

Perspective

A roadmap for nature-based solutions to extreme wildfires

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SUMMARY

Extreme wildfires are escalating in frequency and intensity as climate change, land abandonment, and decades of fire suppression create landscapes primed to burn. Yet wildfire management remains largely absent from the global nature-based solutions (NbSs) agenda. This perspective outlines a roadmap for deploying NbS to reduce wildfire risk and enhance landscape resilience. Key strategies include integrated fire management, close-to-nature forest practices, targeted biomass extraction for bioenergy, and strategically designed green firebreaks. However, several barriers hinder their implementation: public misconceptions of fire, the erosion of traditional fire knowledge, policy fragmentation, limited long-term funding, and insufficient incentives for rural stewardship. Mainstreaming a “fire-smart” approach into NbS requires inclusive governance, local leadership, cross-sector collaboration, and better alignment of environmental, energy, and wildfire policies. Enhanced monitoring, capacity building, and innovative financing are also essential. By addressing these challenges, NbS can become a transformative tool to promote wildfire resilience and long-term sustainability in fire-prone regions.

SETTING THE SCENE

The frequency of extreme wildfire events (EWEs) is expected to increase worldwide in the decades to come due to the combined effects of global climate warming and regional land-use change.¹ The perception of fire as a fundamental ecological process is being increasingly accepted by the scientific community,^{2,3} but not yet acknowledged by civil society. The result is that policy makers have responded to this increased wildfire hazard with large investments in fire suppression, which has increased the accumulation of fuel (vegetation), accelerating the transition to more flammable landscapes—a side effect known as “wildfire paradox”.⁴ The “zero-fire” policies also create a “fire-fighting trap”, in which firefighters are trapped in a cycle of self-reinforcing feedback, whereby the wildfire problem continues to grow, yet the solution remains the same.⁵ The ancient use of fire as a management tool by local communities is another critical factor for understanding the role that fire has historically played in shaping landscapes and fire regimes.

Nature-based solutions (henceforth “NbS”) are getting attention, being globally used in science, policy, practice, and private sectors to solve societal challenges such as climate change and biodiversity loss.⁶ Defined as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits,”⁶ NbS have been endorsed by key international bodies such as the

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) global assessment report (IPBES, 2019), the United Nations Framework Convention on Climate Change (UNFCCC; <https://unfccc.int/>), and the World Economic Forum (2020). In this new era of extreme wildfires, sustainable solutions to the ever-worrying wildfire problem are urgent.⁷ The integration of the interlinked socioeconomic and ecological aspects of the wildfire problem remains a long-standing demand of fire ecologists and land managers. However, despite being a hazard strongly affected by anthropogenic climate change, the fight against extreme wildfires remains apart from the NbS framework (Figure 1) and, in turn, from its political and financial support. In fact, within Horizon 2020 and Horizon Europe, the European Commission has allocated funding for 76 research and innovation projects centered around NbS. These projects aim to combat climate change and biodiversity loss, enhance public health, and stimulate job creation. They cover a wide array of themes including climate resilience, water security, nature protection and restoration, social inclusion, and co-governance, among others, spanning urban, freshwater, marine, coastal ecosystems, and beyond. Notably, however, none of these initiatives are specifically tailored to address the pressing societal challenges posed by extreme wildfires (see list of EU-funded NbS R&I projects).

In recent years, there has been a marked increase in the number of scientific publications aimed at addressing the challenge that large wildfires pose to our society and ecosystems.



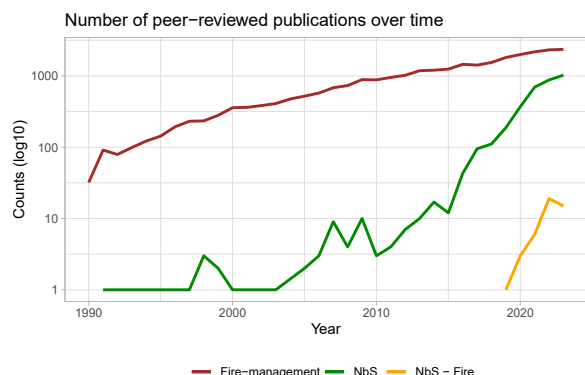


Figure 1. Number of scientific studies published over the last 30 years on fire management (fire management [topic]), nature-based solutions (nature-based solution* [topic]), and nature-based solution to wildfires (nature-based solution* [topic] AND *[fire topic]) (source: Web Of Science, last accessed 03/04/2024)

Knowledge across various disciplines, including environmental science, forestry, and ecology, has grown substantially, with the goal of applying sustainable management strategies to tackle the growing impact of large wildfires (red line in Figure 1). Yet, despite this scientific progress, our capacity to identify and ultimately implement cost-effective, sustainable solutions to address the ever-increasing wildfire hazard remains limited. Notably, although the number of publications on NbS has increased exponentially, those explicitly linking NbS and wildfire risk management remain anecdotal (yellow line in Figure 1). Furthermore, a recent content analysis of EU policies and initiatives under the European Green Deal reveals that, while there is a coherent policy framework for wildfire risk reduction, there is still a lack of clearer guidance on “fire-smart” land management practices and limited conceptualization of wildfire-relevant NbS.⁸ This gap underscores the urgent need to better align scientific knowledge, policy framework, and practical implementation to develop and deploy context-specific NbS that effectively address wildfire risk.

By leveraging natural processes and ecosystem services, NbS offer sustainable, cost-effective strategies for fire management. These approaches promote biodiversity, enhance ecosystem resilience, and engage local communities, making them particularly suitable for mitigating the severity and frequency of extreme wildfires while supporting climate change adaptation. This holistic approach contributes to the development of fire-resilient landscapes and communities, reducing dependence on conventional firefighting methods that are often inadequate in the face of increasingly intense fire events.

Building on this foundation, several NbS emerge as promising candidates for mitigating EWE. These strategies share a set of cross-cutting features that align with the core principles of NbS: they leverage natural ecological processes to reduce wildfire hazard; aim to enhance ecosystem resilience rather than suppress natural disturbances; often provide co-benefits such as biodiversity conservation and rural livelihoods; and are most effective when embedded in participatory, locally adapted management frameworks. For instance, prescribed fire (i.e., the stra-

tegically planned and controlled use of fire under specific environmental conditions; see⁹) has proven effective in reducing wildfire hazard^{9–11} (see Table 1). Rewilding initiatives, such as the reintroduction of large herbivores, can also help maintain more heterogeneous and discontinuous vegetation structures, which may reduce the risk of intense fires under certain conditions.^{12,13} In the absence of natural processes like fire or large herbivores that control vegetation and, in turn, wildfire hazard, various proxies can be used to manage and mimic these ecological functions (Table 2). These include extensive agropastoralism, eco-friendly agriculture practices, and sustainable production systems for chestnuts and mushrooms, each contributing to reducing fire risk and enhancing ecosystem resilience.^{14,15} Implementing green firebreaks (i.e., vegetated strips with low-flammability species, also known as live fuel breaks) strategically in vulnerable areas can create fuel breaks and reduce landscape connectivity, thereby limiting the spread of wildfires.^{4,16} Moreover, land-use conversion to native and less flammable vegetation types (e.g., native woodlands) can contribute to reducing fire hazard in fire-prone areas, while also promoting biodiversity and ecosystem stability.¹⁷ Finally, adopting sustainable “fire-smart” forest management integrates fire-risk reduction with conservation goals, ensuring ecosystems remain resilient in the face of changing fire regimes.^{18–20} These NbS are grounded in scientific understanding and evidence, offering comprehensive approaches to tackling the challenges posed by extreme wildfires. However, they should be seen as candidate NbS, recognizing that their suitability and classification may vary depending on local fire regimes, landscape characteristics, and socio-economic contexts.

THE CHALLENGES AHEAD

NbS are designed as a response to a societal challenge that has been identified as a priority by all stakeholders directly affected by the challenge (IUCN criteria 1). EWEs often overwhelm firefighting capacities, making them difficult to control and requiring extensive coordination and resources. They exceed the current capacity of fire suppression systems, leading to large ecological and socioeconomic losses.²⁶ Examples include Australia’s Black Summer (2019–2020), California’s Camp Fire (2018) and Pedrógão Grande in Portugal (2017), and the Mati fire in Greece (2018), which—despite its relatively small extent—resulted in over 100 fatalities. These examples highlight the urgent need for new mechanisms to achieve more effective fire management. EWEs are characterized by their high intensity, rapid spread, and severe impact on both the environment and human communities.²⁶ These fires are often fueled by adverse weather conditions such as strong winds, high temperatures, and low humidity, which can lead to the transition from surface fires to crown fires and firestorms. These extreme events cause extensive damage to vegetation, soil, and wildlife, necessitate large-scale evacuations, destroy properties, and impair air quality, posing serious health risks. These impacts have been widely documented worldwide, from a wide spectrum of approaches covering different ecological, economic, and even psychological viewpoints.^{26–28}

However, the intrinsic complexity of the wildfire problem makes the identification of the societal challenges associated

Table 1. IUCN criteria and key points for implementing nature-based solutions (NbS) to extreme wildfire events (EWEs)

IUCN criterion for NbS	Key recommendations and aspects	Prescribed burning as NbS
Criterion 1. <i>NbS effectively address societal challenges.</i>	Acknowledge fire as an ecological process and learn from the traditional use of fire as a landscape management tool.	It recognizes fire as an ecological process, contributing to ecosystem health and addressing challenges like wildfire risk reduction ²¹
Criterion 2. <i>Design of NbS is informed by scale.</i>	Tailor NbS to site-specific needs and align them with global initiatives. Use local stakeholder perspectives and scenario planning to assess cost-effectiveness.	It can be designed considering local ecosystems, sector-specific needs, and global initiatives for fire management ⁹
Criterion 3. <i>NbS result in a net gain to biodiversity and ecosystem integrity.</i>	Incorporate spatial conservation prioritization into land-use planning, explicitly considering fire suppression policies in conservation planning.	Properly managed prescribed fire can improve habitat diversity and maintain ecosystems adapted to fire ²²
Criterion 4. <i>NbS are economically viable.</i>	Conduct comprehensive economic evaluations of NbS, identifying who pays and benefits, and consider alternative solutions and regulations.	Prescribed fire can be cost-effective in reducing wildfire risks and conserving ecosystem services, and create job opportunities in rural areas. ²³
Criterion 5. <i>NbS are based on inclusive, transparent, and empowering governance processes.</i>	Engage stakeholders through inclusive, transparent dialogue, mutual respect, and advocate for their needs to prevent marginalization.	Engaging stakeholders in prescribed fire planning respects local knowledge, covering their needs (see Box 1).
Criterion 6. <i>NbS equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits.</i>	Balance trade-offs by managing them over space and time, considering the benefits and costs of NbS to EWEs (including avoided damages on other ES).	Prescribed fire balances trade-offs by reducing fire risks while promoting ecosystem health and economic benefits. ²⁴
Criterion 7. <i>NbS are managed adaptively, based on evidence.</i>	Implement NbS adaptively based on evidence, monitoring for risks and impacts, and integrating burn severity and post-fire indicators.	Prescribed fire can adaptively respond to changing fire conditions, informed by monitoring and research. ²⁵
Criterion 8. <i>NbS are sustainable and mainstreamed within an appropriate jurisdictional context.</i>	Ensure the sustainability and integration of NbS within existing policy frameworks, seeking reforms and fostering stakeholder consensus through strategic communication and outreach.	Integrating prescribed fire into land management aligns with long-term sustainability and can be mainstreamed within existing policies and frameworks. ²¹

The third column illustrates how a candidate for NbS to EWEs (e.g., prescribed fire programs) can align with these eight criteria.

with this natural hazard context-specific, and not always straightforward. Globally, EWEs are being favored by climate change, which fosters extreme fire-weather situations under which these phenomena tend to occur.^{29,30} Nevertheless, the severity of a wildfire event is strongly influenced by the characteristics of the available fuels—a component of the “fire triangle” that directly determines fire spread and behavior.³¹ While fire spread is more closely linked to fuel structure and continuity, fire intensity is largely proportional to fuel load. This factor is critical and tightly related to the main socioeconomic activities of each region.

In this context, the lack of forest management, the abandonment of traditional agropastoral activities, “slash and burn” agriculture practices, or large-scale forestation programs—particularly those involving exotic, fast-growing and flammable tree species—are all contributing to the regional emergence of altered fire regimes worldwide.³² In addition, fire suppression policies have modified fire regimes in unexpected and counterintuitive ways by boosting the accumulation of fuel, making it difficult to identify drivers and, in turn, solutions to EWEs. Such suppression-based approaches, which aim to eliminate fire rather than

work with its ecological role, stand in direct contrast to the principles of NbS. In response to the ever-growing wildfire risk, governments react by increasing fire-fighting resources, which are very effective in suppressing wildfires under moderate fire-weather situations. However, this capacity is largely overwhelmed under extreme weather conditions, being ineffective at halting high-intensity fires.²⁶ Moreover, these policies have contributed to the marginalization of Indigenous fire governance, the erosion of traditional knowledge systems, violations of indigenous rights, and the increase in wildfire risk due to disrupted fire regimes.³³

Recognizing fire as an ecological process that has shaped ecosystems and species adaptations over evolutionary time is crucial for properly identifying the challenges associated with these extreme events.² In many fire-adapted ecosystems—such as Mediterranean shrublands, savannas, or certain coniferous forests—periodic fire plays a vital role in maintaining ecological structure, biodiversity, and function.³⁴ Without fire, these ecosystems may undergo vegetation shifts, fuel build-up, or even collapse, resulting in long-term social-ecological consequences. Importantly, reintroducing or maintaining natural “flows of fire”—particularly through both wildfires and

Table 2. A concise overview of the potential trade-offs (“pros” and “cons”) of candidate management options for NbS to EWEs, previous a more comprehensive evaluation of their viability and potential impacts

Candidate NbS	Main benefits (pros)	Challenges (cons)
The use of fire (“integrated fire management”)	Reduces fuel loads and wildfire severity (fire regulation services); maintains fire-adapted ecosystems; and supports rural employment	Risk of fire escape and liability; air quality and smoke concerns; and requires expertise and favorable social perception
Targeted grazing	Reduces fine fuels and promotes mosaic landscapes; combines fire prevention with food production; and supports rural livelihoods and cultural landscapes	Low profitability; labor-intensive and often lacks generational renewal; and requires shepherding infrastructure and incentives
Green firebreaks (low-flammability vegetated buffers)	Slow fire spread and reduce landscape connectivity; enhance biodiversity and habitat value; and aesthetically compatible with natural landscapes	Require ongoing maintenance; land acquisition or easement constraints; and may compete with other land uses
Biomass extraction for wood products (e.g. bioconstruction) and bioenergy	Reduces fuel loads while generating renewable energy; creates local jobs and circular economy benefits; and can support rural development	High upfront investment in infrastructure and risk of overharvesting or ecosystem degradation if not managed sustainably
Close-to-nature forestry/sustainable fire-smart forest management	Increases forest resilience to fire and climate change; long-term wood and energy production; and enhances biodiversity and ecological stability	Requires long-term planning and investment and need for skilled workforce and adapted silvicultural practices
Rewilding with large herbivores	Maintains open habitats and reduces fuel continuity and contributes to biodiversity conservation; cultural and eco-tourism potential	Low direct economic return; potential land-use conflicts; and limited scalability without social acceptance
Agropastoral systems and traditional crops (e.g., chestnuts, mushrooms)	Reduce landscape homogenization and fuel buildup and offer food provisioning, rural employment, and cultural heritage preservation	Dependent on market access and seasonality; competition with other land uses; and often lacks formal support or subsidies

prescribed burns—can also reduce the risk of EWE by managing fuel loads and continuity.^{35,36} It is therefore essential to acknowledge and learn from the traditional use of fire as a landscape management tool—often applied through small, patch-scale burns—to harness fire as a fundamental component within the NbS framework.^{3,37}

The NbS concept presented by the IUCN offers a framework to address the operational challenges and risks associated with these novel fire regimes.^{7,38} However, several barriers undermine the implementation of NbS (Table 3). One major challenge is the biased perception of fire among parts of society—particularly among more urbanized populations or certain interest groups—which hampers acceptance of fire-related NbS.³⁸ These biases often stem from the widespread framing of fire solely as a destructive force, reinforced by decades of fire suppression policies and media coverage of catastrophic wildfires. As a result, there is limited public and political support for proactive fire use—such as prescribed burning or cultural burning—despite its ecological and social benefits.²⁴ A second barrier is the erosion of traditional fire management knowledge among indigenous peoples and local communities (IPLCs), which limits the capacity to apply fire effectively and appropriately in contemporary land management. It is critical to recognize that this knowledge belongs to IPLCs, and any revitalization of cultural burning must be led by them, with full respect for their rights and knowledge sovereignty.³⁹ Many IPLCs also face unique vul-

nerabilities to large and high-intensity wildfires, particularly those living in remote, forested areas with limited financial or institutional support to mitigate wildfire risk. Upholding indigenous leadership in fire stewardship is essential to developing effective, equitable, and context-specific NbS initiatives.⁴⁰ Furthermore, the lack of expertise—partly due to the erosion of traditional fire knowledge among Indigenous and local communities—hampers the effective execution of NbS projects in some regions. In particular, a shortage of professionals with practical experience in prescribed burning, or with interdisciplinary training across forestry, agriculture, conservation, and social science, remains a challenge in many contexts.⁴¹ This gap is being addressed through initiatives such as the prescribed fire training exchanges (TREXs), which aim to build local capacity (see Box 1). Additionally, fragmentation across sectors and administrative boundaries further complicates coordinated action on NbS initiatives.

The absence of clear and supportive policies and legal frameworks tailored to fire-smart NbS exacerbates implementation challenges.⁸ In many fire-prone regions, the short-term nature of funding and political cycles undermines the continuity and effectiveness of NbS initiatives. For example, public lands managers in the southern region of the US identified limited budget as major institutional impediment to prescribed fire, in contrast to private individuals, more of whom chose liability as a key challenge.¹¹ In Australia, fire regulations and risk-averse

Table 3. Barriers to implementing nature-based solutions (NbSs) for extreme wildfire events (EWEs) and strategies to overcome them

Barrier	Strategies to overcome
Biased perception	Public awareness campaigns and Stakeholder engagement Education on benefits of NbS Highlight success stories and case studies
Lack of expertise	Collaborate with indigenous and traditional communities Revitalize traditional knowledge through partnerships Develop training programs and workshops
Shortage of skilled professionals	Invest in interdisciplinary education and training Create vocational programs and internships
Fragmentation across sectors and administrative boundaries	Establish inter-agency task forces Develop integrated management plans Improve communication channels between sectors
Absence of supportive policies	Advocate for policy reforms and incentives Engage policymakers and legislators Align regulations with NbS principles
Short-term funding and political cycles	Secure long-term funding commitments Foster political support for enduring NbS initiatives
Aligning regulations	Address regulatory gaps and inconsistencies Reform existing policies to support NbS Integrate NbS into legislative frameworks

governance structures have created administrative burdens that discourage the use of cultural burning by indigenous communities, despite its ecological and social benefits.⁴²

In southern Europe, overly strict environmental regulations and poor harmonization between forestry and agricultural policies often lead to delays or outright rejection of fire-based interventions, even when they are ecologically justified. These regulatory inconsistencies create confusion and limit the ability of land managers to act proactively in reducing wildfire risk. Moreover, the lack of payment schemes for ecosystem services (PESs) further undermines the potential of fire-smart NbS.⁴³ Farmers and rural landowners, who play a crucial role in maintaining mosaic landscapes that act as natural firebreaks, are rarely compensated for the fire regulation and prevention services their land management practices provide. This lack of recognition and economic incentive discourages active land stewardship and contributes—alongside broader social and economic drivers—to land abandonment, which in turn increases fuel continuity and wildfire risk across the landscape.

In Canada, indigenous communities provide a particularly stark example of institutional and financial barriers. Many of these communities are in remote, forested areas with a high accumulation of flammable biomass but face chronic underfunding and lack the institutional support needed to implement fuel

management strategies. Most are also heavily reliant on diesel for electricity, adding layers of energy insecurity and dependency on external supply chains. A recent study identified 33 such communities at high wildfire risk due to limited fire management and the absence of integrated, community-led strategies.⁴⁴ While fire-smart fuel treatments could simultaneously address energy needs and wildfire risk,^{45–47} the lack of stable investment, insufficient coordination between energy and wildfire policy, and limited inclusion of Indigenous leadership in decision-making processes remain key obstacles.

These barriers underscore the complexities unique to NbS implementation in wildfire management, necessitating targeted efforts to overcome these challenges and promote their adoption effectively. This perspective identifies key barriers to the implementation of NbS and provides strategies, initiatives, and actions to overcome these challenges. It outlines a roadmap for implementing NbS to address EWEs, emphasizing key steps for effective wildfire management and ecosystem resilience. This roadmap will assist policy- and decision-makers in steering toward socioecological systems that are more resilient to EWEs. Illustrated with examples and candidates for NbS to EWEs, it adheres to the global standards set by the International Union for the Conservation of Nature (IUCN 2020).

THE SOLUTION

Navigating policy intersections when implementing NbS

The design and implementation of NbS are shaped by scale—encompassing not only geographic and ecological dimensions but also institutional, economic, and cultural factors. In this regard, NbS to EWEs must align local stakeholder priorities with the broader context of the regional legislation and supranational policies across sectors potentially affected by wildfires (IUCN criteria 2) (see Figure 2). This multi-level governance context creates intersections—and sometimes frictions—between overlapping and competing policies objectives.⁴⁸ For instance, efforts under the European Green Deal to promote renewable energy and biodiversity conservation may clash with existing land-use practices or forest management regimes, creating administrative uncertainty or implementation bottlenecks. Fire-smart NbS require coordinated action across sectors and levels of governance to reconcile such policy tensions and ensure coherent implementation. Sustainable forest management offers a compelling example of this challenge. When properly aligned with policy objectives, it can simultaneously reduce wildfire hazard, contribute to carbon sequestration and climate regulation, and provide economic returns through biomass extraction for renewable energy^{44–46} (see Table 2). However, if poorly coordinated, these overlapping goals can result in regulatory contradictions or fragmented incentives. Recognizing and addressing these institutional and policy-level barriers is crucial to advancing the systemic integration of NbS for wildfire resilience. A promising example of recent policy innovation can be found in Brazil, which in 2024 passed law no. 14,944/2024, establishing the country's first national policy for integrated fire management. This legislation represents a significant shift from a suppression-based paradigm toward one that recognizes the ecological role of fire in fire-adapted ecosystems. It explicitly supports the use of

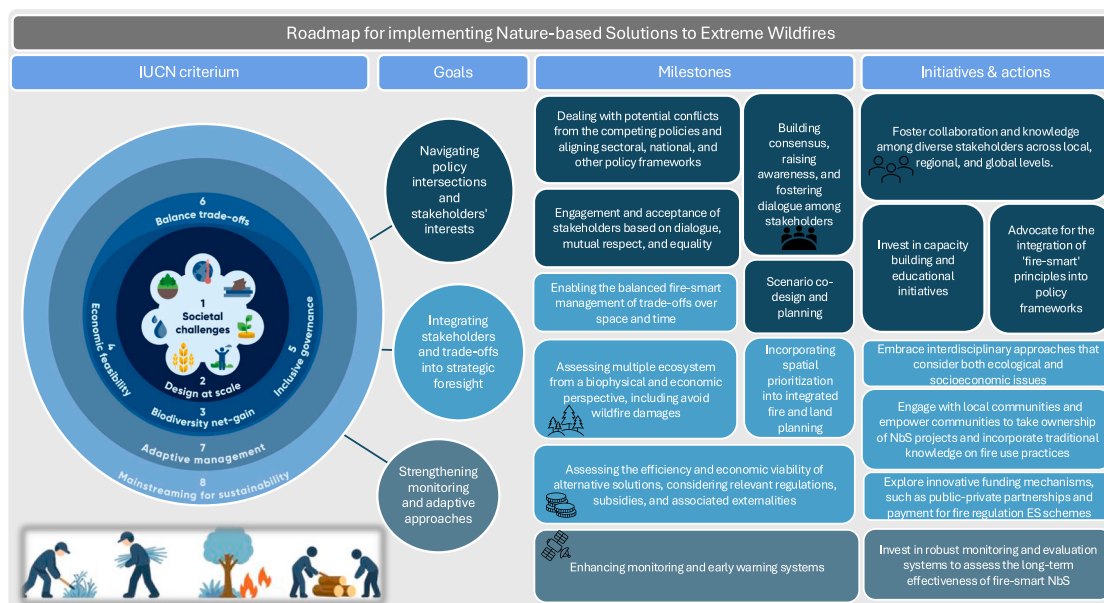


Figure 2. Roadmap for implementing nature-based solutions to extreme wildfires

The diagram illustrates the main goals or objectives to address, along with the milestones and potential initiatives and actions required to achieve these goals.

controlled burning by Indigenous and traditional communities, incorporating ancestral knowledge into modern governance frameworks. The law also promotes the development of local fire brigades and supports community-based strategies to manage wildfire risk. Brazil's integrated approach offers a compelling model for aligning national fire governance with NbS, highlighting how policy reform can create enabling conditions for the use of fire as a tool for ecological restoration and wildfire resilience.

Conflicts among local stakeholders are expected to appear due to legitimate claims and particular sectorial needs.⁸ NbS must come up with an inclusive, transparent, and empowering governance process (IUCN criteria 5). This implies an adequate engagement and acceptance of stakeholders based on dialogue, mutual respect, and equality.^{38,49} In the case of wildfires, this issue is particularly important since local communities and indigenous people have used fire as a management tool (e.g., pastures, agricultural, and forestry uses) for millennia.⁵⁰ Local stakeholders, who are directly and indirectly affected by the NbS, must be identified and engaged to actively participate in the design and implementation, advocate clearly to uphold their own needs and demands, and prevent further marginalization (see [Box 1](#)).

In Portugal, the ICNF (*Instituto da Conservação da Natureza e das Florestas*) started in 2017 a program oriented to shepherds aimed at covering the needs of pasture renewal for livestock. Shepherds often use fire during winter to renew pastures⁵¹—illegal actions under the current legislation—being stigmatized by a part of the society, mostly detached from the needs of rural communities. The program entails the active involvement of local shepherds and landowners, working in collaboration with fire experts. The prescribed fires are strategically implemented in areas that are prioritized based on the specific requirements and needs of the shepherds.

Other innovative programs have successfully involved local communities such as shepherds: [FireShepherds](#) is an educational training program that started at the beginning of 2019 in Spain with the aim to prepare next generations of shepherds in the management of extensive livestock with wildfire prevention purposes. Training courses for shepherds are key actions of the program that aims to achieve a fire resilient landscape, simultaneously facing the long-standing decrease of shepherds working with livestock in extensive regime.

Another exemplary case is the TREX—a collaborative initiative designed to provide training and hands-on experience in the use of prescribed fire as a land management tool. TREX programs typically bring together a diverse group of participants, including land managers, firefighters, conservationists, scientists, and other stakeholders, to learn about and practice controlled or prescribed burns in a safe and controlled environment. The training exchange concept was developed within the [Fire Learning Network](#), supported through a cooperative agreement between the USDA Forest Service and The Nature Conservancy called "[Promoting Ecosystem Resilience and Fire Adapted Communities Together](#)."

NbS interventions must be designed and managed in a long-term perspective, aligning with sectoral, national, and other policy frameworks (IUCN criteria 8). While NbS are increasingly being recognized and supported through policy initiatives at various governance levels, fire-specific NbS often lack clear integration within these frameworks, particularly in relation to wildfire prevention, mitigation, and resilience. The successful implementation of NbS is contingent upon navigating through a complex and often fragmented policy landscape, where environmental, forestry, agricultural, and energy policies may not be harmonized (see [Figure 2](#)). This lack of coherence can lead to administrative bottlenecks or even unintended negative outcomes, such as the degradation of ecosystem functions or reduced landscape resilience.

Box 1. Capacity-building and educational training programs

To address these hurdles, it is crucial to adopt a proactive approach that encompasses two essential components. Firstly, stakeholders must be cognizant of the limitations imposed by existing policy, regulatory, and legal frameworks. Recognizing these constraints allows for a realistic assessment of the scope and feasibility of NbS interventions within the prevailing governance landscape. Secondly, collaboration with local and/or national decision-makers, as well as other key stakeholders, becomes vital. By engaging with these influential actors, the obstacles arising from inconsistent policies and regulations can be highlighted and effectively addressed. This entails advocating for necessary changes, seeking policy reforms, and identifying enabling solutions that can facilitate the implementation of NbS interventions. Highlighting the benefits of fire-smart strategies in contributing to climate, biodiversity, and energy goals can create openings for policy alignment and multisectoral collaboration.^{44,48,52,53}

Through such collaborative efforts, it becomes possible to bridge the gap between policy realities and the requirements for successful NbS implementation at regional scales. By building consensus, raising awareness, and fostering dialogue among stakeholders, a more conducive environment can be created for NbS initiatives to thrive. NbS to EWEs can make significant contributions to national economic, social, and conservation targets and help achieve national commitments to international processes on climate change, human rights, human development, and biodiversity. Making these linkages

explicit, documenting and communicating them, help further reinforce the profile and role of NbS nationally, and secure broad-based and durable political commitment as well as societal support, thereby enhancing the long-term sustainability of the intervention. In this regard, strategic communication and outreach approaches are critical to trigger transformative change.

Integrating trade-offs and strategic foresight into NbS

All stakeholders must acknowledge and understand the potential costs and benefits associated with the inevitable trade-offs involved in each NbS intervention (IUCN criteria 6, [Figure 2](#)). To achieve this, a fair, transparent, and inclusive process must be implemented, enabling the balanced management of trade-offs over space and time^{54–56} (see [Table 2](#)). Furthermore, this process should incorporate negotiations and compensations among the parties affected by any damage or trade-off, ensuring the long-term effectiveness of NbS outcomes.

In the context of wildfire-related NbS, certain trade-offs and synergies are frequently observed. For instance, there is a well-documented tension between climate regulation goals and wildfire risk: afforestation or dense tree planting for carbon sequestration may inadvertently increase fuel loads and fire hazard if not carefully managed.^{57,58} Similarly, prioritizing timber production can conflict with the need for fuel reduction, particularly when short-rotation plantations replace more fire-resilient or biodiverse landscapes.^{59,60} Conversely, synergies can be

achieved through silvicultural practices rooted in close-to-nature forest management, which aim to balance wildfire mitigation, biodiversity conservation, and climate benefits.⁵⁵ The integration of fire-smart biomass extraction for bioenergy can further enhance this synergy by providing renewable energy while reducing landscape flammability.^{44–46}

To illustrate the significance of these dynamics, let us envision a hypothetical scenario set in a marginalized mountainous region profoundly affected by both rural depopulation and frequent wildfire occurrences. In such areas, the viability of solutions such as extensive agropastoral practices is severely limited by the absence of active land managers. Therefore, any NbS based on traditional land use must be accompanied by broader social policies—such as incentives for rural repopulation, investments in infrastructure and services, and long-term financial support for young farmers and shepherds. In this scenario, we contemplate the possibility of incentivizing extensive agropastoral practices through financial regulations and subsidies, which compensate landowners for the mitigated damages caused by wildfires on various ecosystem services. These services may encompass climate regulation functions, quantified by carbon sequestration metrics, fire regulation capacities measured by the reduction in burnt areas, as well as recreational and cultural services like birdwatching and gastronomic tourism. The valuation of these diverse ecosystem services, in terms of the economic benefits derived from averting wildfire-induced costs, would serve as supplementary incentives for landowners, increasing the traditional outcomes associated with food and timber production.^{43,61} Such a scenario could potentially support traditional agroforestry and pastoral activities in regions where their viability has been compromised from a socioeconomic perspective¹⁵ (see Table 2). Importantly, this approach intertwines closely with the dynamics of wildfire incidence and behavior, ultimately portraying a potential NbS for EWEs within marginal mountainous areas.²⁰

In an alternative scenario where rural development and agricultural policies fail to reverse land abandonment trends, rewilding initiatives could emerge as NbS to address climate change and biodiversity conservation⁶² (see animation video from the [FirESmart project](#)). However, it is important to consider the impact of such NbS on the most vulnerable and marginalized stakeholder groups, such as local shepherds and farmers. Failing to provide them with a cost-effective alternative, such as a prescribed burning program to maintain pastures (see Box 1) or economic incentives for local agricultural products, would result in clear repercussions.

In this sense, strategic foresight approaches based on local stakeholders' perspectives and scenario planning become powerful tools to assess the cost-effectiveness and impacts of alternative NbS to EWEs (see Box 2). The development of modeling platforms wherein multiple ecosystem services can be simultaneously evaluated from a biophysical and economic perspective should be part of the toolkit of land managers to support more evidence-based decision-making (see e.g., [LandTender](#)). Transfer knowledge and capacity building are critical steps in this regard to ensure innovative NbS can be incorporated into decision-making and management plans ([Figure 2](#)).

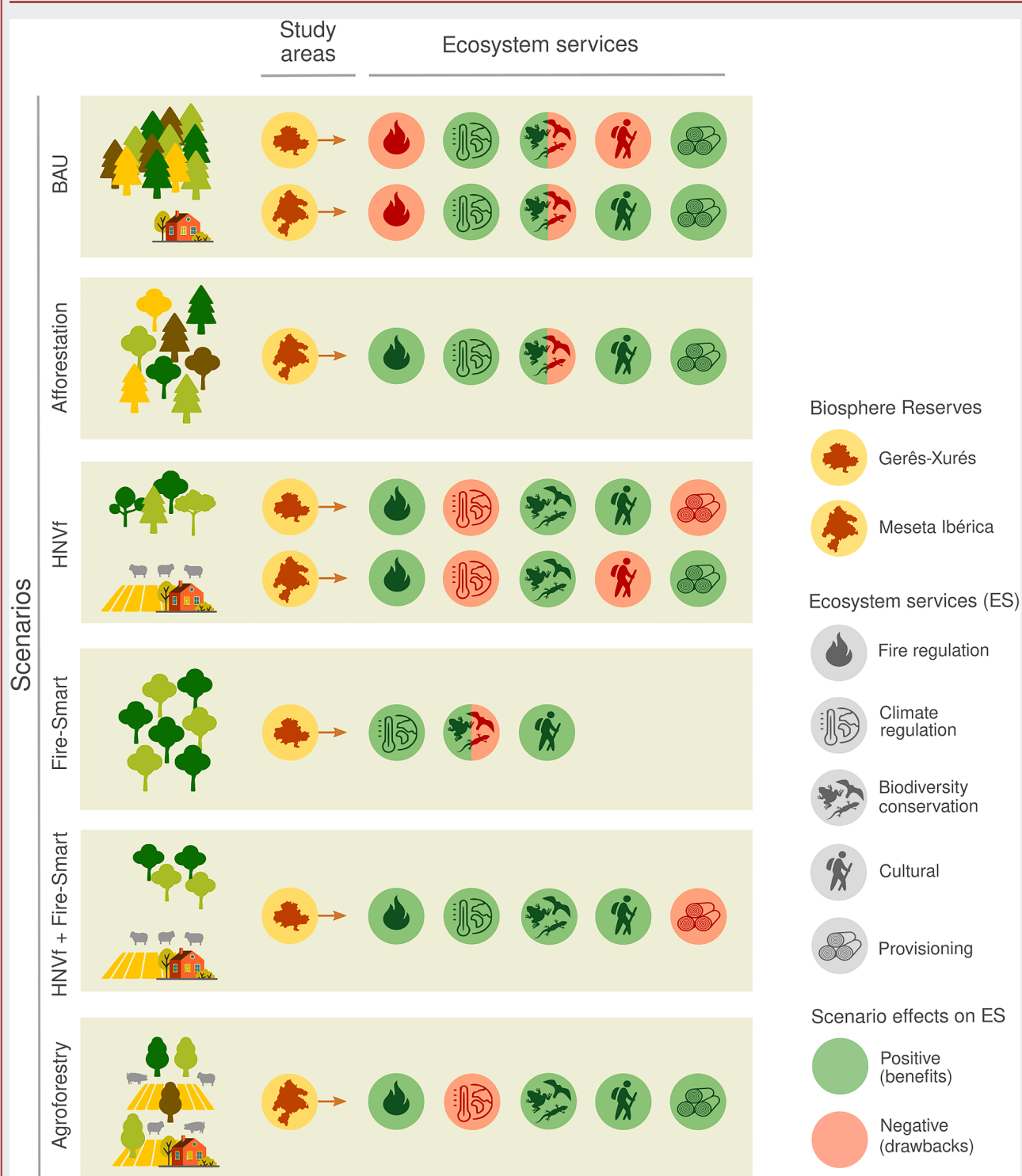
The [FirESmart project](#), funded by the Portuguese government after the dramatic events caused by EWEs of 2017, assessed the impacts of alternative land management scenarios on wildfire protection while accounting for climate regulation services, food/wood provisioning, cultural/recreational services, and biodiversity conservation for the transboundary biosphere reserve “Gerês-Xurés” and “Meseta Iberica”, both located in NW Iberia. Six plausible land-use scenarios were simulated in collaboration with local stakeholders³⁸: (1) “business-as-usual” scenario describes the current trend of land abandonment; (2) “afforestation” aims to boost forested areas through “tree planting” and forest restoration; (3) “high nature value farmland” (HNvf) represents a policy promoting traditional agricultural activities; (4) “fire-smart” scenarios aim to create landscapes more resistant to wildfire; (5) “HNvf plus Fire-smart” combines these two policies; and (6) “agroforestry recovery” focuses on replacing highly flammable areas with mixed systems of agropastoral and agroforestry activities (infographic extracted under the CC BY-NC-ND License²⁰).

Furthermore, in accordance with IUCN criteria 3, the design and implementation of an NbS cannot impact ecosystem integrity and should proactively enhance ecosystem functionality to ensure the long-term resilience and persistence of such NbS. This requires the establishment of specific conservation targets that can be monitored over space and time to ensure adaptive management. For instance, changes in fire regimes—either through intensification, suppression, or altered seasonality—is a threat for at least 15% (4,403) of species threatened with extinction according to the IUCN Red List.⁶³ However, fire is also a vital ecological process for many ecosystems, especially in fire-adapted landscapes, where it sustains the life cycles of fire-dependent species and helps maintain habitat heterogeneity.⁶⁴ This apparent contradiction underscores the importance of designing NbS that support context-specific fire regimes—not suppressing fire altogether but using it strategically to reduce extreme wildfire risk while conserving biodiversity. Moreover, under accelerating climate change, some ecosystems—historically fire-sensitive—are transitioning into more fire-prone landscapes. In these cases, NbS can help navigate ecological transformations rather than resist them, supporting ecosystem reconfiguration while minimizing biodiversity loss.⁶⁵ This requires integrating projected fire regime shifts into NbS planning and management frameworks.

Evidence is emerging on the biodiversity impacts of fire-smart NbS interventions, including benefits from mosaic landscapes created through controlled burning or agro-silvopastoral practices.^{66,67} However, long-term, multi-taxa monitoring is needed to fully assess the trade-offs and co-benefits of these strategies.⁶⁸ Integrating conservation planning with fire-smart land management, including the use of spatial prioritization tools, will help optimize NbS for both wildfire prevention and biodiversity outcomes, especially in protected and high-risk areas.^{48,56}

According to IUCN criteria 4, NbS must be economically viable, which implies a thorough consideration of economic feasibility to ensure long-term success in implementation ([Table 2](#)). This aspect is particularly crucial in complex socioecological systems prone to extreme wildfires. In 2017, more than one hundred people died in Portugal due to large fires that overtook firefighting capabilities and caused losses of 1.5 million €. Significant financial resources, amounting to billions of euros,

Box 2. Trade-offs among ecosystem services under alternative management scenarios



The case of two Transboundary Biosphere Reserves in NW Iberia—the FirESmart project.

have been allocated to wildfire suppression, with an annual expenditure of approximately 2,500 million euros recorded in the Mediterranean basin in recent years.⁶⁹ Despite these high suppression costs, preventive approaches, such as NbS, receive limited and often short-term funding. It is essential to recognize that effective fuel management—such as prescribed burning, agro-silvopastoral systems, or green firebreaks—can preserve a wide range of ecosystem services (e.g., carbon sequestration, soil stability, cultural heritage) that contribute to long-term economic resilience. Yet, these benefits are rarely accounted for in cost-benefit assessment.

To better understand economic viability, a comprehensive economic evaluation of each NbS concerning EWEs should encompass an exhaustive analysis of both the direct and indirect economic implications, covering a diverse spectrum of ecosystem services.⁴³ It should also clearly identify who pays and benefits from the implementation of such a management option, and over what time frame.⁴⁹ For example, agropastoral systems may require short-term subsidies but become self-sustaining with PES schemes or income from specialty products (e.g., chestnuts, sheep cheese). Close-to-nature forestry practices may not yield immediate returns but improve long-term wood quality and reduce fire suppression needs. Subsidy levels and support mechanisms also differ by region. In Europe, programs under the common agricultural policy (CAP) could co-finance fire-smart land uses, while in the US, initiatives like the Joint Chiefs' Landscape Restoration Partnership provide funding for prescribed fire and forest restoration. At the local scale, municipalities or utility companies (e.g., water providers) can also fund fire prevention through PES, recognizing their dependence on ecosystem services maintained by fuel management. Emerging carbon markets also offer new opportunities to finance NbS by rewarding carbon storage and avoided emissions—particularly through actions such as maintaining peatlands, promoting extensive grazing in wet grasslands, or planting fire-resilient native tree species in strategic areas. These interventions not only reduce fuel loads and fire risk but also contribute to climate mitigation goals. Additionally, the insurance sector can play a key role in promoting and de-risking NbS implementation by linking reduced wildfire risk to lower premiums and by supporting risk-transfer mechanisms that reward proactive landscape management.⁷⁰

In this regard, conducting a thorough analysis of the cost-effectiveness associated with each fire management strategy becomes essential. Such an analysis would play a pivotal role in determining the efficiency and economic viability of various approaches, ultimately aiding in the informed decision-making process that favors NbS. Such analysis must be tested against alternative solutions, considering relevant regulations, subsidies, and associated externalities. Scenario co-design and planning, metamodeling development, and cutting-edge economic tools are intended to co-evolve together to successfully address this critical but challenging task (Figure 2).

Strengthening monitoring and early warning systems for enhanced NbS

A robust monitoring and evaluation plan is indispensable for assessing the effectiveness of the NbS strategy in achieving its intended outcomes and addressing the societal challenge at hand.

It is crucial to identify whether any risks or unexpected impacts arise during implementation that necessitate a change in strategy or action. A proactive and adaptive approach is vital in this regard (IUCN criteria 7). Additionally, iterative learning plays a pivotal role in informing adaptive management actions, enabling a response to the factors influencing NbS interventions. The continuous feedback provided by both monitoring and evaluation plans is essential for learning and adapting the NbS intervention.

In this context, enhanced monitoring and early warning systems are critical not only for anticipating fire risk but also for guiding post-fire responses. For example, wildfire early warning platforms, such as the European Forest Fire Information System, provide real-time fire danger assessments using remote sensing, fuel moisture models, and meteorological data. These tools support early action and emergency planning. However, to fully support fire-smart NbS, these systems should be further developed to integrate fire-vegetation interactions, such as fuel accumulation, vegetation recovery rates, and ecosystem flammability.^{71,72} Incorporating these ecological dynamics would allow for more holistic forecasting and support adaptive restoration strategies after wildfires.

This is especially relevant in Europe, where post-fire management is expected to become a key priority under the new EU Nature Restoration Law (regulation [EU] 2024/1991). The regulation emphasizes the importance of implementing effective strategies for restoring ecosystems, including those impacted by wildfires. In this context, remote sensing technologies and Earth observation products—such as satellite-based burn severity indices or vegetation productivity time series—offer powerful tools for assessing the impacts of fire on key ecosystem functions like carbon cycling and surface-energy balance.⁷³ Together, improved modeling and monitoring frameworks will strengthen the role of NbS in promoting resilience throughout the entire fire regime.

Furthermore, incorporating burn severity and post-fire recovery indicators into monitoring frameworks enhances NbS effectiveness—particularly when embedded within adaptive management processes that use monitoring results to adjust strategies and actions over time. However, to comprehensively assess their impact on EWE reduction, indicators should not be limited to the post-fire response of vegetation. A broader suite of indicators—covering both ecological and social dimensions—should be considered. These may include changes in soil erosion, water quality, fuel structure, biodiversity, and hydrological functioning, as well as human perception of fire risk, community engagement, and land-use management. Developing such targeted indicators allows for the identification of specific system components affected by NbS, helping to clarify potential trade-offs and synergies. This proactive and holistic approach supports prevention, preparedness, and adaptation to wildfire events, ultimately promoting ecosystem resilience and sustainability.

OUTLOOK

Moving forward, the integration of a “fire-smart” perspective within the framework of NbS presents a promising avenue for addressing the escalating challenges posed by extreme

wildfire events. To action this proposed solution effectively, the research, policy, and practitioner communities should prioritize five key steps.

- 1) **Knowledge exchange, capacity building and interdisciplinary collaboration:** foster knowledge sharing and collaboration at local, regional, and global levels. Facilitate platforms for exchanging best practices, lessons learned, and innovative approaches to wildfire management within the NbS framework. This should include collaboration among scientists, policymakers, land managers, local communities, and other rightsholders. Embracing interdisciplinary approaches that consider both ecological and socio-economic factors is essential for developing effective and context-specific strategies (e.g., the [Fire-Adapt](#) project, funded by the EU Marie Skłodowska-Curie Actions Staff Exchanges 2021). Invest in capacity building and educational initiatives to enhance understanding and awareness of “fire-smart” management practices. Provide training opportunities for policymakers, land managers, and community members to equip them with the knowledge and skills needed to implement effective NbS approaches (e.g., prescribed fire training exchanges, [TREX programs](#)).
- 2) **Policy integration and advocacy:** advocate for the integration of “fire-smart” principles into national and international policy frameworks. Lobby for policy changes that support the implementation of NbS for EWEs, emphasizing the importance of inclusive governance processes and transparent decision-making (e.g., [FireSmart Canada](#)).
- 3) **Recognition, engagement, and support for indigenous peoples:** recognize indigenous peoples as rightsholders with distinct governance roles and rights. Ensure NbS initiatives support their autonomy and provide the necessary resources and conditions for them to lead or participate meaningfully in wildfire management if aligned with their own goals. This includes supporting the revitalization and use of traditional knowledge systems, where desired, and respecting their leadership in shaping fire-adapted landscapes.
- 4) **Financial support and incentives:** allocate financial resources and provide incentives to support the implementation of NbS for EWEs. Explore innovative funding mechanisms, such as public-private partnerships and payment for ecosystem services schemes, to incentivize sustainable wildfire management practices.
- 5) **Research, monitoring, and adaptive management:** prioritize research efforts aimed at further understanding the ecological, socioeconomic, and cultural dimensions of EWEs and their management. Invest in robust monitoring and evaluation systems to assess the effectiveness of NbS interventions and adapt management strategies based on real-time data and feedback.

By taking these actions, the research and policy community can effectively translate the principles outlined in this article into tangible solutions for mitigating the impact of EWEs and promoting resilience in society and ecosystems. Together, we can

harness the power of NbS to address the complex challenges posed by extreme wildfires and secure a sustainable future for generations to come.

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AUTHOR CONTRIBUTIONS

Conceptualization, methodology, formal analysis, investigation, visualization, writing – original draft, and writing – review & editing, R.A.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author used with caution Chat-GPT 3.5 in order to improve language and readability of some paragraphs. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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