 366:eaaw9256. doi: 10.1126/science.aaw9256

Moya, D., Certini, G., and Fulé, P. (2019). Fire regime and ecosystem responses: adaptive forest management in a changing world (Part 2). *Int. J. Wildland Fire* 28, 471–472. doi: 10.1071/wfv28n7_fo

Mucioki, M., Sowerwine, J., Sarna-Wojcicki, D., Lake, F., and Bourque, S. (2021). Conceptualizing Indigenous Cultural Ecosystem Services (ICES) and benefits under changing climate conditions in the Klamath River Basin and their implications for land management and governance. *J. Ethnobiol.* 41, 313–330. doi: 10.2993/0278-0771-41.3.313

Nikolakis, W., and Roberts, E. (2021). Wildfire governance in a changing world: insights for policy learning and policy transfer. *Risk Haz. Crisis Publ. Policy* 13, 144–164. doi: 10.1002/rhc3.12235

Nikolakis, W., Welham, C., and Greene, G. (2022). Diffusion of indigenous fire management and carbon-credit programs: opportunities and challenges for "scaling-up" to temperate ecosystems. *Front. For. Global Change* 5:967653. doi: 10.3389/ffgc.2022.967653

Nolan, R., Anderson, L., Poulter, B., and Varner, J. (2022). Increasing threat of wildfires: the year 2020 in perspective: a Global Ecology and Biogeography special issue. *Glob. Ecol. Biogeogr.* 31, 1898–1905. doi: 10.1111/geb.13588

Nolan, R., Bowman, D., Clarke, H., Haynes, K., Ooi, M., Price, O., et al. (2021). What do the Australian black summer fires signify for the global fire crisis?*Fire* 4:97. doi: 10.3390/fire4040097

OECD (2023). *OECD Environmental Performance Reviews: Portugal 2023*. Paris: OECD Publishing.

Oliveira, M., Delerue-Matos, C., Pereira, M., and Morais, S. (2020). Environmental particulate matter levels during 2017 large forest fires and megafires in the Center Region of Portugal: a public health concern?*Int. J. Environ. Res. Public Health* 17:1032. doi: 10.3390/ijerph17031032

Palacios-Abrantes, J., Badhe, R., Bamford, A., Cheung, W. W. L., Foden, W., Santos, C. F., et al. (2022). Managing biodiversity in the Anthropocene: discussing the Nature Futures Framework as a tool for adaptive decision-making for nature under climate change. *Sustain. Sci.* doi: 10.1007/s11625-022-01200-4

Pausas, J., and Bond, W. (2020). Alternative biome states in terrestrial ecosystems. *Trends Plant Sci.* 25, 250–263. doi: 10.1016/j.tplants.2019.11.003

Pausas, J., and Keeley, J. (2019). Wildfires as an ecosystem service. *Front. Ecol. Environ.* 17, 289–295. doi: 10.1002/fee.2044

Penna, D., Hopp, L., Asano, Y., Thompson, S., and Yang, Y. (2021). Virtual special issue "Advances in forest hydrology in the light of land use change and disturbances". *J. Hydrol.* 601:126788. doi: 10.1016/j.jhydrol.2021.126788

Pereira, P., Bogunović, I., Zhao, W., and Barcelo, D. (2021). Short-term effect of wildfires and prescribed fires on ecosystem services. *Curr. Opin. Environ. Sci. Health* 22:100266. doi: 10.1016/j.coesh.2021.100266

Pereira, C., Tabarelli, M., Barros, M., and Vieira, I. (2023). Restoring fire-degraded social forests via biocultural approaches: a key strategy to safeguard the Amazon legacy. *Restor. Ecol.* 31:e13976. doi: 10.1111/rec.13976

Poon, P., and Kinoshita, A. (2018). Estimating evapotranspiration in a post-fire environment using remote sensing and machine learning. *Remote Sens. (Basel)* 10:1728. doi: 10.3390/rs10111728

Prichard, S., Hessburg, P., Hagmann, R., Povak, N., Dobrowski, S., Hurteau, M., et al. (2021). Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecol. Appl.* 31:e02433. doi: 10.1002/eap.2433

Raeofy, Y., Samburova, V., Berli, M., Sion, B., and Moosmüller, H. (2023). Hyperspectral reflectance and chemical composition of pre- and post-fire soils from three 2021 western USA megafires. *Fire* 6:471. doi: 10.3390/fire6120471

Regos, A., Pais, S., Campos, J., and Lecina-Diaz, J. (2023). Nature-based solutions to wildfires in rural landscapes of Southern Europe: let's be fire-smart!*Int. J. Wildland Fire* 32, 942–950. doi: 10.1071/wf22094

Roces-Díaz, J. (2023). Australia's megafires: biodiversity impacts and lessons from 2019 to 2020. *Int. J. Wildland Fire* 32, 1487–1488. doi: 10.1071/wf23135

Roces-Díaz, J., Santín, C., Martínez-Vilalta, J., and Doerr, S. (2021). A global synthesis of fire effects on ecosystem services of forests and woodlands. *Front. Ecol. Environ.* 20, 170–178. doi: 10.1002/fee.2349

Roche, J., Ma, Q., Rungee, J., and Bales, R. (2020). Evapotranspiration mapping for forest management in California's Sierra Nevada. *Front. For. Global Change* 3:69. doi: 10.3389/ffgc.2020.00069

Rodriguez-Franco, C., Page-Dumroese, D., Pierson, D., and Nicosia, T. (2024). Biochar utilization as a forestry climate-smart tool. *Sustainability* 16:1714. doi: 10.3390/su16051714

Roos, C., Scott, A., Belcher, C., Chaloner, W., Aylen, J., Bird, R., et al. (2016). Living on a flammable planet: interdisciplinary, cross-scalar and varied cultural lessons, prospects and challenges. *Philos. Trans. R. Soc., B* 371:20150469. doi: 10.1098/rstb.2015.0469

Russell-Smith, J., Cook, G., Cooke, P., Edwards, A., Lendrum, M., Meyer, C., et al. (2013). Managing fire regimes in north Australian savannas: applying Aboriginal approaches to contemporary global problems. *Front. Ecol. Environ.* 11, e55–e63. doi: 10.1890/120251

Russell-Smith, J., Yates, C., Vernooij, R., Eames, T., Lucas, D., Mbindo, K., et al. (2024). Framework for a savanna burning emissions abatement methodology applicable to fire-prone miombo woodlands in southern Africa. *Int. J. Wildland Fire* 33:WF23193. doi: 10.1071/wf23193

Saksa, P., Bales, R., Tague, C., Battles, J., Tobin, B., and Conklin, M. (2020a). Fuels treatment and wildfire effects on runoff from Sierra Nevada mixed-conifer forests. *Ecohydrology* 13:539429. doi: 10.1002/eco.2151

Saksa, P., Conklin, M., Tague, C., and Bales, R. (2020b). Hydrologic response of Sierra Nevada Mixed-Conifer headwater catchments to vegetation treatments and wildfire in a warming climate. *Front. For. Global Change* 3:e2151. doi: 10.3389/ffgc.2020.539429

Sample, M., Thode, A., Peterson, C., Gallagher, M., Flatley, W., Friggens, M., et al. (2022). Adaptation strategies and approaches for managing fire in a changing climate. *Climate* 10:58. doi: 10.3390/cli10040058

Santos, X., Belliure, J., Gonçalves, J., and Pausas, J. (2022). Resilience of reptiles to megafires. *Ecol. Appl.* 32:e2518. doi: 10.1002/eap.2518

Saunders, M., Andrew, R., Mitchell-Williams, J., Pemberton, P., Wandrag, E., and Hunter, J. (2024). Rapid on-ground assessment after the 2019–2020 megafires reveals new information on rare and threatened plants in northern New South Wales, Australia. *Austral. Ecol.* 49:e13514. doi: 10.1111/aec.13514

Schmidt, A., Ellsworth, L. M., Boisen, G. A., Novita, N., Malik, A., Gangga, A., et al. (2024). Fire frequency, intensity, and burn severity in Kalimantan's threatened Peatland areas over two decades. *Front. For. Global Change* 7:1221797. doi: 10.3389/ffgc.2024.1221797

Schoennagel, T., Balch, J., Brenkert-Smith, H., Dennison, P., Harvey, B., Krawchuk, M., et al. (2017). Adapt to more wildfire in western North American forests as climate changes. *Proc. Natl. Acad. Sci.* 114, 4582–4590. doi: 10.1073/pnas.1617464114

Schug, F., Bar-Massada, A., Carlson, A. R., Cox, H., Hawbaker, T. J., Helmers, D., et al. (2023). The global wildland–urban interface. *Nature* 621, 94–99. doi: 10.1038/s41586-023-06320-0

Schultz, C. A., McCaffrey, S. M., and Huber-Stearns, H. R. (2019). Policy barriers and opportunities for prescribed fire application in the western United States. *Int. J. Wildland Fire* 28:874. doi: 10.1071/wf19040

Shen, Z., Giljohann, K., Liu, Z., Pausas, J., and Rogers, B. (2025). Novel wildfire regimes under climate change and human activity: patterns, driving mechanisms and ecological impacts. *Philos. Trans. R. Soc. B* 380:20230446. doi: 10.1098/rstb.2023.0446

Six, L. (2025). Riparian vegetation layers differ three years after mixed severity wildfire in Oregon. *Sci. Rep.* 15:36247. doi: 10.1038/s41598-025-20242-z

Smith, A., Kolden, C., Paveglio, T., Cochrane, M., Bowman, D., Moritz, M., et al. (2016). The science of firescapes: achieving fire-resilient communities. *Bioscience* 66, 130–146. doi: 10.1093/biosci/biv182

Srinivasan, J., Jones, K., and Morgan, M. (2025). Unpacking the taxonomy of wildland fire collaboratives in the United States West: impact of response diversity on social-ecological resilience. *Environ. Manag.* 75, 1349–1367. doi: 10.1007/s00267-025-02170-w

Stephens, S., and Ruth, L. (2005). Federal forest-fire policy in the United States. *Ecol. Appl.* 15, 532–542. doi: 10.1890/04-0545

Stephens, S., Westerling, A., Hurteau, M., Peery, M., Schultz, C., and Thompson, S. (2020). Fire and climate change: conserving seasonally dry forests is still possible. *Front. Ecol. Environ.* 18, 354–360. doi: 10.1002/fee.2218

Taccaliti, F., Marzano, R., Bell, T., and Lingua, E. (2023). Wildland–urban interface: definition and physical fire risk mitigation measures, a systematic review. *Fire* 6:343. doi: 10.3390/fire6090343

Talmage, C., Allgood, B., Ashdown, B., Brennan, A., Hill, S., Trevan, E., et al. (2022). Tethering natural capital and cultural capital for a more sustainable post-COVID-19 world. *Int. J. Community Well-Being* 5, 657–678. doi: 10.1007/s42413-021-00151-5

Thom, D., and Seidl, R. (2016). Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biol. Rev.* 91, 760–781. doi: 10.1111/brv.12193

Thomas, A., Escobedo, F., Sloggy, M., and Sánchez, J. (2022). A burning issue: reviewing the socio-demographic and environmental justice aspects of the wildfire literature. *PLoS One* 17:e0271019. doi: 10.1371/journal.pone.0271019

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A., et al. (2020). Carbon release through abrupt permafrost thaw. *Nat. Geosci.* 13, 138–143. doi: 10.1038/s41561-019-0526-0

van Eeden, L. M., Nimmo, D. G., Bower, M., Howell, S. A., and Dickman, C. R. (2020). *Impacts of the Unprecedented 2019–2020 Bushfires on Australian Animals*. Sydney, Australia: World Wide Fund for Nature Australia.

Vargo, J., Lappe, B., Mirabelli, M. C., and Conlon, K. C. (2023). Social vulnerability in US communities affected by wildfire smoke, 2011 to 2021. *Am. J. Public Health* 113, 759–767. doi: 10.2105/ajph.2023.307286

Walker, K., Baldwin, C., Conroy, G., Applegate, G., Archer-Lean, C., Arthington, A., et al. (2022). Ecological and cultural understanding as a basis for management of a globally significant island landscape. *Coasts* 2, 152–202. doi: 10.3390/coasts2030009

Williams, J., Quinn-Davidson, L., Safford, H., Grupenhoff, A., Middleton, B., Restaino, J., et al. (2023). Overcoming obstacles to prescribed fire in the North American Mediterranean climate zone. *Front. Ecol. Environ.* 22:e2687. doi: 10.1002/fee.2687

Wine, M., Makhnin, O., and Cadol, D. (2018). Nonlinear long-term large watershed hydrologic response to wildfire and climatic dynamics locally increases water yields. *Earth's Future* 6, 997–1006. doi: 10.1029/2018ef000930

Wlostowski, A. N., Jennings, K. S., Bash, R. E., Burkhardt, J., Wobus, C., and Aggett, G. R. (2021). Dry landscapes and parched economies: a review of how drought impacts non-agricultural socioeconomic sectors in the US Intermountain West. *Wiley Interdiscip. Rev. Water* 9:e1571. doi: 10.1002/wat2.1571

Yackulic, E., Elias, M., Shannon, J., Gilbert, S., Koontz, M., Plumb, S., et al. (2025). Rising from the ashes: treatments stabilize carbon storage in California's frequent-fire forests. *Front. For. Glob. Change* 8:1498430. doi: 10.3389/ffgc.2025.1498430

Zald, H. S., and Dunn, C. J. (2018). Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape. *Ecol. Appl.* 28, 1068–1080. doi: 10.1002/eap.1710

Zhang, Q., Wang, Y., Xiao, Q., Geng, G., Davis, S. J., Liu, X., et al. (2025). Long-range PM2.5 pollution and health impacts from the 2023 Canadian wildfires. *Nature* 645, 672–678. doi: 10.1038/s41586-025-09482-1