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Nature-based Solutions to address forest disturbances under climate change: the case of fire and pests

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Summary

In a context of global change, European forests are facing increasing pressure related to the evolution of their climate and economic exploitation conditions. In this context, this report focuses on two types of climate-related disturbances that are becoming increasingly destructive: wildfires and pest outbreaks. We explore how Nature-based Solutions (NbS) can be applied in forested landscapes to reduce wildfire and pest outbreak risks, but also to improve the resilience of forests and support their recovery after such disturbances. Recognizing that the NbS approach in a forest context can still have unclear conceptual boundaries, we rely on current definitions and criteria (mainly from IUCN and the European Commission) and on existing scientific literature to present relevant examples of NbS targeting three main situations: pre-fire, post-fire, and pest outbreak. This literature review is complemented with case studies analysed under a biophysical, socio-economic, and governance lens, with the aim of identifying favourable factors for replication or scalability. The report discusses commonalities and divergences in conditions and strategies for NbS implementation across case studies, and identifies key learning points and remaining challenges.

Keywords: 'Nature-based Solutions' 'climate adaptation' 'fire-risk management' 'post-fire management' 'pest management' 'wildfire' 'resilient forests' 'Europe'

Introduction

In the past years (2021-2023), the European Topic Centre on Climate change Adaptation and LULUCF (ETC-CA) investigated the potential of Nature-Based Solutions (NbS) to address climate change adaptation and disaster risk reduction. Following the EEA scoping paper about NbS policy knowledge and practice (EEA, 2021), a concise overview of available NbS assessment frameworks based on literature and practical cases was described in a first ETC-CA report (Veerkamp et al., 2021) together with the identification of key elements for designing and implementing NbS assessments. In 2022, the scaling potential of selected case studies where NbS have been implemented was discussed, leading to a framework where socio-economic and geophysical aspects are seen as critical for defining the scaling roadmap of each case (Martire, et al., 2022). More recently, in 2023, the focus moved to reflect on socio-economic enabling conditions for NbS scaling (Breil et al., 2023), with particular emphasis on the importance of the distribution of costs and benefits among private, public actors, and society as a whole.

NbS as climate change adaptation solutions in forestry are not as well-known and have not been specifically addressed by EEA and ETC-CA assessment reports so far. The use of NbS concepts has not yet been fully mainstreamed in forest adaptation strategies; as a result, while some foresters apply forest management practices that are aligned with the definition of NbS, they do not always use the NbS terminology. Some foresters also state that working with forests is intrinsically working with NbS, arguing that they make minimal use of fertilizers and chemical pest management. However, as presented in this report, NbS go way beyond this definition, involving multiple management perspectives, from tree species and age management to landscape approaches (Springgay, 2019).

As part of the EU Green Deal and the EU Forest Strategy for 2030, actions to increase the resilience of forests to climate change are highly encouraged. These actions should enhance the socio-economic functions of forests within the limits of sustainability; protect, restore and enlarge forest ecosystems; and improve monitoring and reporting frameworks. They should contribute to achieving the EU's climate commitments and the objectives of the binding LULUCF regulation that strengthens the link between climate mitigation, adaptation and environmental protection measures. In addition to these frameworks, the recently adopted EU Nature Restoration Law provides further encouragement for the use of NbS to improve risk reduction and protection from natural hazards and disasters (EU, 2024).

Building on above-mentioned policy frameworks and on literature describing the potential of NbS for climate change adaptation and disaster risk reduction, this report addresses two climate change impacts that can be mitigated by NbS in forests: wildfires and pest outbreaks. These two issues are increasingly causing economic losses, ecosystem disruption (leading to loss of services), as well as degradations of LULUCF contribution capacities to climate change mitigation. In addition, wildfires represent a severe threat to human lives.

The way NbS are used to mitigate climate change induced disturbances such as wildfires and pest outbreaks are three-fold:

1. Wildfire risk management. Key to wildfire risk management is the reduction of fuel in the forest: fire management starts with understanding forest processes and forest management. Ways to do this comprise grazing, agroforestry, fuel removal and prescribed fires.

2. Post-fire management. Key to post-fire management is the reduction of landscape connectivity and fuel continuity; improving water infiltration capacities of the soil and the reduction of overland flow to restore the vegetation and functions of the land; as well as landscape and vegetation restoration.

3. Forest pests. Key to pest-management is tree species diversification and biological pest control.

This report builds upon a literature review and a selection of case studies about NbS implemented in forests to address fire risk and pest outbreaks in relation to climate change.

A first objective of this report is to provide an overview of existing NbS for preventing and managing fire risk, for recovering after large wildfires have occurred, and for managing the risk of forest pest outbreaks, all based on a literature review. A second objective is to present a set of case studies where NbS are implemented for fire and pest related threats, to learn from practical experiences. A third objective of the report is to explore governance settings that can promote NbS in privately owned forests. And finally, lessons learned are discussed that show the replication and scaling potential of NbS by considering biophysical, socioeconomic and governance aspects.


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1 Nature-based solutions and forests – Context, concepts, and definitions

Nature-based solutions are defined by the IUCN 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". (IUCN, 2016; Cohen-Shacham, 2016; IUCN, 2020). They are also defined by EU institutions as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions. Nature-based solutions must therefore benefit biodiversity and support the delivery of a range of ecosystem services" (EC, 2021b). These two definitions are mostly aligned; however, while the IUCN definition emphasizes natural or modified ecosystems, the European Commission admits the possibility of including artificially created systems (e.g. recreated wetlands) as a type of NbS (UNDRR, 2021).

NbS approaches can be implemented in three categories: (i) minimum or no intervention, close to the nature protection concept; (ii) management approaches, involving limited interventions; (iii) extensive and intrusive ecosystem management, including creating new ones (Eggermont et al., 2015; FAO, 2023).

The IUCN NbS Standard provides the following criteria (IUCN, 2020):

- Criterion 1. NbS effectively address societal challenges.
- Criterion 2. Design of NbS is informed by scale.
- Criterion 3. NbS result in a net gain to biodiversity and ecosystem integrity.
- Criterion 4. NbS are economically viable.
- Criterion 5. NbS are based on inclusive, transparent, and empowering governance processes.
- Criterion 6. NbS equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits.
- Criterion 7. NbS are managed adaptively, based on evidence.
- Criterion 8. NbS are sustainable and mainstreamed within an appropriate jurisdictional context.

Due to their role as carbon sinks, and to the multiple other ecosystem services they can provide, forests are sometimes described as a "nature-based solution" per se as part of climate mitigation or climate adaptation strategies. However, not all forests have high levels of biodiversity, nor do they all provide significant ecosystem services – this is only partially the case in monoculture forests. Furthermore, forests are also directly impacted by climate change and need to adapt to increasingly severe disturbances (extreme heat and droughts, storms, fires, native and imported pests and pathogens), that compromise their capacity to sustain multiple ecosystem services (Larsen et al., 2022; Lecina-Diaz et al., 2023). Forestry as an activity is itself subject to impacts from climate change. In this context, applying NbS can help mitigating forest damages and losses.

In general terms, natural forest ecosystems owe their robustness to long-term adaptation to regional and local conditions, their resistance and resilience relying mainly on structural, functional and genetic diversity. However, studies highlight that a widespread focus on wood production in previous centuries has resulted in a simplification and homogenization of European forests in many regions (Larsen et al., 2022). This has weakened the natural robustness of the forests, which is further challenged by global change. Mixed forests tend to be more resistant to various disturbances than single-species planted forests (Jactel et al., 2017). Compared with 'natural forests' or mixed-species forests, planted forests usually have a lower level of biodiversity (e.g. Barlow et al., 2007; Brockerhoff et al., 2017), and it is likely that their ability to provide certain ecosystem services is reduced. These relationships between forest type, biodiversity and ecosystem services are highly relevant for informing forest policy and management (Brockerhoff et al., 2017) including NbS implementation.

In that context, the Nature-Based Solutions framework provides an interesting lens for the design and assessment of forest wildfire and pest control strategies. The IUCN standard (IUCN, 2020) has been used in scientific literature to analyse measures ranging from agroforestry to rewilding (Lecina-Diaz et al., 2023). However, NbS approaches have not yet been fully mainstreamed into management practices and policymaking, resulting in remaining challenges for funding and deployment at scale (Smeenk et al., 2024). Furthermore, NbS concepts have not yet been fully adopted by forest practitioners; as a result, while some foresters apply forest management practices that are aligned with the definition of NbS, they do not always use the NbS terminology. In grey and scientific literature, it is not uncommon to encounter descriptions of forest and landscape management practices that, while not being explicitly named as NbS, actually match this definition. This is the case for instance in a recent OECD report describing forest fire management strategies in Portugal (OECD, 2023a).

In the context of this report, we do not consider forests as NbS per se, but rather we look at NbS as solutions inspired or supported by nature, in line with the IUCN and EU definitions, that can be applied in managed forests or forested landscapes to support their adaptation to disturbances, with a focus on wildfires and pest outbreaks. For example, Nature-Based Forest Management (NBFM) or "Closer-to-Nature Forest Management" is considered among the most prominent NbS (UNEP and IUCN, 2021) to adapt future forests to global change pressures and ensure their ecosystem service provisioning (Larsen et al., 2022). EFI defines "Closer-to-Nature Forest Management" as an overarching "umbrella" covering all approaches and terminologies which support biodiversity, resilience, and climate adaptation in managed forests and forested landscapes. In this report, we explore several forest fire and pest management solutions that can be positioned under the Closer-to-Nature Forest Management umbrella, as well as a range of NbS applying both within and beyond forest "borders". Such measures, acting on the interfaces between forests and other types of landscapes (urban areas, agricultural land such as grassland or cropland, river basins, abandoned land) are key to developing integrated landscape approaches for the prevention and reduction of climate change impact on forests.

2 Methodology

The methodology for this task comprises of 3 steps:

1. LITERATURE REVIEWS

i. Wildfire risk management: A review of literature on wildfire risk reduction options was done. The literature review shows the clear distinction between NbS and non-NbS and gives an overview of existing practices. Each practice was evaluated based on feasibility for different areas of Europe and challenges (from a socio-economic and cultural viewpoint). Lastly, trade-offs for ecosystem services were considered.
ii. Post-fire management: An evaluation was made on the current knowledge related to the effects of the implementation of post-fire management practices that can be classified as NbS.
iii. Forest pests: A literature review was made, and existing NbS for this purpose were identified.
iv. Socio-economic barriers and enablers for the upscaling of NbS in forest management were investigated, to present key factors for the wider adoption of NbS for forest fire and pest management in Europe related to governance, ownership, and socio-economic benefits.

2. CASE STUDIES IDENTIFICATION

Case studies of practical implementation of NbS used to address fire and pest risks in European forests were identified.
This activity started from the forest management case studies available and in the process of publication in Climate-ADAPT, the key European reference platform for knowledge on climate change adaptation, as

recognized by the 2021 EU Adaptation Strategy (EC, 2021a). Climate-ADAPT case studies[1] showcase implemented adaptation options and initiatives to create and improve the enabling conditions for adaptation at all governance scales. By March 2023, Climate-ADAPT included 13 case studies related to climate change adaptation in forests. However, only one of them ("Building fire resilience using recycled water in Riba-Roja de Túria, Spain") directly addresses fire risks with NbS and none dealt with pest management. Two other case studies (Sustainable forestry for increasing climate change resilience in Soria, Spain, and Pest management in North Rhine Westphalia Germany) were available as draft versions and their publication on Climate-ADAPT was not completed.

Other resources were then explored, including the previous EEA/ETC-CA assessment reports and exchanges with Forest Europe[2].

The selection of case studies was made with the objective of covering:

- Different forest ecosystems: production forests (wood and non-wood products) and non-production forests (conservation sites).
- Different geographical distribution: Northern Europe and Southern Europe.
- Different climate hazards: fire prevention, post-fire management, pest outbreaks.

3. ANALYSIS OF CASE STUDIES

Eight case studies were finally selected and analysed to understand what types of NbS have been implemented, what climate risks have been faced, and what are the key factors (biophysical, governance and socio-economic) constraining the replication and upscaling potential of tested solutions. Semi-structured interviews with case study reference contacts (project leaders, responsible authorities) were conducted to gather this information, complementing information available in scientific literature or project deliverables. The results of this activity contributed to feeding the Climate-ADAPT platform with the delivery of 2 new case studies published in June and August 2024 and the update of one existing case study[3].

[1] https://climate-adapt.eea.europa.eu/en/knowledge/tools/case-study-explorer.

[2] Forest Europe is a Pan-European voluntary high-level forest policy process, that support the development of common strategies for the 46 signatories (45 European countries and the EU) on how to protect and sustainably manage forests. https://foresteurope.org/, accessed on 26/08/2024.

[3] https://climate-adapt.eea.europa.eu/en/metadata/case-studies/a-community-of-practice-for-the-sustainable-management-of-forests-surrounding-the-occhito-lake-in-puglia-italy
https://climate-adapt.eea.europa.eu/en/data-and-downloads/prescribed-fire-and-grazing-as-integrated-approach-to-make-forests-climate-resilient-in-viseu-dao-lafoes-portugal
https://climate-adapt.eea.europa.eu/en/metadata/case-studies/building-fire-resilience-using-recycled-water-in-riba-roja-de-turia-spain


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3 Literature review - NbS in forest fire management strategies

This section presents results from a literature review on fire and relevant NbS in European forest. The first part of the section describes the fire context in Europe, including climate change impacts on fire processes, fire risk determining factors, and approaches in land management. Furthermore, examples of NbS applied for wildfire risk reduction and post-fire management across European ecoregions are explained.

3.1 Forest fires in Europe

3.1.1 Fire in the Earth System

Fire has been inextricably linked with biodiversity throughout history. It is one of the natural elements that maintains the functioning of ecological processes (Pausas and Paula, 2012; Keeley et al., 2019). Regular natural fire in ecosystems contributes to natural regeneration, natural pest control and natural nutrient management. The beneficial effects often link to low-intense, low-frequent fires in naturally balanced systems. Over the past few decades, fires in natural vegetation have been increasing in likelihood, frequency, scale, and intensity. Important factors are the effects of climate change, management practices and land-use change (Jones et al., 2022). The impact of these wildfires, both on society and nature itself, is increasing rapidly. Wildfires, including forest fires, are defined as "any uncontrolled vegetation fire that requires a decision, or action, regarding suppression" (European glossary for wildfires and forest fires (Stacey, 2012)). Internationally, a division is made between vegetation fires (e.g. forest fire, bush fire) and wildfires, which are unplanned, unwanted, and uncontrolled.

3.1.2 Fire risk factors in Europe

Much of recent literature points out that fire weather, as an important factor in fire risk, has become more widespread, longer-lasting, and more intense in many regions, also in regions that were less commonly fire-prone until recently. Fire weather is defined as the weather conditions conducive to the occurrence and sustenance of fires of wildfires, like increased heat, extended droughts, wind and often a combination (IPCC et al., 2023; Jones et al., 2022; Senande-Rivera et al., 2022). This change in fire weather, together with the impact of land management, land use and changing climate conditions on the potential available fuel load in regions, shows that regional trends are shifting and emerging. The fire season, the period where wildfires most likely occur, is changing -often lengthening. Changing weather patterns as a result of climate change make for an increase in the number of days of high wildfire danger annually (Oester, 2024).

In Europe, interesting regional trends can be observed. On the one hand, regions that were already facing wildfires frequently – especially the Mediterranean – are challenged by more extreme and prolonged conditions, leading to more and extended wildfires (higher occurrence, higher intensity), extreme fire behaviour and extremely difficult to control or suppress. On the other hand, regions in which wildfires, like Northwest Europe, were less common or extreme, also see the frequency of occurrence and intensity of wildfires increase due to changing conditions. In Europe, it has thus far mainly been the Southern European countries that experienced greater fire danger; however, this is now shifting to more temperate regions, too (Fernandez-Anez et al., 2021; Stoof et al., 2024). Regional fire regimes – defined by the European Glossary as "the pattern of fire occurrence, fire frequency, fire seasons, fire size, fire intensity, and fire type that is characteristic of a particular geographical area and/or vegetation type" (Stacey, 2012) are changing. They are intrinsically linked to climate and thus climate change.

Unlike the smaller fires that are part of the Earth system, large-scale fires can cause disastrous impact on landscapes, flora, and fauna on the one hand, and cause important societal challenges (Nolan et al., 2021). Due to more frequent occurrence and intensity of fires, the vitality and resilience of areas to multiple stressors is also under pressure. After a wildfire, a chain reaction of potential risks can arise – for example, where soil, surface and vegetation have been heavily damaged, (flash) floods are more likely to occur in the case of heavy rain. Additionally, climate change, land-use change, mismanagement, and pests are hampering the resilience of current ecosystems.

Forests, either managed for wood production or biodiversity, or unmanaged, are adapted to the prevailing climate conditions. Under the pressure of climate change, these conditions are changing, posing a threat to ecosystem functioning. Some of the forest management practices today, such as single species, single age plantations, might reduce the resilience of the forest to fire events, causing more and larger scale fires (Regos, 2022; Lindenmayer et al., 2023) and pest outbreaks that kill a large number of trees (Montagnini et al., 1995; Anderegg et al., 2022). At the same time, forest disturbance regimes are projected to change, putting ecosystem services and biodiversity at risk. The fire regime that the forest was adapted to will also change as a result of this (Hagmann et al., 2021).

No single factor determines whether a fire will take place. Fires occur when certain thresholds are passed related to ignition patterns (in the EU, mostly human induced and less frequent natural causes), fuel availability (vegetation, composition and condition/vitality) and the weather (temperature, precipitation, wind speed), time of year (when sap stream has not started yet), affecting the moisture content of the surface fuels. Climate change and specific land (use) management practices as well as land use change often increase the frequency of crossing these thresholds (Pausas and Keeley, 2021). Vice versa, management practices and land use change could also help in reducing risks. As mentioned, wildfires in the EU are often human induced; urbanization, infrastructure, recreation and tourism are all important factors to consider. The Wildland-Urban Interface (WUI) is still growing, including human settlements and infrastructure near or even penetrating forested or natural areas (Navarro-Carrión et al., 2021). This increases the risk of ignition and occurrence and lengthened fire season, but also increasing the potential impact. According to some authors (Tang et al., 2024) a 24% increase in WUI has occurred globally over the last 20 years (2001-2020). Europe has a substantial WUI. Depending on the exact definition, Europe's WUI ranges somewhere between 7.4 % and 15% in average (Bar-Massada et al., 2023; Schug et al., 2023). Tang also projects an increase in the WUI in the upcoming decades (up to 16% until 2030) – noting these numbers are averages. Events like Wennington (UK, 2022) and Greece (2023, 2024) showcase the direct impact on communities and challenges for the emergency services when wildfires hit (peri-urban) areas.

3.1.3 Approaches in landscape management

A wildfire management transition

Up to this point, fire management generally has focused its efforts on suppression rather than prevention (Regos, 2022). Landscapes, however, actually became more prone to inflammation, due to an accumulation of fuel, but also prolonged periods of drought, changing weather conditions, and a growing Wildland Urban Interface. To reduce wildfire risks, rather than solely fighting wildfires, there is a need to recognize the importance of occasional fire for the ecological functioning of natural systems in Europe too. This approach must be characterized by preventive, integrated and sustainable solutions embedded in local knowledge and considerate of the needs of different land-use and management sectors (Ruane et al., 2020). This will require a shift in the public mindset, from wildfires being perceived as a threat to society to an essential part of ecological processes.

This approach favours wildfire risk management over fire prevention. "Growing evidence shows us that healthier, more diverse ecosystems – including those with a variety of vegetation, wetland habitats, key species of wildlife, and healthy water-retaining soils – are more resilient against the effects of extreme weather events like wildfires. And of course, they are exactly what we need to help prevent further climate change too" (Rewilding Britain, 2024).

Fire smart European landscapes

In Europe, we already see a trend in wildfire risk management that increasingly addresses the root causes of wildfire outbreaks rather than the effects only. This trend specifically zooms in on driving factors that influence the landscape scale conditions with regards to flammability, fuel management and fire spreading.

Besides changing climatic conditions and fire weather, management and land use is a critical factor. In Southern Europe, lack of forest management and land abandonment are major contributors to increasing wildfires, as it leads to more vegetation, which equals more fuel[4]. In North-West and Central Europe, ecosystems suffer especially more from low vitality (due to nitrogen deposition, more frequent droughts, extreme precipitation and bark beetle outbreaks). In all regions monocultures and the use of specific tree species also often amplify increasing risks.

Healthy ecosystems are less prone to wildfire outbreaks and more resilient to the effects of wildfires. An approach to wildfire risk management is to combine nature conservation and development to improve ecosystem functioning, with spatial fire management strategies such as fuel breaks in fire-smart landscapes or fire smart territories (FST). These landscapes will not only enhance ecosystem services but can also generate socio-economic benefits on a local scale. FST propose productive activities to break up the landscape and reduce fuel loads, hence reducing wildfire risk and vulnerability of nearby communities, while simultaneously offering livelihood opportunities (Ascoli et al., 2023; Leone et al., 2020). We need to learn to co-exist with wildfires but manage the risk by applying climate adaptation and mitigation measures to help reduce the frequency and intensity. For that we need a systemic approach.

Policies in Europe are showing great potential to achieve FST, although in North-Western Europe this is still in development. “A major goal of European policies is to foster FST in which land use activities (e.g., agroforestry, nature conservation) concur with planned fuel treatments (e.g., fuel breaks) in regulating the spatial distribution of fire and its impacts, improving fire suppression effectiveness while obtaining benefits for ecosystem services and local economic development.” (Ascoli et al., 2023, p. 2).

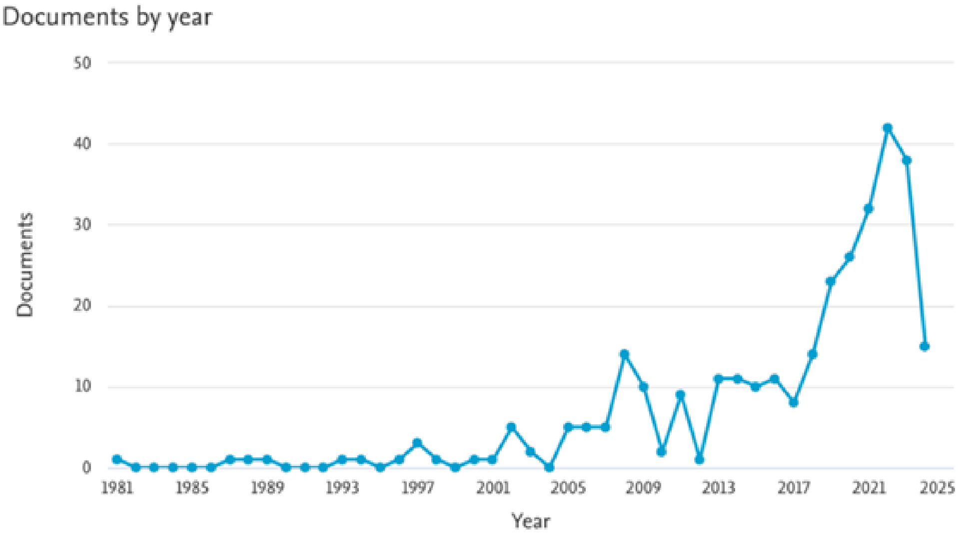
European strategies, programs and subsidies are made available to enable the transition to FST. However, there are challenges to their implementation at the local policy level. Often, fire and land management is subdivided and spread across various agencies. Additionally, when it comes to the governance of landscapes, land ownership issues complicate the involvement of private owners in big fuel management programs (Ascoli et al., 2023). These are substantial barriers to achieving a transdisciplinary, integrated approach to wildfire risk management and being able to establish synergies and optimally use the resources as made available by the European Commission. It is necessary to overcome these constraints in order to achieve landscape-level management and fuel reduction in an economically viable way (Ascoli et al., 2023).

3.1.4 Nature-Based Solutions (NbS) and fire

NbS can be an effective tool to mitigate the negative effects of changing fire regimes. In recent years, there has been a sharp increase in the number of papers addressing fire and NbS, from just a few 10 years ago to around 40 in the last years (Figure 1). Adaptation to increased fire occurrence and risk lies in managing our forests in a different way than done up to now. In the case related to fire management, NbS fall under two targets categories: Wildfire risk management/prevention and Post-fire Management. Both topics will be addressed in this report.

[4] Fire Smart, https://firesmartproject.wordpress.com/

Figure 1: Published peer reviewed articles found on Scopus with search items: fire AND nature AND based AND solutions (1st May 2024).



3.2 NbS for wildfire risk reduction and management

Nature-based Solutions present an option for finding sustainable, preventive solutions that not only reduce wildfire risks, but also help improve ecosystems, infiltrate and retain water, and store carbon. NbS are tailored to changing conditions and designed to be future-proof. Examples of types of relevant NbS are rewilding, building fire resistant and resilient landscapes with fire-resistant vegetation and more diverse ecosystem structure like more mixed forests, agroforestry and rewetting. From a fire-fighting perspective, it is essential that the vitality and diversity of natural areas are being taken care of and improved, but additionally, it is key that compartmentalization[5] (taking into consideration the size of the compartments) and accessibility are understood and realized. How do NbS contribute to vital and diverse nature? How do they contribute to fire-risk management and adaptation? And how can they meet the requirements for firefighting?

Literature provides evidence of the potential of Nature-based Solutions as wildfire-management tools. When well-implemented, they can offer great potential in integrated, adaptive strategies that combine climate mitigation benefits with wildfire-risk reduction, ecosystem restoration, and various other socio-economic advantages. For wildfire control, it is worthwhile combining NbS with traditional management strategies for maximum impact. Last but not least, lessons learnt in design and management in natural areas for fire resilient landscapes are crucial to connect. Simple and effective guidelines are needed, for instance on preventing ladder fuels.

3.2.1 Examples of Nature-based Solutions for fire risk management

3.2.1.1 Close-to-nature and adaptive forestry

Close-to-nature forestry (also sometimes called silviculture or nature-inclusive forestry) can be defined as the “art and science of managing the establishment, growth, composition, health and quality of forests on an ecologically sustainable basis. These practices are used to manage forests for wildlife, water, timber, recreation aesthetics, or any combination of these or other forest uses” in a coherent and sustainable manner (British Columbia, 2024). Close-to-Nature Forest Management will promote components, structures and processes characteristic of natural forests and cultural woodlands, thereby improving the

[5] A fire prevention strategy that divides an area into separated compartments with barriers (fuel breaks), to reduce the spread of fire.

diversity of tree species and structures, variation in tree size and development stages, and a range of habitats including habitat trees and dead wood (Larsen et al., 2022).

Close-to-Nature Forest Management integrates the following principles (Larsen et al., 2022):

- Retention of habitat trees, special habitats, and dead wood.
- Promoting native tree species as well as site-adapted non-native species.
- Promoting natural tree regeneration.
- Partial harvests and promotion of stand structural heterogeneity.
- Promoting tree species variation and genetic diversity.
- Avoidance of intensive management operations.
- Supporting landscape heterogeneity and functioning.

Close-to-nature forestry can substantially lower the risk of wildfire in forested areas through measures such as the conversion of monoculture forests into polyculture, or the planting of a barrier of fire-resistant or retardant species to reduce the risk and slow down the spread of forest fire (Waldwissen, 2020). Such proactive sustainable forest management strategies could substantially reduce the risk of losing vital ecosystem services (Mauri et al., 2023).

Close-to-nature forestry measures are particularly of interest to pine monoculture areas. In such pine forests, the understory layer of biomass is extremely flammable and so are the dry, lower branches of the pine trees.

It is important to note that the second principle of closer-to-nature forest management ("Promoting native tree species as well as site-adapted non-native species") can conflict with traditional forest conservation strategies that focus on maintaining past potential natural vegetation – such conservation strategies may exclude the introduction of new, non-native species, even though older management plans may become obsolete under new climate conditions.

3.2.1.2 Prioritizing fire-resistant vegetation

The effective prevention of wildfires requires extensive knowledge on the (distribution of) vegetation and how it responds to fire. Some species are more prone to fire than others, hence an area that is mainly covered by fire-prone species presents a real risk. This NbS consists of adapting the species composition of the landscape by planting fire-resistant vegetation. Such an intervention contributes to reducing fire risk, and also increases diversity in habitats and therefore indirectly biodiversity, creating more thriving ecosystems. They help slow down the spread of fire and offer an alternative to chemical fire retardants. Key environments where wildfires can flourish are, for example, extensive pine forests with a ground cover that is prone to inflammation. The internal climate in these forests is dry and the tree branches are often low-set and highly flammable. As we are seeing an increase in periods of drought in Western Europe, the risk of wildfires in these areas is increasing too. There is not only a need for mixed species composition, but also heterogeneous age structure and genetic diversity to make forests more resilient to climate change and its impacts, though this can conflict with conservation objectives. Understanding and overseeing such short-term and long-term investments and impacts requires an integral management approach.

Broadleaved or deciduous trees are known to be less prone to fire than coniferous trees and can therefore be used to halt or slow down the spread of wildfires. It is important to consider species proneness to fire when planting a new area, so that ignition risk and risk of easy spread of fire can be reduced. Coniferous trees, for example, easily dry out, have loose bark and can hold on to dead branches for quite a long time. These branches can then function as a fire ladder. Deciduous trees, on the other hand, lose their leaves, contributing more to fuel accumulation (Tersmette, 2023).

3.2.1.3 Prescribed fire

Prescribed fires consist of "small-scale, low-intensity, controlled fires ignited to achieve specific land management objectives, including wildfire prevention and ecological or agricultural management" (OECD, 2023b). This controlled application of fire aims to reduce accumulated fuel, such as dry vegetation and dead wood. By carefully managing these burns, ecosystems become less prone to severe wildfires, creating safer conditions for nearby communities and wildlife. Prescribed fire also helps maintain biodiversity by promoting the growth of fire-adapted plant species, cycling nutrients into the soil, and supporting habitats that benefit diverse species. This approach, guided by ecological principles and climate conditions, not only reduces wildfire risks but also strengthens ecosystem resilience (through more healthy ecosystems by e.g. increasing nutrient availability and increasing biodiversity), making landscapes more adaptable to environmental changes. There is no complete agreement about defining the use of prescribed fire as an NbS. However, this technique can be considered part of a sustainable management approach of forests, whenever it is done to mimic the natural fire cycle, with the aim of preventing large wildfire risks and delivering benefits for biodiversity.

3.2.1.4 Agroforestry

Agroforestry can be defined as a land management strategy that enhances soil quality, provides habitats for wildlife and helps increase yields, by planting trees, shrubs and hedges[6] in combination with either livestock, pasture or agricultural crops (Damianidis et al., 2021). Damianidis et al. review whether agroforestry can also be applied as a tool in wildfire reduction management in the European Mediterranean region, by correlating fire occurrences with land cover and use data during the period 2008-2017. Their findings are that indeed "agroforestry areas had fewer wildfire incidents than forests, shrublands or grasslands, providing evidence of the potential of agroforestry to reduce fire risk and protect ecosystems" (Damianidis et al., 2021). The key explanation for this is that agroforestry creates barriers in forest landscapes and reduces the understory layer of biomass that is usually found in forests.

3.2.1.5 Rewilding

Wildfire risks have increased because of land surface and land-use changes. In some places, (agricultural) land abandonment has led to unmanaged forest areas and an increase in fuel in forests. In other places, land-use change has led to the drainage of land (e.g. peatlands and moorlands). Additionally, wildfire risks are determined by the quality of the soil. Due to its altered structure and increased density, degraded soil has much less capacity to absorb and store water than healthy soils and as such being more sensitive to fires.

Some of today's landscapes are characterized by extensive monocultures where originally, diverse vegetation and habitats determined the landscape. Different types of landscapes such as marshes, wetlands and woodlands have their own way of interacting with fire and hence cooperate as a natural barrier for wildfires. These so-called mosaics in the landscapes have been replaced by meadows and monocultures, with limited species, which work as a catalyzer for wildfire spread. In order to reduce wildfire risks, natural habitats need to be restored to more complex and diverse landscapes. One essential element to achieving that is rewilding, through the (re-)introduction of wildlife species. Rewilding in essence is allowing nature to return to a wilder landscape by recovering or (re)creating biophysical wilderness qualities (Forest and Nature Conservation Policy et al., 2020). The extent of intervention can be situationally dependent and range from passive rewilding, meaning as little intervention as possible, to full management that allows limited structural interventions into forests (e.g. prescribed burning) and non-harmful activities such as agriculture, forestry and fishing. Next to becoming more fire resilient, rewilding efforts can also contribute to multiple ecosystem services like biodiversity (due to large scale ecosystem restoration), climate change mitigation, clean air and water, food provision and other livelihood opportunities, however, all under the condition that they are carried out properly.

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[6] soilassociation.com

In Europe, many projects opted for the (re-)introduction of large herbivores. Herbivores can have a variety of influences on their surroundings (Johnson et al., 2018), with one of the key impacts being on fire risk. With their grazing and trampling, herbivores remove plant matter and reduce the density of vegetation, while also altering the composition of vegetation respective to their diets. Fuel accumulation is highly dependent on the amount, distribution and type of vegetation in an environment. Herbivore presence can also lead to a more heterogeneous landscape at a larger scale. This is a result of their interaction with the terrain and water availability and can lead to more differentiated zones in terms of flammability, which helps prevent rapid spread of landscape fires (Johnson et al., 2018). Additionally, by their tramping, trampling and digging, herbivores and other animals can for example create bare paths that function as fire-barriers with little to no vegetation, dust baths or even bury fuel in the process of digging for food (Johnson et al., 2018). Winter grazing by cattle can help increase fine fuel moisture and reduce fuel material (Rewilding Britain, 2024; Davies et al., 2016). Not only can the reintroduction of herbivore grazers and animals such as pigs and wild boars help reduce fuel material by eating vegetation, they also bury leaves, small twigs and other flammable litter in the ground where they root (Rewilding Britain, 2024). Beavers also play a crucial role in restoring mosaic landscapes as their dam-building contributes to enhancing wildlife in aquatic environments, slow down water flows, maintain rivers, streams and wetlands as a natural fire break (Cleveland, 2023). It is important to note that the presence of ungulate populations can create conflicts with reforestation objectives – this is the case of roe and deer population in many parts of Central Europe, where browsing is an important limiting factor for the growth of new tree seedlings (see, e.g. Kupferschmid et al., 2020). Different situations may require different rewilding approaches and gradations; managing the balance in rewilding efforts can help prevent new issues such as overgrazing.

In some cases, the transformation processes triggered in mediterranean areas by land abandonment are described as “passive rewilding” (see, for instance, Regos et al., 2023, p. 4); however, such areas, as rewilded areas in general, are more fire prone. To reduce fire risk, additional interventions will be necessary, such as the introduction of grazing species to keep fuel amounts under control (Johnson et al., 2018).

3.2.1.6 Rewetting

Healthy soils can store more water and create a natural firebreak (Rewilding Britain, 2024). Peat fires are an example of wildfires that are difficult to manage. Peat fires are characterized by “smouldering combustion; once ignited, the peat can burn for long periods despite prolonged rainfall and snow cover” (Sirin et al., 2020). Rewetting can help reduce the peat oxidation and hence the risk of fire.

The draining of peatland for agricultural purposes and eventually the abandonment of these agricultural peatlands has increased the sensitivity to fire risk of the areas. The deeper the groundwater levels, the deeper the groundfire can invade. Sirin et al. conducted a study to analyse the relationship between rewetting and peat fire occurrences. It became apparent from their analysis that rewetting can help reduce both the number of peat fires, as well as the area they covered. Moreover, it can help recover some of the ecosystem’s services (Sirin et al., 2020).

3.2.2 Differences across Europe

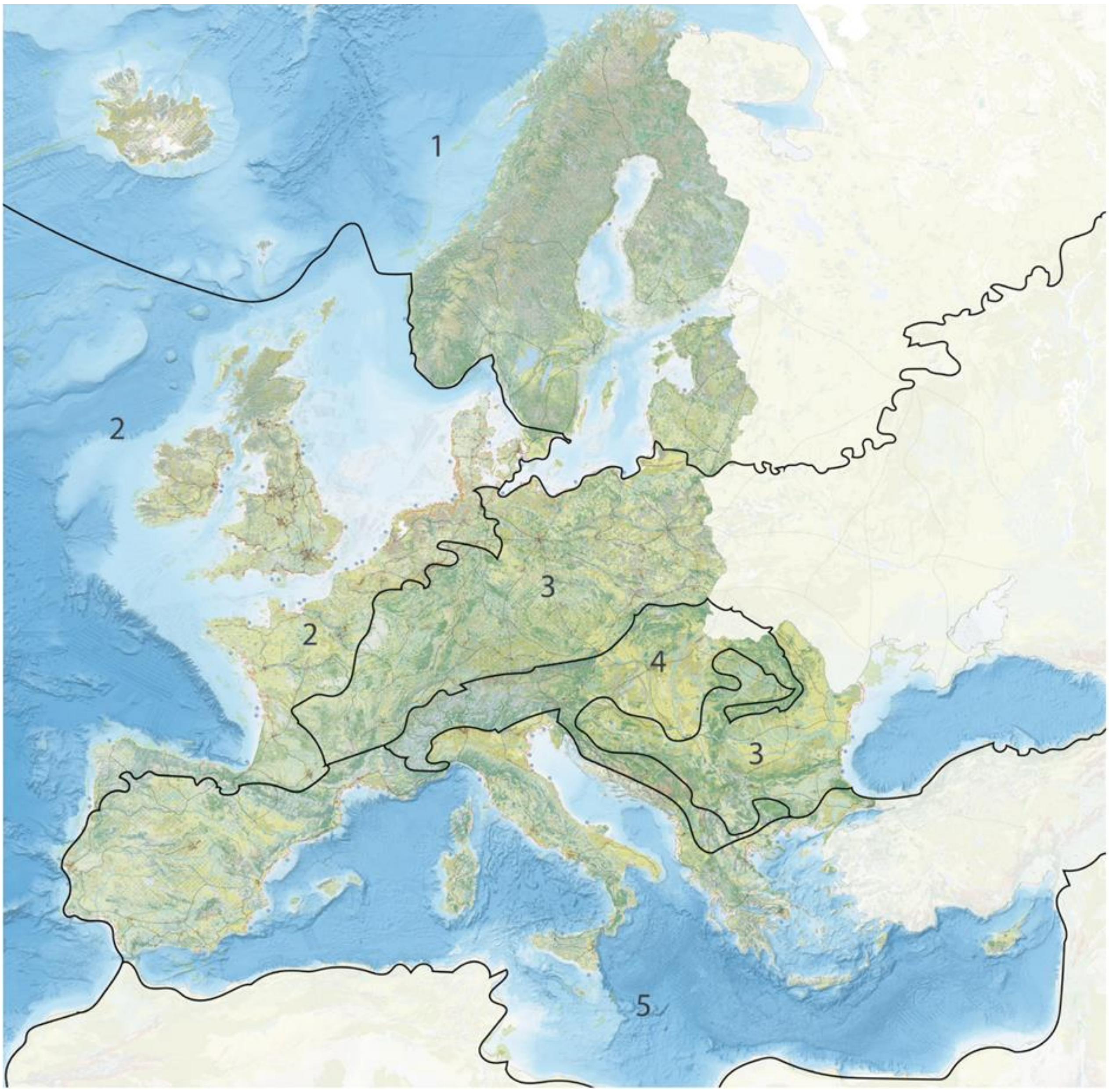
Specific questions arise when adapting to increased fire risk: 1) Are extreme fires more frequent than earlier? And 2) How to select the right NbS?

To select the right NbS for a specific area, it is important to understand the ecosystem functioning (Herbert et al., 2022). Beside ecosystem functioning the place-based characteristics, (spatial) composition and connected systems are as much important, because NbS are specifically about unlocking multiple benefits.

With rapidly rising temperatures, Europe is already dealing with the consequences of a warmer climate (Van Hattum et al., 2023). Because of a warmer climate, Europe is increasingly affected by wildfire danger, with wildfire risk also expanding into areas that are typically not susceptible to it. Recognizing geographical diversity, each regional context requires a fitting response and risk management strategy.

Europe can be roughly divided into 5 ecoregional clusters (Van Hattum et al., 2023). Each of these regional clusters, experiences different types of fire danger and adaptive management strategies, including relevant NbS, can vary per region. This geographical clustering provides an interesting framework to understand the specific contextual needs and challenges for the implementation of NbS for fire and pest management in European forests.

Figure 2: Adaptive management in the regional clusters: (1) North; (2) West; (3) East; (4) Central; (5) (Source: Van Hattum et al., 2023, p. 41).



3.2.2.1 North: The Arctic and Boreal region

The Nordic countries and the Baltic states are home to boreal and hemiboreal forests, as well as to alpine forests in their mountainous areas. The region has a low population density. This ecoregion generally experiences cooler, wetter climates than southern Europe, making wildfires less frequent. However, recent heatwaves have raised concerns. Following the extreme period of drought in 2018, the Nordic countries faced the biggest forest fires ever recorded (Nordic Forest Research, 2021). With a changing climate, the risk of forest fire increases drastically. The Nordic Forest Research stresses the importance of cross-border collaboration and knowledge exchange in their knowledge compilation on forest fires in the Nordic region. For forestry, integrated adaptive cross-border forest management is needed to create resilient, climate smart forests, taking into account potentially conflicting objectives such as biodiversity, carbon sequestration, fire prevention and productivity (Nordic Forest Research, 2021). Crucial in that is an improved water strategy, to retain water in the system which helps reduce potential fire and pest risk and other hazards (Van Hattum et al., 2023).

Fire management in Norway and Sweden is highly decentralized and mainly organized around suppression. It is arranged locally by the local Fire and rescue services, that aim to prevent all fires and minimize damage to forests, people and infrastructure (Fire-Res, n.d.). “Active forest management actions towards resilient landscapes are currently limited” (Fire-Res, n.d.).

Fire risk prevention using NbS include prevention strategies such as:

- **Peatland Restoration** where NbS efforts focus on restoring and protecting peatlands.
- **Forest thinning with Natural Approaches to reduce the fuel load** by selective thinning, promoting biodiversity in forest management.
- **Biodiversity Enhancement in Forest Management** by promoting mixed-species forests, making the northern forests more resilient to fire by reducing the dominance of highly flammable species like coniferous trees.

3.2.2.2 West: The Atlantic and North Sea region

This region is one of the most densely populated areas of Europe. As a result, the wildland urban interface (WUI) is very important in fire mitigation plans. The changed climatic conditions have a tremendous impact on the ecosystems’ resilience and the occurrence of wildfires (Van Hattum et al., 2023). Wildfires mostly occur in spring, when sap flows have not yet restarted, but occasionally summer wildfires do occur after periods of drought. Typically, in this region, wildfires occur in open landscapes such as heathlands, peatlands and/or agricultural land rather than forests (Stoof et al., 2024). Southern Atlantic areas such as south-western France have been subject to large-scale fires (e.g. in Nouvelle-Aquitaine in 2022 where 30.000 ha of forest were burned), but the risk is not restricted to these areas anymore. Citizen education to fire risk is lacking, and there is urgent need for educating land managers to make the landscape more resilient. For example, in Nouvelle-Aquitaine, large-scale fire outbreaks mid-20th century led to a completely different approach of wildfire risk management, leading to the set-up of efficient prevention systems enrolling forest owners in municipal fire prevention associations[7](Fire-Res, 2022). This approach helped prevent the fire events from 2022 from further escalating despite the large risks.

Key NbS strategies in this area are focusing on:

- **Urban Green Infrastructure** such as planting fire-resistant vegetation around urban areas and using fire resistant vegetation in green roofs and green walls in cities to reduce heat and fire risk.
- **Natural Forest Management:** Western European countries emphasize sustainable forest management practices that integrate biodiversity. For example, planting mixed-species forests and promoting native species over monocultures enhances forest resilience to fire. These forests are managed to include more fire-resistant trees, which can reduce the spread of fires.

[7] DFCI, *défense des forêts contre les incendies,* https://www.dfci-aquitaine.fr/qui-sommes-nous

- **River and Wetland Restoration:** In regions like southern France, NbS include restoring rivers and wetlands to create natural firebreaks. Wetlands and riparian (riverbank) zones help in creating moist areas that resist the spread of wildfires.
- **Buffer Zones and Green Corridors:** Like Southern Europe, Western Europe uses natural buffer zones to protect critical infrastructure. However, these regions focus more on integrating green corridors into urban planning to act as firebreaks while enhancing biodiversity.

3.2.2.3 East: Continental Region

The Continental region is characterized by a central land mass that encompasses anything from flat terrain to hilly and mountainous landscapes. Forest degradation caused by soil acidification forest monoculture and erosion (Glatzel, 1991; Liu et al., 2018) is a serious issue in this region and intensified land use through agriculture, mining, and other industrial activities lead to soil and land degradation, as well as water issues (Van Hattum et al., 2023). The region nowadays regularly experiences periods of drought, heatwaves and hence also forest fires. Changes in the climate also leads to an increase in bark beetle outbreaks, which in turn causes forest degradation, making them more prone to wildfire and pests (Hlásny et al., 2021b). Specific NbS that can play a key role in managing landscapes to mitigate fire risks in this region are:

- **Sustainable Forest Management:** promoting mixed-species forests and managing the forest floor (e.g., controlled grazing or selective thinning), focussing on native species that are better adapted to the local climate and are more resilient to fires.
- **Wetland and Grassland Management:** restoring grasslands and wetlands, which act as natural barriers against fire spread and create fire-resistant landscapes.
- **Agroecology and Land Stewardship:** planting fire-resistant crops and using hedgerows and other natural barriers to slow fire spread.

3.2.2.4 Central: Alpine and Pannonian region

The Alpine region covers the mountain ranges of the Alps, the Pyrenees and Carpathians. Due to the melting of glaciers in this area, the water system is changing. Due to their characteristics, especially the shallow soil and steep slopes vulnerable to erosion, the ecosystems in this region are often vulnerable to change, which significantly determines their resilience to external shocks. Land use in this region is mainly agriculture and tourism, both of which are putting pressure on the natural system (Van Hattum et al., 2023). Due to changing ecosystems under climate change pressure, the forests are more vulnerable to fire.

- **Adaptive forest management strategies** are needed to face climate change induced challenges. Nature-Based Solutions in this region are tailored to leverage the region's natural features—such as forest diversity, grazing landscapes, and water-rich zones—to reduce fire risk while promoting ecosystem health and community resilience. These strategies balance fire prevention with sustainable land use and ecosystem conservation, making the Alpine region more resilient to the increasing threats posed by climate change.
- Especially on the mountain slopes, it is key to implement **Green Infrastructure for slope stabilization and firebreaks.**
- Higher up in the mountains it is important to focus on **restoring alpine wetlands and use low flammability grasses.**
- Furthermore, **reforestation and afforestation with mixed, native species** improves water retention, prevents further soil erosion, and reduces avalanche risk. As side effect, many of these are measures that can also be put into place to reduce wildfire and pest-risks.

3.2.2.5 South: The Mediterranean region

The hilly and mountainous landscapes, inland plateaus, islands and long coastlines of the Mediterranean ecoregion make it a popular region for tourism (Van Hattum et al., 2023). The soils in this region typically have low moisture-holding capacity levels and face pressures from overgrazing and deforestation, which creates high risks of wildfire outbreaks and spread. Of all European regions, this region experiences the highest rate of heat stress, drought, water scarcity, and thus wildfire outbreak risks. The increasing aridification of the landscape makes water storage and retention difficult, and in the case of heavy precipitation the chances of flooding events increase (Van Hattum et al., 2023).

NbS in these areas focus on enhancing landscape resilience to wildfires by using nature to limit fire spread, reduce fuel loads, and restore ecosystems. Key NbS strategies are:

- **Agroforestry and Grazing Management:** Traditional practices like agroforestry (integrating trees and agriculture) and managed grazing by livestock (e.g., goats and sheep) help reduce vegetation density, lowering the amount of combustible material (fuel load) in fire-prone areas.
- **Forest Restoration with Native Species:** Replacing fire-prone monoculture plantations (such as eucalyptus) with native, fire-resistant species helps in slowing the spread of wildfires.
- **Green Infrastructure and Buffer Zones:** Natural vegetation buffers are established around urban areas and critical infrastructure, acting as firebreaks. These green belts are strategically planted with low-flammability species, which can slow or stop the spread of wildfires.

3.3 NbS for post-fire management and forest recovery

Post-fire management in Europe varies widely across regions due to differences in climate, vegetation types, fire regimes, and ecological priorities (Vallejo et al., 2012). Implementing NbS after wildfires can lead to healthier, more resilient ecosystems that are better equipped to withstand future fires and climate-related challenges. NbS also provide additional benefits such as enhancing biodiversity, improving water quality, and supporting local communities through sustainable livelihoods related to grazing or tourism. However, NbS implementation requires case-by-case evaluation, as in some instances, it is better to do nothing, and let nature take its course.

3.3.1 Examples of Nature-based Solutions for post-fire management

Post-fire nature-based solutions (NbS) are strategies that utilize natural processes to restore and enhance ecosystems after wildfires. Here are some key post-fire NbS options.

3.3.1.1 Reforestation and Assisted Natural Regeneration

- **Reforestation:** Planting fire resilient tree species in areas severely impacted by fire to restore forest cover, stabilize soils, and promote biodiversity. Selected fire-resistant species can enhance future resilience (Zuazo and Pleguezuelo, 2009).
- **Assisted Natural Regeneration/prioritizing fire-resistant vegetation:** Supporting the natural regrowth of forests by protecting young seedlings and controlling invasive species can accelerate recovery, but without planting seedlings (Cerdà and Robichaud, 2009).
- **Natural Regeneration/rewilding:** Protecting natural regrowth of native species help restore forest cover and stabilize ecosystems (Cerdà and Doerr, 2008; Navidi et al., 2022).

3.3.1.2 Erosion Control and Soil Stabilization to stimulate recovery

- **Contour Log Terracing:** Placing logs or other natural barriers across slopes to slow water and sediment runoff to reduce landscape connectivity: this reduces soil erosion: detachment by overland flow; and sedimentation in reservoirs and waterways (Keesstra et al., 2018; López-Vicente et al., 2021b, 2021a; Bombino et al., 2024).
- **Mulching and Ground Cover:** Applying organic materials like straw or wood chips to burned areas can protect the soil against splash erosion and overland flow erosion. In addition, it can retain soil moisture and protect seedlings (Cerdà and Doerr, 2008; Moody et al., 2013; Wittenberg et al., 2020; Wittenberg and Shtober-Zisu, 2023). “Log erosion barriers can be used on moderate or

severely burned slopes with erosive soils, or where erosion rates have increased significantly because of the fire and where there are high values at risk downstream[8].

- **Soil microbial restoration:** biotechnological strategies by introducing native or external micro-organisms to create a cohesive layer that covers the soil surface to protect fragile soil surfaces (Wittenberg and Shtober-Zisu, 2023, 2023). Such practices are also relevant for preventing pest proliferation.
- **Application of biochar:** adding biochar to the soil increases the soil organic matter and improves the soil structure and possibility to recover faster (Alkharabsheh et al., 2021; Das et al., 2021).

3.3.1.3 Species Management

- **Native Species Planting:** Prioritizing the planting or seeding of native species that are adapted to fire-prone environments (Castro et al., 2015; Leverkus et al., 2015; Wittenberg and Shtober-Zisu, 2023).
- **Early Detection and Removal:** Monitoring burned areas for invasive plant species and removing them before they become established can prevent them from outcompeting native vegetation during recovery (Pyke et al., 2013; Keeley, 2001).

3.3.1.4 Hydrological Restoration

- **Check Dams and Retention Structures:** Constructing small dams or retention structures in burned watersheds can slow water flow and promote sedimentation in the valleys. The reduced connectivity also reduces downstream erosion and improves infiltration, and supports ecosystem restoration (Martínez-Murillo and López-Vicente, 2018; Lucas-Borja et al., 2018).
- **Stream and riparian vegetation restoration:** Rehabilitating streams affected by increased sedimentation and altered flow patterns can restore aquatic habitats and improve water quality. Restoring vegetation along streams and rivers to limit the flow of water and sediment (lower the landscape connectivity) to catch runoff and sediment to allow infiltration and sedimentation in the valley (Nunes et al., 2020).
- **Wetland Restoration:** Rehabilitating wetlands affected by fires can enhance water storage, improve biodiversity, and reduce the risk of flooding in downstream areas (Long, Jonathan W. et al., 2004; Tan et al., 2022).

3.3.2 Differences across Europe

Post-fire management in Europe differs significantly due to the contrasting climates, vegetation types, fire regimes, and ecological priorities in these regions (Aaltonen, 2020; Fernandez-Anez et al., 2021).

3.3.2.1 North: The Arctic and Boreal region

In Northern Europe, boreal forests dominate. Such forests have short growing seasons, consist of predominantly coniferous forests, such as Scots pine and Norway spruce, with some temperate deciduous species like birch. The fires are generally infrequent but can occur during dry periods. When they do happen, they tend to be low-intensity surface fires. In cold, wet climates, vegetation recovery is slow. Therefore, post-fire NbS focus on natural regeneration, replanting native conifers, and protecting peatlands. The focus lies on minimal human intervention and on protecting soil, promoting natural regeneration, and stabilizing permafrost in some areas (Ibáñez, 2022). Soil stabilization and erosion control are crucial due to slow soil organic matter decomposition rates and the risk of permafrost thaw (Aaltonen, 2020), which is specifically an issue in sloping areas. Generally, water is more abundant, so post-fire water management focuses on maintaining stream flow and protecting water quality rather than dealing with scarcity. In addition, peatland and riparian restoration is an important element in Nordic areas to protect

[8] https://www.nrcs.usda.gov/resources/guides-and-instructions/after-the-fire-log-erosion-barriers .

waterlogged soils and ensure water regulation, especially in areas with extensive peatlands (Kominoski et al., 2022; Wilkinson et al., 2023).

3.3.2.2 West: The Atlantic and North Sea region

In Western Europe, the climate is temperate, with a mixed deciduous and coniferous forest as the natural vegetation type. The climate makes fires infrequent; however, under the current climate change prolonged droughts in summer provoke more frequent and severe fire.

Post-Fire NbS in this region focus on replanting mixed species to increase forest resilience, controlling invasive species, and restoring habitats like heathlands and wetlands that may be impacted by fires (Falk et al., 2022) and preventing the spread of non-native species that can establish after fires. Erosion control and water management are less critical but still important in areas with steep slopes. Lastly, there is a lot of room for improvement in community engagement. Local communities should be involved more in restoration efforts and promoting fire-resilient landscaping practices.

3.3.2.3 East: Continental Region

In Eastern Europe climate varies from temperate to continental and has diverse forest ecosystems; with a mix of temperate deciduous forests (beech, oak) and coniferous forests. The fire regime is equally variable, due to both natural and human-induced factors (Berčák et al., 2023). Therefore, the post-fire NbS include many different strategies, such as reforestation with native hardwoods, and restoring mixed forests to enhance biodiversity and resilience. Protecting soil fertility and water resources is essential due to the region’s varied topography. In hilly and mountainous areas, focus lies on preventing erosion with similar techniques as in southern Europe.

3.3.2.4 Central: Alpine and Pannonian region

In the mountainous areas the emphasis is on immediate erosion control, water management, and reforestation with fire-resistant species due to frequent, intense wildfires. NbS focus on stabilizing the slopes and fragile soils. Log-barriers are often used to stop overland flow. But also spreading seeds is often used as a means to quickly reduce overland flow and stabilize the soils (López-Vicente et al., 2021b).

3.3.2.5 South: The Mediterranean region

In Southern Europe, there are hot dry summers with mild, wet winters. Natural vegetation is composed of drought and fire-adapted species such as pines, oaks, and shrubs like Mediterranean maquis. These plants are adapted to dry, hot conditions and often have fire-resistant traits. However, the area has frequent intense wildfires, often driven by dry conditions and strong winds. Fires can be fast-spreading and severe, affecting large areas.

Post-fire NbS focus on immediate erosion control, especially in sloping areas through terracing and mulching, stimulating natural regeneration and replanting ground cover; reforestation with fire-resistant species; and managing invasive species like eucalyptus. Water management is critical due to scarce resources and increased desertification risk (Girona-García et al., 2021). Post-fire strategies often include restoring riparian zones and managing water retention to support reforestation and protecting water resources and creating natural firebreaks by restoring riparian zones (Wagenbrenner et al., 2021).

Invasive species like eucalyptus and acacia can quickly colonize burned areas, outcompeting native vegetation. Managing these invasions could be a priority. Reintroducing native species such as trees, shrubs and grasses helps restore natural habitats and supports ecosystem resilience (Schlau, 2022). Furthermore, there is a need to involve and restore local rural communities, to support smallholder farmers and to fight land abandonment. Agroforestry and grazing management can be introduced to reduce fire risks. These activities are crucial to create fire-Resilient Landscapes (Lucas-Borja et al., 2021).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4 Literature review – NbS in forest pest management strategies

This section presents a literature review on pests and relevant NbS in European forests. The first part of the section describes the climate-change-related pest context in Europe. Then, examples of NbS used for pest outbreak prevention and management across European ecoregions are highlighted.

4.1 Climate change-related forest pests in Europe

Next to changing wildfire regimes, insect and disease outbreaks in forests are important disturbances affected and altered by climate change. Like wildfires, events are more frequent, intense, and also come with geographical shifts. Introducing the Database of European Forest Insect and Disease Disturbances (DEFID), Forzieri recalls that, according to the FAO, insects and diseases affected over 1 million hectares annually – accounting for more than 50% of total naturally disturbed forest area (FAO, 2022; Forzieri et al., 2023). Changing conditions (temperature, drought, extensive rain) make forests more vulnerable to insect disturbances and diseases. One of the recent most impactful and visible impacts is related to the bark beetle.

Tree-killing bark beetles have an increasing impact on the conifer forests in the northern hemisphere, with climate change further intensifying the trend (Seidl et al., 2014; Washaya et al., 2024). Bark beetle outbreaks have severe ecological, social, and economic consequences (Morris et al., 2017). While these insects are often valued for their contribution to ecosystem functioning and biodiversity (Beudert et al., 2015), they can also disrupt timber markets (Montagné-Huck and Brunette, 2018) and reduce ecosystem services, such as climate regulation and water purification (Thom and Seidl, 2016). It has been estimated that the European spruce bark beetle *Ips typographus* has triggered up to 8% of natural tree mortality in Europe before 2000 (Schelhaas et al., 2003) and this proportion is increasing (Senf et al., 2018).

The lifecycle of bark beetles involves entering trees, mating, laying eggs under the bark, feeding, and eventually emerging to attack new hosts. This lifecycle often leads to economic losses for humans as they compete for the same resource, particularly Norway spruce, which is the economically most important tree species in Europe (Raffa et al., 2015). The beetles can cause extensive damage to trees through their feeding mechanisms, leading to disruptions in nutrient transport and the formation of infection by fungi that further weaken the trees (Krokene, 2015). Bark beetle species vary in their strategies for reproduction, some avoiding biological tree defenses by only entering trees that have recently died (*Ips amitinus* and *Pityogenes chalcographus* in Europe) while others exhaust them through mass attacks using aggregation pheromones (e.g. *Ips typographus*) (Huang et al., 2020). Climatic events, such as windstorms, drought or heatwaves, can trigger population increases by reducing tree defenses or increasing beetle numbers (Marini et al., 2017; Mezei et al., 2017). When beetle populations exceed a critical threshold, they transition from an endemic to an epidemic phase, where they attack healthy trees in addition to weakened ones, leading to widespread damage (Kausrud et al., 2012).

Climate change significantly affects bark beetle outbreaks, with an amplifying effect on the frequency and severity of these disturbances. Hlásny et al. (2021a) list three key mechanisms by which climate change affects bark beetle outbreaks:

1) Climate change facilitates bark beetle survival and development by reducing winter mortality and allowing beetles to complete additional generations per year (Baier et al., 2007).
2) It expands potential beetle habitats, enabling them to colonize higher altitudes and latitudes (Jakoby et al., 2019).
3) It increases the likelihood of extreme weather events like droughts, which in turn reduce tree resistance to beetles (Huang et al., 2020).

These factors contribute to an overall increase in bark beetle outbreaks. It is projected that regions in the Sub-Atlantic Europe will experience a significant relative short-term increase in bark beetle damage during the 2021-2030 decade compared to the 1971-2010 period, with a predicted annual increase almost sixfold (Seidl et al., 2014). As climate change continues to warm temperatures and alter precipitation patterns, it is expected that almost all spruce forests in temperate Europe will face increased risk from bark beetle infestation (Hlásny et al., 2021a). The impact of climate change on bark beetle outbreaks is expected to be uneven, occurring in waves triggered by extreme weather events like droughts and storms, which can synchronize across large areas (Senf and Seidl, 2018). The risk of increasing bark beetle outbreaks in Europe highlights the need for a more holistic approach to managing disturbances in forests, considering both social and ecological dimensions (Hlásny et al., 2021a).

4.2 NbS for pest control

4.2.1 Examples of Nature-based Solutions for pest management

Forest pest management has historically focused on controlling pests to protect timber resources, which has often come at the cost of considering the consequences on non-target insects and their ecological functions. As awareness of forests as diverse ecosystems with high biodiversity grows, there is a shifting paradigm towards more holistic approaches that balance forest conservation and pest management. Here we present ecosystem-based solutions for pest control based on the extensive reviews by Hlásny et al. (2021b) and Gazzea et al. (2024).

4.2.1.1 Biological control

Invasive insects pose a significant threat to forests globally, particularly in temperate regions. While classical biological control has been successfully used to manage non-native pests with only a few reported negative impacts, there are concerns about potential competition with native organisms (Kenis et al., 2017). However, with careful decision-making processes, including risk acceptance and benefit assessments, classical biocontrol remains a viable and sustainable method for managing invasive pests in Europe (Ferracini et al., 2019). At the same time, North America is witnessing a decreasing trend in the adoption of this approach (Van Driesche et al., 2020).

4.2.1.2 Increasing tree diversity

Pest damage in forests can be managed by increasing tree diversity through associational forest stand resistance (Jactel et al., 2017) and improved natural enemy pressure (Staab and Schuldt, 2020). This approach aligns with general conservation goals to increase insect diversity due to habitat heterogeneity. Structural diversity can be increased by replacing monocultures mixed species stands, or by silvicultural treatments like shelterwood and selection cutting systems (Williams et al., 2017). While these approaches have been successful, they also depend on the context of social decisions and commercial forestry practices.

4.2.1.3 Increasing landscape diversity

It is suggested that the positive effects of tree diversity on insect herbivores at a stand level could be extended to larger spatial scales through landscape diversification. This approach has been used in forest management to reduce pest damage and overall timber loss due to the co-occurrence of multiple host species (Marini et al., 2022). The concept of landscape diversification is also proposed as a strategy to boost insect diversity through increased habitat diversity (Arroyo-Rodríguez et al., 2020). However, while research on forest-dominated landscapes is limited, it is recognized that many forest generalist species thrive in a mixture of forests and open habitats (Marini et al., 2009). For specialist species, increasing habitat heterogeneity can lead to area and dispersal limitations (Kadmon and Allouche, 2007).

4.2.1.4 A context-dependent management framework

Europe's approach to managing natural disturbances has evolved over the last two centuries with a focus on monitoring, controlling, and intervening to reduce negative impacts on forests and economies. While the level of obligation varies by country, top-down control approaches are prevalent – this is the case for *I. typographus* management strategies relying on intensive salvage and sanitary loggings. This approach has been criticized for its centralization, simplification, and lack of consideration for local knowledge and practices, potentially leading to degradation of social-ecological systems (Holling and Meffe, 1996). To address these issues, a context-dependent management framework is proposed that incorporates diverse fields of study. It emphasizes tailored solutions based on the specific societal objectives of forests, ranging from economic value generation (e.g., wood and biomass production) to conservation of biodiversity and natural processes. Management responses will vary depending on whether the primary goal is economic output or environmental conservation (Hlásny et al., 2021a).

4.2.2 Differences across Europe

4.2.2.1 North: The Arctic and Boreal region

In the boreal region, the shift in temperature could lead to the expansion of species that are currently at the northern limit of their distribution range, potentially increasing population density and outbreak areas for certain pests as well as their predators. This includes the European spruce bark beetle (*I. typographus*), which may experience more frequent outbreaks due to increasing temperatures and drought episodes, making the growing conditions suboptimal for Norway spruce (Venäläinen et al., 2020). Moreover, extreme weather events such as windstorms increase the risk of large-scale insect outbreaks in Northern Europe (Gohli et al., 2024; Venäläinen et al., 2020). Changes in climatic parameters could also reduce the effectiveness of natural controls on pest outbreaks, such as the defoliating insects that depend on precise timing with host development. The impact of climate change is expected to be more pronounced in areas where there are high-frequency low winter temperatures, as they play a role in limiting pest populations and can cause significant losses of foliage (Venäläinen et al., 2020). Warmer temperatures could also accelerate the transition of birch-dominated forests into coniferous ones due to increased herbivory from defoliating insects.

In the Nordic countries, bark beetle damage has been effectively managed over the last four decades through legislation, management instructions, and a dense forest road network. However, increasing spruce volumes as a result of past forest management and higher temperatures may facilitate more frequent outbreaks of spruce bark beetles, emphasizing the need for improving forest resilience through promoting tree species that are less susceptible to insects (Gohli et al., 2024). The positive association between mature spruce volume and bark beetle numbers suggests that reducing the area and volume of spruce at a landscape level can decrease bark beetle damages. Shifting from monoculture forests to mixed species is seen as a potential but little studied means of to enhance resistance against biotic disturbances (Jactel et al., 2017). In addition, new stand edges after clearcutting can increase bark beetle populations, potentially causing damage over larger areas. The advantages of alternative harvesting strategies like continuous cover forestry, which avoids creating edges, are not fully understood and warrant further investigation. Uneven-aged management might also have downsides, such as increased root rot infection (Piri and Valkonen, 2013). Given the long-term perspectives in boreal forestry, swift implementation of the management changes is crucial. Overall, improving the resilience of forests in the Nordic countries will require ongoing efforts to adapt legislation and management practices, enhance scientific knowledge transfer, and foster transboundary collaboration between countries to effectively manage disturbances.

4.2.2.2 West: The Atlantic and North Sea Region

Temperature increase associated with an increase in summer droughts can have significant impacts on forest ecosystems in the temperate oceanic region of Western Europe. Climate change is predicted to accelerate development and reduce mortality rates for various species of insect herbivores, leading to an increased incidence of pest species outbreaks (Lindner et al., 2010; Netherer and Schopf, 2010).

Additionally, prolonged warm periods are expected to enhance bark beetle populations, as they can establish additional generations and multiply their population densities. Range expansions and shifts are anticipated for pest insects such as *L. dispar* and *Th. pityocampa*. In Belgium, for example, warmer temperatures could lead to an increase in insect populations like the oak processionary moth (*Th. processionea*) and the oak splendour beetle (*A. biguttatus*) (Campioli et al., 2012).
From a practical perspective, managing these risks is challenging because forest managers may lack experience or knowledge about dealing with new threats. Developing crisis plans and crisis units to handle large-scale biotic outbreaks can be beneficial (Campioli et al., 2012). These plans should include practical recommendations based on previous experiences or typical threats, while crisis units would coordinate efforts between various stakeholders. Adaptive forest management, such as selecting more drought-resistant tree species, is suggested as one potential solution to prevent large-scale pest outbreaks. The similarities between Belgian forests and those in other temperate oceanic European regions indicate the need for coordinated research and management strategies across countries. Sharing knowledge and best practices can help improve resilience to climate change (Campioli et al., 2012).

4.2.2.3 East: Continental Region

The temperate continental zone is characterized by forest production that is heavily dependent on water availability. Decreases in annual precipitation or shifts in the distribution of rainfall are expected to lead to increased water stress, potentially reducing forest productivity at sites already vulnerable to this stress. Conversely, areas experiencing an increase in both temperature and precipitation may see enhanced growth. The European spruce bark beetle (*I. typographus*) is predicted to benefit from increased temperatures and a fully developed second generation, potentially leading to more frequent outbreaks (Hlásny et al., 2021b). The gypsy moth (L. dispar) is projected to benefit from higher summer temperatures, potentially leading to expanded range expansions northwards and increased outbreak areas (Hlásny et al., 2016). The nun moth (*L. monacha*), on the other hand, could suffer from heat stress due to elevated temperatures (Lindner et al., 2010; Netherer and Schopf, 2010).

The continental region has been affected by forest decline due to various environmental factors and human activities. Long-term acid deposition, nutrient degradation, and climate change have weakened local forests, making them more susceptible to bark beetle attacks, primarily by *I. typographus*. Planting tree species outside their natural ranges (e.g., Norway spruce plantations) has increased susceptibility to disturbances. Traditional forestry approaches have focused more on timber production than adaptation to climate change, which has led to an insufficient focus on resilience-building measures, such as climate-smart forest management (including diverse stand compositions), national crisis plans for cross-sectoral cooperation, early identification and processing of infested trees, as well as effective salvage and sanitation operations. Overall, improving the resilience of forests in the continental region requires a comprehensive approach that addresses the root causes of forest decline, promotes adaptive management strategies, and enhances cross-sectoral cooperation to effectively manage disturbances like bark beetle outbreaks (Hlásny et al., 2021b).

4.2.2.4 Central: Alpine and Pannonian region

Global warming is expected to have substantial effects on forest ecosystems also in mountain regions. It is predicted to lead to increased damage from bark beetles such as the European spruce bark beetle (*I. typographus*), and a potential range expansion for other insect pests like *Tomicus piniperda* and *Pityogenes chalcographus*. The sensitivity of mountain forests to climate change varies due to factors such as geomorphology, microclimate, and soil formation. While some areas may experience reduced growth on water-limited sites, others might see an increase in growth due to higher temperatures. This could result in changes to the structure and composition of mountain forests. The impact of global warming on the tree line ecotone is significant, with some species potentially shifting their range upward due to warmer temperatures (Lindner et al., 2010).

Managing mountainous forests sustainably in the face of increasing natural disturbance requires a dynamic, adaptable approach that recognizes both economic and ecological objectives (Kulakowski et al., 2017). Adaptive management strategies include, for example, selective logging that can maintain some ecologically important characteristics of the forest while reducing the negative impact of disturbances and allowing disturbances to shape forest ecosystems in a way that promotes resilience and other desired ecosystem services. This involves working with, rather than against, natural processes, optimizing ecological benefit, and ensuring public acceptance. Applying large-scale forest management is often difficult in mountain forests because they are often diverse in conditions, scattered in the landscape and difficult to reach. By developing tailor-made management solutions, forest managers can mitigate the negative impacts of disturbances while preserving crucial ecosystem services for human well-being and environmental resilience.

4.2.2.5 South: The Mediterranean region

The Mediterranean region faces significant challenges due to climate change, including an increased risk of droughts and decreased rainfall. Distributional shifts of insect populations are probable, and highly thermophilic pathogen species may become more virulent, posing threats to the structure and composition of Mediterranean forests (Netherer and Schopf, 2010). The Pine processionary moth (*Thaumetopea pytocampa*) is a species native to Southern Europe whose range expansion northwards has benefited from global warming. The species parasites pinewoods and the larvae contain thaumetopoein in their hairs. Such substance is responsible for strong allergic reactions in humans. Among the suggested organisms that can control this moth species, two carabid species (*Carabus sycophanta* and *Carabus inquitisor*) may represent good candidates as they predate hairy caterpillars such as those of *T. pytocampa*. However, such beetles are particularly susceptible to pesticides and, therefore, their use as biological pest control agents should come with changes in crop pest control relying on the intensive use of chemicals (Balla et al., 2021). A study by Tortosa and colleagues investigated the role of landscape structure on biological pest control in forest patches and crop fields jointly in Southern France. Specifically, the authors found that cover proportion leads to opposite effects in the two ecosystems, with woody semi-natural habitats promoting caterpillar predation in woodlands while reducing aphid predation in crop fields. In this context, landscape heterogeneity could represent an asset in a trade-off management of different ecosystems (Tortosa et al., 2023). The importance of landscape structure in biological pest control in Europe is also supported by recent work by Klinnert and colleagues (Klinnert et al., 2024).


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5 Literature review - Socio-economic and governance conditions

Policies for promoting the implementation of NbS in forested landscapes need to consider the availability of forest owners for implementation, as this can determine the amount and kind of management actions to be undertaken on their premises. The relationship between costs for investment made into forest biodiversity and benefits derived from forest ecosystems determine the economic basis of owners' availability for participating. As will be explained below, an increasing share of private owners do not act exclusively on economic grounds. While landowners cannot exclude anyone from benefits produced by forests as public goods, they hold fundamental rights to shape the structure and exploitation of forest ecosystems. The trade-offs between landowners' property rights and society's conservation interests are a cornerstone of what forest biodiversity policies seek to address.

5.1 Forest ownership characteristics

Characteristics and structures of forest ownership vary widely across Europe, with larger shares of public ownership in some European regions and prevalence of private property, often consisting of smallholders as well as of commercially acting enterprises, in other areas. The rate of privately owned forests in Europe varies between approx. 70% in countries like Austria, Denmark, Finland, France, Norway, Portugal, Spain and Slovenia, while the share between private and public owners is more balanced in most Eastern, South-eastern and Central European countries (Weiss et al., 2019, p. 10). Most of the private forest property is below 10ha (Muys et al., 2022).

The group of public owners comprises state, sub-national (e.g. regions) and local institutions (mainly municipalities). The group of private owners includes family owners, heirs, absent landlords, as well as industrial timber producers. However, it is too simplistic to consider private owners as purely profit-oriented forest owners (due to their interest in the economic exploitation of forests) as opposed to public owners as purely interested in the production of ecosystem services. To a certain extent, some owners (including public owners), who are not committed to commercial exploitation, do eventually harvest timber to cover their management costs.

At a closer view, the attitudes and expectations of both private and public owners are rather multifaceted. Private owner typologies include for example: institutional investors (e.g. in Romania, Latvia, Finland and the UK) purchasing forest land for intensive management (Weiss et al., 2019, p. 13); groups of small-holders or small-medium forest owners forming associations to create the necessary economy of scale for the commercial exploitation of forests, promoted for instance in France, (Welten, 2023), but also in central eastern and south eastern Europe where recently restituted or privatised forests have created big groups of small scale forest owners with little forest resources and knowledge for forest management (Lawrence et al., 2020); private owners that are interested more in biodiversity conservation than in the exploitation of their forests; and owners that do not live in the area of their forests and thus do not directly manage forests and in some cases have completely abandoned them.

A third group of forest owners, the community or common properties, are treated as a private form of ownership, although most of them are "more akin to local public forests than to private" (UNECE, 2020, p. 2). Such forest communities often have historic roots linked to local communities and defined through customary rights; they are mostly defined and protected through law which provides them with a special status. In some countries, such as in Finland, such communities have been created recently. In Belgium, such a form of co-owned forests has been piloted as statutory partnerships between stakeholders and public forest owners with the specific aim of providing ecosystem services (Weiss et al., 2019, p. 15). Compared to public owners, these groups consist of a limited number of generally private members, which generally are part of the same community. Shareholders of community forests have, differently from private owners, more restricted property rights, and therefore, less expectations with regards to intense commercial exploitation. Involving local communities in forest management and in pest and post-fire forest management provides access to traditional knowledge and practices, can enhance restoration efforts further to providing sustainable livelihoods, such as harvesting non-timber forest products and offering grazing opportunities (Prats et al., 2022). Such ownership models occur in many European countries, especially in Spain where in some regions up to 60 % of agricultural areas, including forests, are common lands (Lana and Iriarte-Goñi, 2015).

5.2 Locally specific governance frameworks

While in theory, forest owners have the exclusive legal rights to "use, control or transfer" when it comes to benefiting from their forests (UNECE, 2020), expectation with regards to benefits produced and obtained by their forest diverge broadly: while commercial investors and forest enterprises focus exclusively on timber production, within the very heterogeneous group of private forest owners, timber production is only one objective or not an objective at all. For forest owners who aim at the production of forest ecosystem services, investment needs for forest management must be covered by different sources of income, as there is a trade-off between NbS-based management strategies and high levels of timber productivity (Schwaiger et al., 2019). Renouncing to forest productivity can, in the case of small forest owners, also imply a lack of capacity for reforestation or afforestation to repair damages from pests, forest fires, or wind, albeit their vulnerability to such risk could in most cases be lower than those of production-oriented forest stands.

Forest owners' rights are restricted by "legal regulations and social customs associated with the forest land in question." (UNECE, 2020). Europe's approach to managing natural disturbances has evolved over the last two centuries with a focus on monitoring, controlling, and intervening to reduce negative impacts on forests and economies. While the level of obligation varies by country, top-down control approaches are prevalent, such as in managing *I. typographus* with intensive salvage and sanitary loggings by public authorities. This approach has been criticized for its centralization, simplification, and lack of consideration for local knowledge and practices, potentially leading to degradation of social-ecological systems (Holling and Meffe, 1996). Such top-down interventions are accompanied, in most countries, by public regulations on forest management, which include, at least, obligations of re-forestation. Beyond regulations, the most recurrent traditional form of interaction of public policy with forest owners is based on advice provided for the design of management strategies (Lawrence et al., 2020). Regulations as well as advice need to recognize the owners' property rights, or reward owners' efforts and losses with subsidies and tax reductions.

Indeed, while "conservation measures are often carried out or compensated for by the public sector, [...] environmental regulations prescribing forest management restrictions can generate costs that are incurred solely by landowners" (Muys et al., 2022, p. 47). Yet, such regulations are needed to manage the trade-off with the need for (commercial) timber production and the need for sustainable raw material (e.g. for buildings) which can store carbon.

Knowledge generation to support forest owners in the design of forest management strategies are a further key element of public strategies, for instance in Sweden and Germany, (Andersson et al., 2017; MLV NRW, 2023a; Lawrence et al., 2020). Such advice services aim generally at supporting commercial forest owners, trying to create a balance between the production of biomass and of ecosystem services, and to limit the costs landowners incur due to such management rules (Muys et al., 2022, p. 47). While guidance documents and advice instruments can represent a valuable scientific basis for guidance towards multifunctional forests with increased biodiversity, co-creation processes for management strategies represent an opportunity for negotiating private commercial interests versus societal needs for benefits for forests. Such negotiation processes can be managed by nonprofit associations supporting groups of forest owner, as well as by public institutions, which negotiate environmental benefits from the implementation on NbS measures. Such context-dependent management frameworks can provide tailored solutions based on the specific societal objectives of forests, ranging from economic value generation (e.g., wood and biomass production) to conservation of biodiversity and natural processes as erosion and can articulate management responses according to the prevalence of management goals (economic output or environmental conservation) (Hlásny et al., 2021a).

Although some private forest owners "protect biodiversity without compensation for their economic losses, even though their objectives and opportunity costs of providing this protection differ ...” (Muys et al., 2022, p. 47), conservation measures are generally carried out or compensated for by the public sector, whereas environmental regulations prescribing forest management restrictions can generate costs that are incurred solely by landowners (Muys et al., 2022, p. 47).

5.3 Insurance schemes

The coverage of forest insurances in Europe is relatively patchy and mostly limited to commercially exploited forests. However, forest owners are increasingly seeking for means for protecting their investments in forests buying storm and fire insurances (Welten, 2023). This growing market potentially represents a means of incentivizing the use of NbS in forest management. Further to the protection of investments in productive forests, there is a role for an insurance function of NbS solutions in forests which could mitigate fire risks for society (Smeenk et al., 2024). In this context, different NbS solutions provide different degrees of protection. For forest ecosystems, which are managed according to the EU directive on biodiversity, with high percentage of standing and lying deadwood, uneven aged forests, high levels of forest connectivity, abundance of stock of organic carbon, the risk of forest fires is relatively high so such forms of management might represent a lower level of insurance against forest fires for the surrounding areas, while solutions for forest management based on fuel reduction via thinning, controlled burns and grazing, as well as planting fire-resistant vegetation, fire breaks and buffers, supporting mixed forests and forest-agriculture landscapes can reduce the fire risk for neighbouring areas (Berchtold, et al., 2023).
Insurance schemes can provide important support for forest owners who are implementing NbS, with the following options (Smeenk et al., 2024):

- Insuring the implementation of NbS and connected liabilities (e.g. regarding fire risk, for instance in prescribed burning campaigns).
- Insuring natural assets to protect them against damages caused by extreme events.
- Creating insurance-based incentives for the adoption of NbS by offering premium reductions or increases based on the implementation of these solutions (e.g. ecological forestry practices in California's French Meadows area can decrease insurance premiums by up to 41% for nearby homes) (Martinez et al., 2021).
- Divesting/Investing/donating: Insurers can contribute to NbS by divesting from activities harmful to the environment and investing in projects that restore and protect natural ecosystems (Smeenk et al., 2024).

Insurances are currently experiencing increasing difficulties to face soaring costs, to a point that in California two major home insurers announced they would leave the home insurance market referring to increasing costs due to, inter alia, rapidly growing catastrophe exposure[9]. For those who still can access insurance coverage, premiums for properties in risk-prone areas are rising, leaving many homeowners with uncovered properties due to problems of affordability.

Studies indicate that beyond impacts from climate change, and socio-economic developments (e.g. urbanization of wildland areas extending the WUI interface), certain forest management practices can also contribute to an increase of wildfire risks. In California, during the last century, wildfires have been actively

[9] https://apnews.com/article/california-wildfire-insurance-e31bef0ed7eeddcde096a5b8f2c1768f#:~:text=Providers%20are%20offering%20fewer%20and,regulation%20of%20the%20insurance%20industry .

suppressed to protect properties. This forest management strategy results in unnaturally dense forests which are prone to severe fires and destruction (Martinez et al., 2021). Modelling the risk reduction effect of an ecological forest management strategy in a watershed, Martinez et al. (2021) find that such a risk reduction could be reflected in home insurances with a reduction of the premiums to be paid between 41 and 52%. To create realistic business models for NbS within insurance mechanisms, reliable quantification of impacts and benefits of NbS are needed, based on experiences made with different NbS implementation.

5.4 Barriers to adoption among private owners

The adoption of NbS among private forest owners is, to a large extent, hampered by insufficient knowledge about NbS and their implementation, a fact which underlines the importance of advisory measures and services and of co-creation processes. Furthermore, there are also structural constraints limiting the access to the resources needed for the implementation of NbS. Andersson et al. (2017) highlight, with regards to adaptation of forest stands in Sweden, the existence of further barriers to adaptive transformation of forest management. These barriers can be psychological (feeling of powerlessness and low self-efficacy after climate related damages to forests leading to lack of self-esteem), economic (high dependency on forests markets), and structural (embeddedness of forest owners in a system of advice services, supply of seedlings and commercialization of timber). Such barriers are embedded within the Swedish system – a strongly export-oriented timber production system which is responsible for a high share of the national GDP (Andersson et al., 2017). Such a dependency on product chains (seedlings and sawmills with specific offers of seedlings and requests for type of timber), alongside with a low level of incentives for the adaptation of forests, may not have the same weight in less timber export-oriented countries, but the lack of knowledge and advice alongside with unfavourable market conditions may play a role, in particular for forest small holders.

The lack of knowledge on the side of forest owners is also a limiting factor for the uptake of specific insurance schemes, as there is a disconnect between insurance companies, which are highly motivated and have significant funds available for investment on the one side and the low level of experience and training of potential underwriters, so that, despite the availability of resources, insurers may find it difficult to provide incentives for NbS (Berchtold, et al., 2023).

5.5 Managing conflicting policy objectives and NbS trade-offs

Trade-offs between the use of NbS in forestry and socio-economic needs and capacities among forest owners and in local communities are emerging, and, as NbS become more widely applied, will keep doing so. For this reason, it is crucial to adopt management measures that are context- and time-specific, as solutions effective in one area might not work in another (Smeenk et al., 2024, p. 10). While policies for forest management must provide large-scale and territorial planning frameworks that align with legislation, they also need to consider local needs and specificities, as well as sectoral conflicts. Inter alia, in such a process, clear and careful communication to forest owners regarding different outcomes and trade-offs of different NbS, for instance with regards to biodiversity conservation vs. fire protection, is crucial, and the definition of priorities needs to be tailored to local circumstances (Smeenk et al., 2024). The focus on fire resilient management needs furthermore to be supported by prevention measures, such as government regulations against construction in fire prone areas.

Potential trade-offs can also appear between policy goals related to carbon sequestration and the mitigating wildfire risks: NbS solutions that involve the reduction of forest fuel to reduce wildfire risk may result in a reduction of forests biomass quantities, while forest managed for carbon storage tend to aim for higher biomass quantities. This has been observed for instance under the Improved Forest Management program in California (Herbert et al., 2022).


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6 Case studies overview

Eight case studies of NbS implementation in various European forest ecosystems to mitigate the increasing risk of fire and pest outbreaks induced by climate change are here proposed. The following table (Table 1) provides an overview of these case studies, while their complete description is reported in Annex 1. With reference to the ecoregional clusters introduced in section 3.2.2, case studies are located (Figure 3): (i) in the Mediterranean Region (Italy, Spain and Portugal, case studies n. 1, 2, 3, 4 and 7), (ii) in the Continental region (Germany, case study n. 6), (iii) in the Atlantic and North Sea region (the Netherlands, case study n. 5); and (iv) in the Arctic and Boreal region (Finland, case study n. 8). The information gathered from case studies was used to identify key learnings, as discussed in chapter 7.

Figure 3: Red dots indicate the approximate location of the eight case studies analysed in this report, with reference to the regions introduced in the chapter 3 of this report.

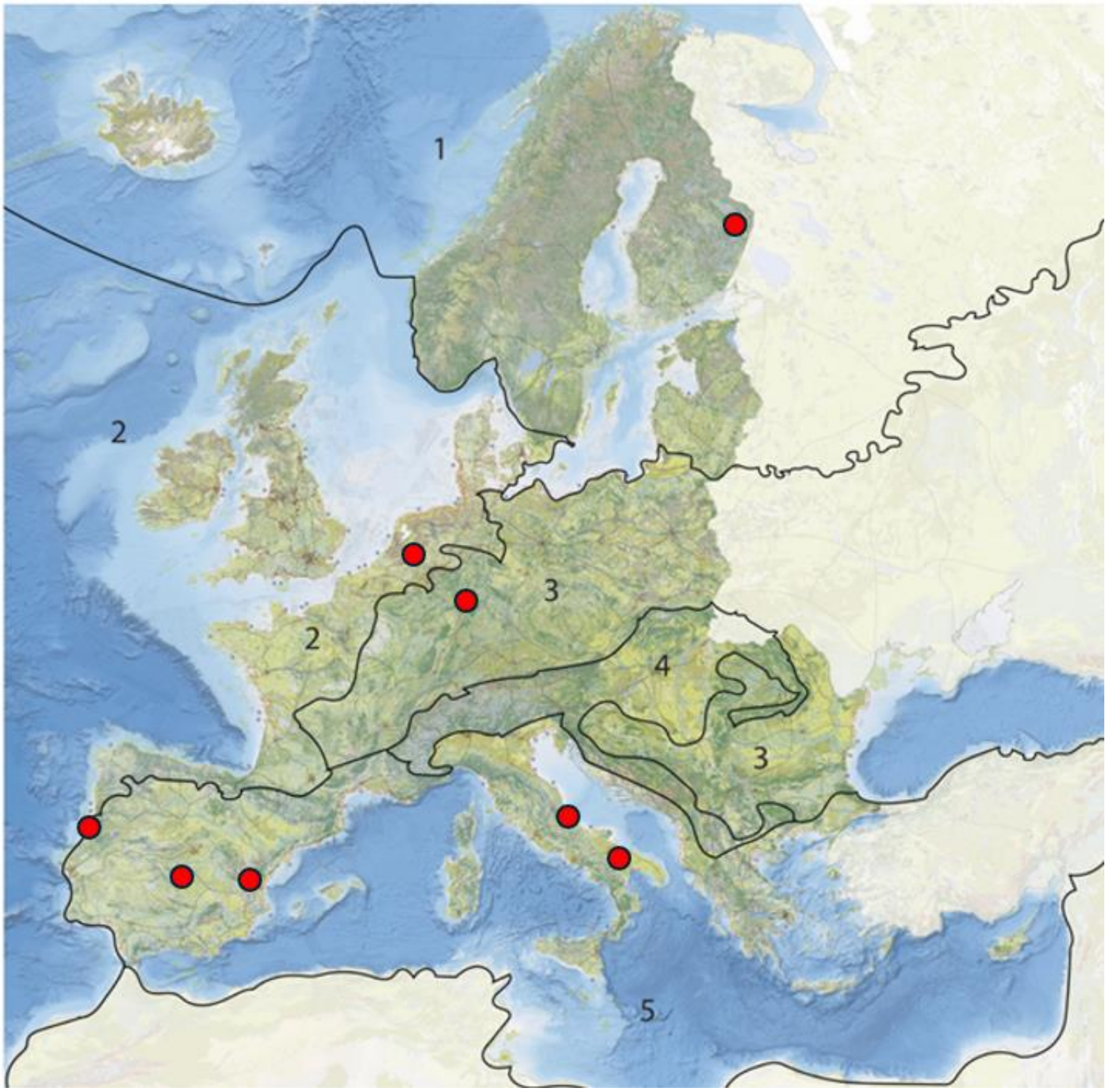

Table 1: Overview of the eight case studies on NbS implementation for fire risk and pest mitigation, with a comparison of biophysical, socio-economic and governance scaling factors.

Case study			Challenges		Implemented solutions		Suitability factors for scaling			Source
N.	**Title**	**Location**	**Main climate change impact addressed by NbS**	**Other challenges addressed by NbS**	**Type of NbS implemented**	**Other actions**	**Biophysical conditions/ environmental success (+) and limiting factors (-) of NbS**	**Socio-economic conditions/socio-economic success (+) and limiting factors (-) of NbS**	**Governance conditions/Governance success (+) and limiting factors (-) of NbS**	
1	**A community of practice for the sustainable management of forests surrounding the Occhito Lake, Italy**	**Occhito Lake, Puglia region, Southern Italy**	Fire risk	Decreasing population Agricultural land abandonment Disorganised silviculture Lack of a common forest management objective	**Prescribed fire** (tested) **Close to-nature and adaptive forestry** (Various actions proposed in the Forest Agreement)	Preparation of a Forestry management plan Development of a Forest Agreement (voluntary public-private partnership for implementing the management plan)	Mediterranean pine forest Dominating species Aleppo pine (*Pinus halepensis*, and Arizona cypress (*Cupressus arizonica*) (+) Various environmental co-benefits of NbS, including biodiversity enhancement, slope consolidation and reducing plant diseases originated by pests	Small, scattered villages surrounding the lake Forest used for timber production and recreational activities The subscribers of the Forest Agreement are both beneficiaries and financial contributors (+) Increased safety from fire risk (+) Circular economy implementation (marketing of wood residues); (+) Positive impact on local economies (short supply chain) and rural development (-) initial skepticism towards prescribed fire	Presence of a mosaic of state, municipal and private properties (+) Forest shared by two neighbour regions (Molise and Puglia) (+) High interest from several municipalities (-) Regional legislation gap (addressed during the project) for scaling the prescribed fire technique	PABLO project https://www.gopablo.it/ Climate-ADAPT case study https://climate-adapt.eea.europa.eu/en/metadata/case-studies/a-community-of-practice-for-the-sustainable-management-of-forests-surrounding-the-occhito-lake-in-puglia-italy
2	**Building fire resilience using recycled water in Riba-Roja de Túria, Spain**	**Riba-Roja, Valencian community, Spain**	Fire risk		**Prioritizing fire-resistant vegetation Green infrastructure, green corridors and buffer zones** (Green belts -fire breaks to slow down or stop the progress of forest fires and to surface wind speed) **Close to-nature and adaptive forestry** (Silvicultural ordinary treatments to reduce fuel load) **Reforestation and afforestation with native and diverse species Reforestation** with fire resistant species	Use of recycled water from municipal wastewater treatment plant to prevent and manage fire risk Use of a large network of sensors to capture early signals of fire	Mediterranean forest Mix of conifers and broadleaved trees with pyrophytic characteristics Wildland-urban interface, i.e. areas of transition between forest and built areas. (+) Various environmental co-benefits of NbS: • increased regeneration • Control of invasive species • Delivery of various ecosystem services (e.g. water preservation, greenhouse gas sequestration) (-) prescribed fire not done due anomaly in the weather conditions (winter high temperatures and winds).	Small villages and communities with economies largely dependent on forestry, agriculture, and, in some cases, tourism (+) Expected Increased safety from fire risk; (+) Circular economy implementation (water reuse), (+) Possible return on investment due to the provision of ecosystem services	(+) High interest from Riba-Roja municipality (+) Proactive and committed leadership throughout the project lifecycle (-) Legislation gap (addressed during the project) for reusing wastewater for fire prevention (-) Possible obstacles due to complex permitting procedures and nature conservation constrains	GUARDIAN Project https://proyectoguardian.com Climate-ADAPT case study https://climate-adapt.eea.europa.eu/en/metadata/case-studies/building-fire-resilience-using-recycled-water-in-riba-roja-de-turia-spain

Case study			Challenges		Implemented solutions		Suitability factors for scaling			Source
N.	**Title**	**Location**	**Main climate change impact addressed by NbS**	**Other challenges addressed by NbS**	**Type of NbS implemented**	**Other actions**	**Biophysical conditions/ environmental success (+) and limiting factors (-) of NbS**	**Socio-economic conditions/socio-economic success (+) and limiting factors (-) of NbS**	**Governance conditions/Governance success (+) and limiting factors (-) of NbS**	
3	**Sustainable forestry for increasing climate change resilience of forests in Soria, Spain**	**Soria province, Central-northern Spain**	Fire risk Pest outbreaks Changing the growth patterns of trees and suitability of species		**Close to-nature and adaptive forestry** (Establishing mixed species composition) **Prioritizing fire-resistant vegetation** (Introduction of broadleaved forest species into large coniferous forest stands) **Grazing management** (managed grazing through alternating fenced off areas) **Pheromone traps** (to monitor the presence of insects, e.g. *pine processionary*) **Natural and assisted natural regeneration** (animals are kept away to allow natural regrowth)	Early detection of fires, based on watchtowers with guards, thermal cameras, smoke detection and visible camera. Forest fire crews for continuous fire prevention	Mixed tree composition of conifers and deciduous species Dominant species: *Pinus sylvestris* (Scots pine), *Pinus pinaster* (maritime pine), *Pinus nigra* (black pine) and *Juniperus thurifera* (Spanish juniper); *Fagus sylvatica* (European beech), *Quercus ilex* (holly oak), *Quercus faginea* (Portuguese oak), and *Quercus pyrenaica* (Pyrenean oak).	High economic value of the forest Natural space for recreational activities (+) Preserved forest wood and non-wood products, including: resin production, mushrooms, truffles, hunting and extensive domestic livestock). (-) Presence of agricultural areas bordering the forest (competing interests)	Mosaic of private, public, industry and educational institutes Forest managed by a group of owners (Montes des socios) (+) Presence of the Association of Forest Owners of Soria (ASFOSO) to save mountains from abandonment and facilitating contact between private owners and the administration. (-) Lack of formal organisation of the shared ownership, left without a management body to make decisions.	LIFE Soria ForestAdapt https://soriaforestadapt.es/en Climate-ADAPT case study https://climate-adapt.eea.europa.eu/en/metadata/case-studies/sustainable-climate-change-adaptation-of-the-forest-sector-in-the-province-of-soria-spain
4	**Prescribed fire and grazing as integrated approach to make forests more resilient in Viseu Dão Lafões, Portugal**	**Viseu Dão Lafões, Central Portugal**	Fire risk	Abandonment of traditional livestock farming Growing rural exodus, transformation of the animal production from extensive to intensive models.	**Grazing management** (preparation of grazing plans for a space and time optimisation of this activity) **Prescribed fire** **Reforestation and afforestation with native and diverse species** (*Quercus robur*, *Quercus pyrenaica* and *Quercus suber*)	Building animal drinking fountains	Mixed rural landscape with both forest and pasture areas Dominant species: pine (*Pinus pinaster*), eucalyptus (*Eucalyptus globolus)* and species of the Quercus family (+) Various environmental co-benefits of NbS: • increased soil fertility • reduced soil erosion • control invasive plant species and pests • increased regeneration (-) High dependence on meteorological conditions and terrain conditions (vegetation type) suitable for prescribed burning	Forest used for *Eucalyptus* production Presence of pasture areas (+) Sustainable food production enhanced, with low carbon footprint (+) Abandoned or low production areas transformed into areas capable of generating high-quality products and services (+) Preserved local culture and tradition (-) Local population initially concerned about the use of prescribed fire	Municipalities joined in a Intermunicipal Community (Viseu Dão Lafões CIM) (+) Role of CIM for preserving forest recognised by law and recently reinforced (+) High attention to training needs for the use of prescribed fire	LIFE landscape fire project: https://life.cimvdl.pt/?lang=en Climate-ADAPT case study: https://climate-adapt.eea.europa.eu/en/metadata/case-studies/prescribed-fire-and-grazing-as-integrated-approach-to-make-forests-climate-resilient-in-viseu-dao-lafoes-portugal

Case study			Challenges		Implemented solutions		Suitability factors for scaling			Source
N.	**Title**	**Location**	**Main climate change impact addressed by NbS**	**Other challenges addressed by NbS**	**Type of NbS implemented**	**Other actions**	**Biophysical conditions/ environmental success (+) and limiting factors (-) of NbS**	**Socio-economic conditions/socio-economic success (+) and limiting factors (-) of NbS**	**Governance conditions/Governance success (+) and limiting factors (-) of NbS**	
5	**Wildfire risk reduction in Deurnse Peel by landscape diversification, the Netherlands**	**Deurnse Peel, Southern Netherlands**	Fire prevention Pest outbreaks		**Green infrastructure, green corridors and buffer zones** (Ecological corridors with deciduous/broadleaved forests) **Reforestation and afforestation with native and diverse species** (of areas hit by pest) **Close to-nature and adaptive forestry** (Creating diverse mixed forests on landscape scale - broadleaved species and pine trees)		Dry sandy soils, poor of nutrition Pine/Fir/Douglas/Lork and different species of broad-leaved deciduous trees (+) Various environmental benefits of NbS related to the increase of biodiversity (insects, birds, mammals, vegetation)	Forests both managed as investment assets and public forests Forest used for recreational activities (-) Lack of funds for implementing measures	Different types of property regimes, including small-scale private owners, and consortia of small-scale owners (+) Forest owners are obliged to reforest areas hit by pest (+) The state authorities as well as national authorities provide subsidies for reforestation of areas destroyed by pest infestation (+) Reforestation must consider suitability of single species under different future climate regimes (+; -) Strict conservation regimes for reforesting some natural areas (-) No forest transformation is possible without the consent of the owner.	LIFE Climate Forest https://www.climateforest.eu/en/climate-smart-forest-management/ SUPERB Project www.forest-restoration.eu/wp-content/uploads/2023/02/Workplan_Netherlands_V1.0.pdf
6	**Large-scale forest restoration solutions for resilience to multiple climate stressors in North Rhine-Westphalia, Germany**	**North Rhine-Westphalia, Northwest Germany**	Wind, drought and subsequent European spruce bark beetle (*Ips typographus*) outbreaks Spruce forests no longer suitable due to changing climate		**Reforestation and afforestation with native and diverse species** (according to the "four tree species principle", i.e. suitable compositions of tree species according to the site typology and future climate suitability) **Natural and assisted natural regeneration** (deer management)		Dominating spruce stands following the demand for pit timber in the 19th century Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) replaced previously existing beech and mountain beech forests (+) Preservation of various ecosystem services delivered by the forest (climate regulation; water regulation and supply; erosion control; habitat provision and recreation) (-) Deer management: large deer populations causing heavy browsing affecting the restoration success	Wood harvesting and hunting are the two main economic activities (+) Expected increase in wood harvest (tangible only in 30 years or beyond) (-) Resource shortages (planting materials, skilled personnel, etc.) are challenging a full and timely reforestation (-) Many forest owners are financially unable to manage reforestation; lacking income from forests	Different types of forest owners, ranging from public (state, local authorities), to church and private owners (+) All restoration measures are developed in cooperation with the landowners or the forest managers representing the landowners. (+) Legal obligation for reforestation, supported by subsidies (-) Rigid rules apply to conservation sites (Conflicting restoration objectives in Natura2000 area)	SUPERB Project https://forest-restoration.eu/demo-area-north-rhine-westphalia/
7	**Biological control and use of mycological resources to reduce**	**Tuscany region, Northern Italy**	Chestnut blight, a disease caused by the invasive pathogen		**Soil microbial restoration** (Biological control and use of mycological resources:		Deep, well-drained soils, moderate acidity Presence of chestnut and other Mediterranean tree species	Chestnut production for timber and fruit Possible sources of funding for scaling NbS come from a combination of European Union programs (like LIFE or	Private owners Model Forest of "Montagne Fiorentine", voluntary and no-profit association dedicated to improving sustainable forest and land management in the region.	LIFE Mycorestore project https://mycorestore.eu/en/

Case study			Challenges		Implemented solutions		Suitability factors for scaling			Source
N.	**Title**	**Location**	**Main climate change impact addressed by NbS**	**Other challenges addressed by NbS**	**Type of NbS implemented**	**Other actions**	**Biophysical conditions/ environmental success (+) and limiting factors (-) of NbS**	**Socio-economic conditions/socio-economic success (+) and limiting factors (-) of NbS**	**Governance conditions/Governance success (+) and limiting factors (-) of NbS**	
	the risk of tree diseases in a chestnut forest, Italy		*Cryphonectria parasitica*. Ink disease, caused by the soil-borne pathogen *Phytophthora cambivora*. Increased forest vulnerability to both biotic (pests and pathogens) and abiotic stressors (drought and fire) due to climate change.		Inoculation of Edible and Non-Edible Mycorrhizal Fungi Biological Control of Chestnut Blight Soil Inoculation with Biocontrol Agents (BCAs)		Presence of tree species that face similar phytopathological issues such as *Phytophthora* and *Cryphonectria parasitica* infections (+) Improved nutrient cycling and soil health. (+) Improved forest biodiversity and health (+) Reduced need for chemical interventions	Horizon Europe), national government incentives for sustainable forestry, and private-sector partnerships (+) Participation of smallholder chestnut producers that directly benefit from the ecosystem services provided by healthier, more resilient forests (+) Preserved economic production (+) Diversified forest products (truffle-producing mycorrhizal fungi)	(+) high level of commitment in sustainable development initiatives that preserve forests (-) Potential lack of awareness, financial constraints, or regulatory gaps	
8	**Introducing mixed species to reduce the risk of spruce bark beetles in North Karelia, Finland**	**North Karelia, South-Eastern Finland**	Increasing risk of pest outbreaks (Increasing summer temperatures and longer growing season of bark beetle). Large damages caused by fire, storms and drought		**Reforestation and afforestation with native and diverse species** Introducing broadleaved tree species to promote resilience and biodiversity **Close to-nature and adaptive forestry** (Sustainable forest management and biodiversity enhancement) **Dead biomass management** (reduce the availability of habitat for bark beetles and improve habitats for predators)		Norway spruce (Picea abies) and Scots pine (Pinus sylvestris) forming varying mixtures with birch (Betula sp.). (+) more biodiversity (+) enhanced soil fertility	Important nature destination Several forest industry companies, such as forest machinery and wood logistics companies, pulp and paper mills and sawmills dispersed throughout the region. Major wood construction companies also play significant roles. (+) Improved nutrient cycling and soil health.	Private, state, other public owners, and companies accounting for 55%, 19%, 5% and 21%, respectively. Finnish Forest Centre (FFC): a crucial entity in forest governance, actively promoting the forestry sector and providing guidance to landowners	North Karelia Living Lab https://www.eco2adapt.eu/living-labs/finland-ll


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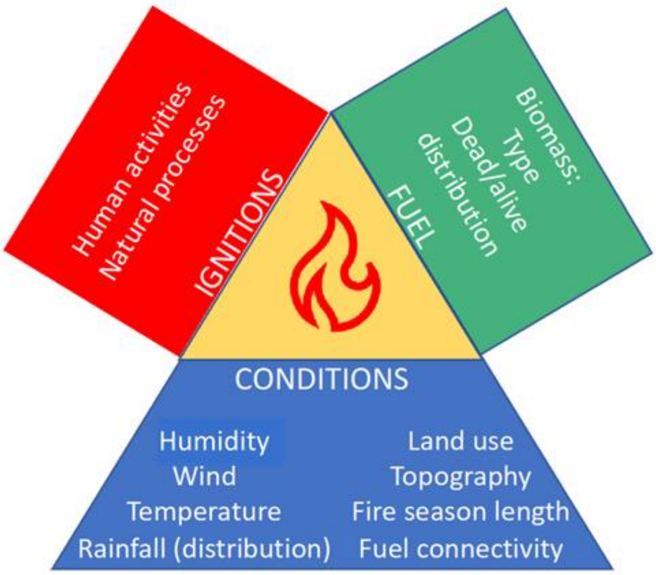
7 Discussion: Scaling factors across case studies

In this section, we focus on how different NbS can be used to create more fire and pest resilient forests and landscapes. First the fuel, climate, and landscape conditions (biophysical elements for the occurrence, intensity, and spread of a fire) are discussed (as shown by Figure 4 for the case of fire). Then the social-economic and governance conditions needed to enable such a resilient landscape are discussed. To support this analysis, the discussion uses examples and learnings from the case studies presented in Chapter 6 and described in Annex 1 in combination with insights from the literature review.

The complete list of main typologies of NbS discussed in this document (both from literature and from case studies), with relevance for fire or pest management or both, is reported in Annex 2.

Figure 4: Elements determining the fire occurrence, intensity, and spread (adapted after Keesstra et al., in prep).



7.1 Biophysical factors

Due to climate change, the conditions for fires and pest outbreaks are changing: humidity, wind, temperature and the amount, intensity and distribution of precipitation over the year changes. This has immediate effects on fire and pest risk, pests and post-fire risks as described in the literature review above. As these climatic changes require adaptation to preserve the integrity of forests and their ecosystem services, NbS come into play to adjust the elements that are depicted in Figure 4.

7.1.1 Using NbS to change fuel conditions: vegetation type

Some of the case studies tested the planting of more fire-resistant species (**case 2 and 3**). This NbS is particularly aimed at preventing crown fire. Planting more fire-resistant species has a smaller impact on groundfire and surface fire, and moderate impact on windborne embers fire (fires caused by hot coal fragments carried by the wind). It is an effective solution, especially considering the extreme difficulty of fighting crown fires. If this option is implemented with consideration for native species and alongside with an active control of alien species, case studies showcase co-benefits in terms of biodiversity. Moreover, if it is done within the framework of reforestation activities, synergies with mitigation (carbon sequestering and storage) are also reported.

The maintenance of wet soil conditions for new planted species can be a critical factor for the effectiveness of this option, especially in dry weather conditions and can limit its scaling potential. The combination with measures that encourage water reuse (**case 2**) can favour the implementation of this option and support water preservation in arid landscapes.

In the analysed case studies, the planting of fire-resistant species has been considered in forests composed of different conifers and broadleaved trees with pyrophytic characteristics (**case 2 and 3**). To be effective and sustainable in the long term, the selection of species needs to be tailored to site-specific conditions, and consider current and projected climate conditions for the future (Waldwissen, 2020).

In some areas, the introduction of species other than flammable pines proves more difficult due to poor soils, or changing, drying climatic conditions. Proper landscape planning such as described in the Dutch (**case 5**) and the German (**case 6**) study show that if the planting plan includes finding optimal 'stand places' the approach is expected to be successful. In suitable areas, it is key to select the right species of deciduous trees for underplanting as they are not equally able to withstand fire and a forest consisting of different species is more resistant to pest outbreaks (Waldwissen, 2020).

Secondly, foresters are working with close-to-nature, or nature inclusive forestry or silviculture. Although it can be considered an efficient intervention to enhance forest resilience to pest and wildfire risks, the results of various silvicultural measures will only be felt after a few years (Waldwissen, 2020).

7.1.2 Using NbS to change fuel conditions: vegetation management

A much-used approach in fuel management is prescribed fire (also known as prescribed or controlled burnings). These burnings (**tested in case 1 and 4**) create a more open landscape which will make a fire during summer easier to extinguish and less intense. This makes the fire not only less dangerous for people, but the fire will also damage less vegetation and forests can recover faster. Apart from this, the co-benefits are high: more biodiversity, increased soil fertility, reduced erosion, and even a way to control invasive plant species and reduce the vulnerability to pests (**case 1**), albeit this may create potential trade-offs with regards to connectivity.

Although prescribed fire can be theoretically implemented in any forest landscape, the identification of strategic fuel management points is crucial for its effectiveness. Moreover, its implementation requires precise weather conditions. In this regard, an activity of prescribed fire in an abandoned cropland had been scheduled as part of **case study 2**, but not actually implemented due to anomalies in the weather conditions (winter high temperatures and winds) that were not compatible with the use of prescribed fire. This limitation needs to be considered when planning this type of intervention.

Another way to manage the fuel condition is to use grazing. Goats, cattle and sheep are used to clean the forest undergrowth, as shown in **case 3 and 4**. Apart from the fire risk reduction, the co-benefits of this solution include a more biodiverse (seed dispersion) and more aesthetically attractive landscape, as well as increased soil fertility. Managing the grazing pressure by domestic animals is particularly suitable for mixed landscapes with both forest and pasture areas. Agroforestry is an option related to managed grazing, especially in regions where the agricultural landscape is dominated by pastures. In addition, in the past, orchards surrounding villages often helped with creating a buffer between the village and the flammable forest. From a fire-risk management perspective, agroforestry creates barriers to fire spread in forest landscape and helps maintaining soil moisture by storing water in the area. In fact, it prevents runoff from the land and can support water retention due to better and deeper rooting of plants and trees. Additionally, since trees provide shade, less evaporation can occur. Furthermore, agroforestry also improves habitat for wildlife and pollinators. Nevertheless, due to their high labour intensity, high maintenance costs, long turn-over times, and high need for knowledge and technology, many of these types of systems have been abandoned. In this regard, also due to changing general socio-economic conditions, the abandonment of agricultural land (rural exodus) and of traditional livestock farming have been reported in some of the case studies investigated (**case 1 and 4**).

A third way to tweak the fuel and vegetation types is reforestation/afforestation. Fire and future proof afforestation, such as promoted in Germany (**case 6**), follows the so-called "four tree species principle", i.e. the use of suitable compositions of tree species within a forest stand, adapted to the specific site characteristics and to current and future climate. Reforestation can be done in any landscape hit by both fire and pest events and can be combined with the use of fire-resistant and climate- adapted species. The case studies analysed in this report showcase different examples of this option, both in southern Europe (**case studies 2, 4**) and in northern Europe (**case studies 5 and 6**). To favour forest regeneration in areas affected by fire and pests, case studies also show the importance of managing the grazing and browsing pressure, highlighting the need of keeping animals away in certain areas to allow natural regrowth (**case 3**) and actively regulating deer population (also including hunting in the reforestation plans (**case 6**).

A fourth way to tweak the fuel and vegetation type is rewilding. However, while this concept is becoming increasingly popular, well-meant initiatives can actually cause harm if they follow the wrong principles. As highlighted by the IUCN, "rewilding principles are inconsistently defined, and often misrepresented and misapplied" (IUCN, 2021). This can even lead to biodiversity loss in some cases, and strong anti-rewilding sentiments among local people. Rewilding should not be confused with unmanaged land abandonment that can instead increase the risk of wildfire, as happened in the regions of **case 2 and 4**. In these areas, land abandonment has been occurring on former agricultural fields that formed an effective fire break between the forest and the urban areas. Rewilding is different from land abandonment in that it aims at restoring natural processes to allow self-sustaining ecosystem functioning that require no or minimum human intervention. For successful rewilding, it is key to consult and involve local communities, both to raise public awareness and to incorporate local knowledge. Rewilding might be also associated with the sustainable development of certain activities, to achieve multiple benefits, offering for instance additional income to counter land abandonment in **case 4**. To mitigate the risk of ill-implementation and adverse effects of rewilding, 10 guiding principles were developed by IUCN's Rewilding Thematic Group together with more than 150 experts, that help decisionmakers and funding organizations to assess the potential impact of initiatives before giving their support (IUCN, 2021).

7.1.3 Using NbS to change landscape conditions: creating fire breaks and landscape mosaics

There are different ways to create a fire break in the landscape: it can be done by creating a barrier without vegetation, or by creating a non-flammable vegetative barrier. As vegetation-free zones cannot be seen as a NbS, we focus on vegetative measures.

Healthy, transpiring vegetation halts fires (Kitzberger et al., 2016). Therefore, broadleaf rows of trees are often planted in pine tree forests to stop or slow down fire. These deciduous trees can also be provided with additional support, as shown in **case study 2** where these firebreaks are irrigated with re-used water (from an advanced wastewater treatment plant) to make them more effective. In the nature conservation area in the Netherlands (**case 5**) a vegetation plan has been created that matches landscape conditions in terms of soil types and hydrological conditions with suitable mixes of tree species.

The mosaic landscape is the result of a careful process of:

I. matching the conditions of each site with the optimal conditions of each tree species,
II. taking into account the location of roads and ensuring the access to the area for fire suppression, and
III. considering land use both in the national park as well as in the surrounding areas (urban areas and agricultural land).

Additionally, alternative vegetative fire breaks can be explored with consideration for integrating ecological added value in functional fire breaks, such as connectivity; not only looking at trees but also in other types of vegetation. In addition, a combination with activation by the fire brigade (wet break) can be considered.

Another effective NbS is rewetting, which especially targets groundfire and ignition rates on formerly reclaimed land, as the specific flammability of peatland vegetation is reduced by increased moisture content of the soil and vegetation. In a situation of dry soil and vegetation, fire can easily and rapidly spread. Moisture levels of soil and vegetation also determine severeness of the fire impact on the ecosystem (Tersmette, 2023). From a fire-fighting perspective, it is key that accessibility is safeguarded – the condition of access roads needed for emergency and firefighting need to be considered. Fire trucks are heavy vehicles that need to be able to get close to the fire and still be agile – access routes should be planned carefully so that these trucks do not get stuck in the wet soil.

7.1.4 Effects of NbS on the soil-sediment-water system

Using the soil-sediment-water system as a foundation for landscape planning creates conditions that naturally reduce fire and pest risks. Healthy soils with balanced organic content and moisture retention reduce vegetation dryness, which lowers fire susceptibility. Effective sediment management, such as minimizing soil erosion on slopes, helps maintain soil stability and nutrient availability, supporting a diverse and resilient plant ecosystem that can better withstand drought and resist pests. After a fire, soils that are deprived of their vegetation are vulnerable to erosion. The vegetation recovery depends on several interdependent characteristics of the forest: total fuel load, vegetation diversity and species, and vegetation health. Together, these factors determine the intensity of the fire and the possibility of vegetation recovery. The intensity of the fire is an important factor for the recovery of a burned forest: with higher fire intensity, vegetation needs more time to recover.

Water systems, including wetlands and riparian zones, act as natural firebreaks and habitat buffers, slowing fire spread and providing refuges for species affected by fire or pests. These areas maintain higher moisture levels and are critical for creating cooler microclimates within landscapes, which can inhibit both fire ignition and pest proliferation. A well-integrated soil-sediment-water approach in landscape planning thus strengthens ecosystem resilience, promoting healthier vegetation that is less likely to experience stress-related pest outbreaks or rapid fire spread.

7.1.5 Effects of NbS on biodiversity

Close-to-nature forestry (sometimes also called close-to-nature silviculture) is an approach that emphasizes forest management practices mimicking natural processes, resulting in healthier ecosystems and enhanced biodiversity. Unlike conventional forestry, which often focuses on maximizing timber yield, close-to-nature forestry prioritizes ecological functions, maintaining diverse tree species, age structures, and vegetation layers within a forest. This approach avoids clear-cutting and instead uses selective thinning and natural regeneration to ensure that forests remain dynamic and rich in species. Close-to-nature forestry was widely mentioned in case studies analysed in this report, both in Southern Europe (**case 1, 2, 3**) and in Northern Europe (**case 5, 8**).

A primary benefit for biodiversity in close-to-nature forestry is the preservation of mixed species and varied tree ages. Diverse tree species offer varied habitats, food sources, and nesting opportunities for a broad range of wildlife, from birds and insects to mammals and fungi. The presence of older trees and deadwood, which are often removed in conventional forestry, supports unique species like woodpeckers, owls, and certain insects that rely on these elements for survival. Deadwood, in particular, provides habitat for decomposers and fungi, playing a crucial role in nutrient cycling and supporting forest soil health.

Moreover, close-to-nature forestry reduces soil disturbance by minimizing heavy machinery and clear-cutting, helping maintain the understory plants and soil organisms that are vital for biodiversity. This approach also protects forest soils from erosion and compaction, preserving the forest floor ecosystem that many plants, animals, and fungi rely upon.

By promoting natural regeneration and allowing forests to maintain their natural composition, close-to-nature forestry creates resilient ecosystems better equipped to adapt to climate change and disturbances like pests or diseases, as well as fire disturbances. The emphasis on maintaining natural structures, species diversity, and minimal intervention creates forests that not only support higher biodiversity but also offer ecosystem services such as carbon sequestration, water purification, and recreational spaces, benefiting both wildlife and human communities (Houria et al., 2022).

Moreover, selecting tree and plant species that are adapted to specific site conditions and future climate scenarios enhances fire resilience in forests (**cases 1, 3, 4, 5 and 6**). Species naturally suited to local soil, moisture levels, and temperature ranges are more likely to establish strong root systems and maintain high moisture content, both of which help in resisting fires. Healthy forests with a rich biodiversity will furthermore be able to better withstand pest outbreaks. Additionally, species chosen with future climate projections in mind are better equipped to withstand potential droughts and temperature fluctuations, reducing stress that can increase flammability. This targeted species selection leads to ecosystems that are healthier, more resilient to fire, and better able to regenerate in post-fire conditions.

7.2 Socio-economic and governance factors

In Europe, forest ownership is a key factor for the adoption of NbS in forestry, with distinct patterns across the continent. Public owners often focus on biodiversity and community benefits at least as part of their management goals, while private owners, who dominate in several countries, show a mix of commercial and conservation motivations. These diverse ownership structures affect NbS implementation, investment needs, and ecosystem management. Smallholders may struggle with the costs of reforestation and fire prevention as well as with increased management costs caused by mixed stands, while institutional investors and community forests can put more focus on sustainable, long-term benefits. Public and private partnerships, subsidies, and support systems are essential to bridging these gaps and ensuring balanced ecological and economic outcomes.

7.2.1 Forest ownership

Forest ownership varies across Europe, with larger shares of public ownership in some European regions and prevalence of private property, often consisting of smallholders as well as of commercially acting enterprises, in other areas. The rate of privately owned forests in Europe varies between approx. 70% in countries like Austria, Denmark, Finland, France, Norway, Portugal, Spain and Slovenia while the share between family and public owners is more balanced in most Eastern, South-Eastern and Central European countries (Weiss et al., 2019, p. 10). Most of the private forest property is below 10 ha (Muys et al., 2022). Implicitly, the divide between public and private could be understood as a distinction between profit-oriented ownership (commercial investors) and those who lack resources, knowledge and eventually interest in managing their forests. While in principle, forest owners have the exclusive legal rights to “use, control or transfer” when it comes to benefiting from their forests (UNECE, 2020), owners’ rights are restricted by “legal regulations and social customs associated with the forest land in question.” (UNECE, 2020, p. 1).

At a closer view the attitude and expectations of private as well as of public owners are much more multifaceted, with “institutional investors e.g. in Romania, Latvia, Finland and the UK that purchase forest land for intensive management,” (Weiss et al., 2019, p. 13), and private owners that are interested more in biodiversity conservation than in exploitation of their forests.

7.2.1.1 Public forests

Throughout the case studies investigated in this report, public forest ownership (forests owned by public institutions) is present in most cases as one element of the mosaic of actors. These publicly owned forests are generally dedicated prevalently to the generation of public benefits (biodiversity conservation, recreation) as the dominant type of benefits generated, although some economic exploitation of timber production may be present and part of the ownership model, mainly to cover management costs. This type of public ownership refers to different territorial administrations (state, sub-national levels, municipalities). Municipalities, alongside with church properties, represent, in some cases, an intermediate type of ownership, which is public (or in the case of church property, private) but closely related to local communities.

7.2.1.2 Community forests

Community forests have long traditions in some countries as Poland, Italy and Spain, and are emerging in some countries, such as Belgium, where a specific form of co-owned forests has been piloted to provide ecosystem services via a new ownership form, a statutory partnership of several public forest owners and stakeholders, and in Scotland, where rural communities were given the right to have the first opportunity to purchase rural estates on sale, provided they can raise the necessary resources for the purchase (Weiss et al., 2019, p. 15).

Among the case studies examined in this report, a traditional form of community ownership is found in the Spanish case study of Soria (**case 3**). Under such forms of ownership of forests and pastures, citizens traditionally had the right to collect firewood and graze their animals. Land is co-owned and ownership rights do not refer to a specific part of the land, but to a percentage of the overall surface, so that differences in qualities and yields are equally shared among co-owners and management decisions and rules are defined collectively. Forest communities, due to their specific model of shared ownership with limited rights to individual exploitation, manage forests as a long-term source of benefits, which comprise, to a certain extent, economic incomes from wood products to satisfy local economic needs (e.g. schools, scholarships), and small benefits for community members, but aim primarily at conserving their forests. This form of ownership based on use-rights can lead to a higher interest in sustainable exploitation of the resources owned collectively and reduce the risk of over-exploitation by social control.

7.2.1.3 Privately owned forests

Privately owned forests represent the third ownership model. Under this model, varying degrees of importance are given to forest productivity, sustainability and conservation of biodiversity, and, as a result, we encounter different intensities and philosophies of forest management. The case studies included in this report reveal the presence of four main types of actors: private land owners with no or low expectation versus profitability of forest management or with low capacities for investing in reforestation, as in the German case (**case 6**); smallholders organized in associations which are able to manage forests in a commercial way, similar to large scale investors; and finally commercial investors interested in profitability of investments in forest properties (**case 6 and case 8**). Yet not all private forest owners are oriented towards commercial timber production, private owners who own forests for the sake of conservation appear to represent an increasing share of this group (Weiss et al., 2019). Among private owners, there are also smallholders or former small holders who have turned into absentee landlords, as they lack resources for managing their properties or have completely abandoned their land due to migration. In Spain and Portugal (**case 2, 3, 4**), where outmigration is heavily affecting socio-economic structures of rural areas, the lack of management of agricultural and forest areas is one of the main drivers of fire risk.

7.2.1.4 Fragmented ownership: a challenge for NbS implementation

The diversity in motivations, attitudes, and capacities among private forest owners can represent a major challenge for policy design and implementation and requires articulated and locally-specific management strategies. Such strategies need to be embedded in consistent overarching policy frameworks and spatial planning strategies. Such an approach which combines a mosaic of management strategies can support biodiversity conservation at the landscape level, particularly if integrated or triad approaches are employed (Weiss et al., 2019).

Forest ownership is fragmented in most of the case studies analysed for this report. Most forest areas analysed in the case studies are situated in areas with low population density, small villages and communities in economically disadvantaged areas (most case studies in Southern Europe) or at the peripheries of larger urban agglomerations (in some of the German pilots – **case 6** as well as the in the Dutch case – **case 5**). In all these cases private and commercial owners represent a part of the forest ownership, alongside public forms of ownership (municipalities, state) and church properties. This reflects well the composition of forest ownership in most northern and central European countries like Austria, Denmark, Finland, France, Norway, Portugal Spain, and Slovenia where private individuals represent more than two thirds of the forest ownership (Weiss et al., 2019, p. 10). The fact that forest owners, in particular those situated in rural and remote areas, are part of a weak socio-economic system with high dependence on agriculture and forestry, and scarce resources for long-term investments into their properties as those required for reforestation and close-to nature management.

7.2.2 Investment needs

Strategies for pest and fire prevention and adaptation of forest to climate change require investments which need to be made by forest owners, as public interventions on private forest areas are generally not foreseen in national legislative frameworks. National legal frameworks do, in some cases, impose rules, for instance the obligation of re-forestation after forest cuts, windfall and fires, as mentioned in the German case (**case 6**). Close-to nature forest management and the implementation of various NbS may reduce forest productivity, which may only partly be out-weighted by reduced risks of future fire or pest outbreaks.

The initial investments required for reforestation and preventive fire and pest management can exceed, in the case of small-holders or in weak socio-economic environments, financial and management capacities of forest owners. Such investments are, in the case of commercially exploited forests, a total renounce on incomes for the forests for the period of re-growth and eventually higher maintenance costs in mixed forest stands. On the other hand, long-term productivity of forests can increase due to higher resilience of forests and reduced risks (**case 7**).

Insurances could potentially support the deployment of NbS for the adaptation of forests to climate change, leveraging the risk reduction value of such actions by applying of premiums for ecologic management.

7.2.3 Support for the development of management strategies

In the case studies analyzed, several forms of support for forest management emerge, which can take the form of associations of smallholders for the joint management of their properties as in the case of one of the pilots in the German case (**case 6**), or associations with the specific goal of driving transformation in forest management (**case 5** in the Netherlands, **case 7** in Italy). While in the first case, the main goal is overcoming lacks in competitivity of small holders in the forest sector, in the case of the Dutch and the Italian associations (**case 5, case 1 and 7**), scientific and practical support is provided to forest owners to drive transformative forms of forest management.

Public support to forest management is provided in different forms throughout the case studies; in the Occhito case (**case 1**), management plans are co-created and jointly implemented in formal agreements as a public-private partnership between private and institutional forest owners to improve forest management and fire and pest prevention, where forest owners contribute financially to the management measures or have an active role in fundraising. In the German and in the Finnish case (**case 6, case 8**), state owned (the Finnish Forest Centre) or public governance agencies (Ministry of Agriculture of NRW) are providing guidance for forest owners and, in some cases, also offer financial support[10]. In the case of the subsidies offered in the German case study to support reforestation after fire and windstorms (**case 6**), the amount of subsidies paid for every measure is related to the extent to which guidance for the creation of mixed forests is followed (i.e. how many trees and which species have been planted per ha). The subsidy also covers follow-up activities and management costs for the first years of the reforestation phase.

7.2.4 Benefits from forest restoration

Forests are managed, in most of the cases analyzed, with the commercial objective of timber production, such as in the German case (**case 6**) and in the Finnish case (**case 8**). This dependency on timber markets exists, to a certain extent, also for private and institutional owners (local authorities, etc.) for whom the expectations on forest productivity are to cover at least costs of forest management and forest maintenance. A specific case among those analyzed is represented by the Italian study on chestnut woods (**case 7**), where the fruits of the trees represent an important economic product.

Damages and the dieback in large forest areas cause long-term economic losses for forest owners. Smaller owners in particular need public subsidies to support reforestation activities. Public subsidies can cover the activities in the first years of reforestation. Nevertheless, if less fire and pest-sensitive species are planted, or if forests are transformed gradually from single-species into more resilient multi-species woods, private return on investments will come later than in a regime of mono-species forestry – the overall level of private economic benefits generated by the forest may be lower.

Other strategies for making such investments viable for forest owners include, in the cases analysed, the reduction of costs for forest management (creating, for instance, synergies with agriculture with grazing and browsing in forest areas to reduce the amount of understory vegetation) and the creation of new products and markets for forestry products, as markets for by-products from forest management. Such by-products are already exploited by forest owners in the Dutch case (**case 5**), while the actors in the Italian case of the Occhito lake (**case 1**) is to creating markets for such products as part of a strategy for developing the rural economies, while also creating opportunities for implementing the principles of circular economy.

Other benefits with the character of private goods which can be extracted from forests and collected by forest owners, are related to hunting (if hunting licenses are connected to land ownership as in Germany and Austria) as well as newly introduced products as fungi which, while improving the health of specific tree species, can be commercialized by forest owners or the associations supporting them, as in the Italian case of chestnut woods (**case 7**).

Measures reducing the risk of forest fires damages create benefits that can be classified both as private and public goods, as such measures also reduce the risk of losses for other owners of nearby forests, as well as for the wider public, while reducing potential costs for firefighting and risks of wider losses of human lives.

Other benefits which classify as public goods are provided by forests in terms of improved water management and protection of drinking water reserves, a function which is mentioned in some of the forests in the German case (**case 6**), as well as erosion protection, which motivated, for example, the original afforestation of the area around the Occhito lake (**case 1**). These benefits replace public services which would otherwise require investments in infrastructures.

[10] A problem in the case of subsidies to forest owners is represented by the "state aid" rules within the EU, which condition the possibilities of supporting commercial forest investors (see, for instance, Assmuth et al., 2024).

Payments for such ecosystem services have not been encountered in the case studies. The benefits generated by healthy forests as carbon sinks, which would classify as public goods, are not widely recognized in economic terms as they encounter multiple obstacles of economic, ecological, social, and legal kind (see, for instance, Assmuth et al., 2024). An exception is represented by the NRW case (**case 6**) where the owner of one pilot area manages an investment fund which operates at global scale, offering investments in sustainable forest management as a business model.

Wider cultural benefits from forests consist of recreational and cultural values which are sustained by forests and distributed across society. In those cases where such benefits also support tourism activities, benefits are directed to a limited regional system, as for instance in the Occhito lake case (**case 1**) where the co-creation of forest management strategies is expected to generate a positive impact on local economies and rural development, including the valorisation of abandoned or marginal rural areas.

The role of societal benefits such as security and human health are emphasized by the cases of public investments related to forest areas, as with the setting of a forest fire prevention system in the Riba Roja case (**case 2**) to reduce wildfire vulnerability of local communities and the measures of prescribed burning in the Portuguese case (**case 4**) and the Occhito case in Italy (**case 1**) which follow similar objectives.

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Conclusions

Forest management in Europe is essential for preserving biodiversity, supporting the production of ecosystem services, including timber production, and mitigating climate change. However, these forests face growing threats due to climate change, including rising temperatures, increased droughts, and more frequent extreme weather events. These changes exacerbate pest infestations, such as bark beetles, and heighten wildfire risks. As conventional management practices may impair forest resilience in the long-term, it is important that European forest managers shift towards NbS that prioritize resilience, such as promoting species diversity, assisting natural regeneration, and expanding protected areas. This will enable the sector to effectively adapt to climate change and maintain the forests' ecological and economic roles.

This report shows that a wide range of NbS can be implemented in forest ecosystems to make them more adapted to a changing climate. Several NbS that are considered suitable for reducing fire risks are found to be suitable also for reducing the risk of pest proliferation, showing interesting synergies and revealing the high potential of NbS to face multiple risks while also achieving multiple benefits for the environment and society. Although different European ecoregions are facing different challenges and NbS need to be tailored to site-specific conditions, both the literature review and the cross-cutting analysis of case studies suggest that some strategies are replicable and can be encouraged throughout Europe. Some of these approaches can be traced back to old practices and traditions and need to be recovered (also by considering the knowledge of local communities) and readapted to changing conditions.

In certain situations, NbS for climate change adaptation can lead to possible conflicts (e.g. with strict nature conservation regulations or with economic production), requiring proper stakeholder engagement, deep understanding of forests, and alignment across different policy sector objectives. In other cases, the implementation of NbS requires addressing legislation gaps (e.g. regarding the use of prescribed fire) or governance reorganisation (e.g. for the creation of forest agreements). However, when implemented, NbS are generally associated with multiple ecosystem services and reveal their potential to contribute to sustainable food production (e.g. agroforestry), wood and non-wood products (close-to nature forestry), valorisation of local economies (short supply chains) and rural development.

Fires in European forests

Fire is part of the Earth system. Many species and ecosystems, especially in the South of Europe, evolved together with periodic forest fire. Some species are adapted or even need fire events to reproduce. Therefore, fire per se is not a problem – the problem lies with large (uncontrolled) fire events causing serious direct and indirect impact: production loss, economic damages, and even loss of lives. Wildlife can be also affected, either because animals are unable to escape the fire, or because their habitats and sources of food are heavily affected or destroyed. Therefore, NbS for fire should focus on creating landscapes that are (bio)diverse, taking the soil-sediment-water system in a landscape as the basic lead for pest and fire risk mitigation. Secondly, landscape-based NbS planning has to be implemented in collaboration with landowners, spatial planners, municipalities and provincial or national governance bodies, providing also broader benefits and embeddedness.

Wildfire risk reduction: fire management starts with understanding the forest

Adaptive fire management starts with understanding natural forest processes, forest management, and the context (natural, socio-economic, and governance). With the understanding of the natural system in the forest, NbS can play a significant role in wildfire management by addressing climate induced impacts in forests. NbS are gaining attention in different sectors, but in wildfire management it is still lacking large scale systemic attention and implementation -although interesting steps are being made throughout Europe. Currently this also limits broader potential political and financial support for implementation and upscaling.

NbS opportunities for wildfire risk reduction comprise of three major pillars: fuel reduction, species management, and landscape diversification. Fuel reduction can be done with NbS such as grazing, agroforestry and prescribed fires (non-NbS measures would be practices such as clearcutting with bulldozers or only acting when the fire is already burning with highly intensive fire brigade interventions). Species management is based on resilience of the vegetation to climatic conditions now and in the future to ensure forests are diverse in species and adapted to the location they are growing. As such, because of climate change, species management may also imply the consideration of non-native species if site-adapted to future climate and lead to transformation of forest typologies with respect to actual (or past) climax vegetation. This may generate debate among scientists and practitioners, require the involvement of various stakeholders, full understanding of ecological processes, and harmonisation of different sector policy objectives. Landscape diversification is all about creating a mosaic of landscape elements and diverse species planning, which also enables the protection of cultural heritage. This also may mean to revalue those traditional practices that have been abandoned over time and adapt them to new challenges posed by climate change, favouring coexistence between humankind and nature (e.g. agroforestry, close-to nature forestry). Special attention needs to be given to vulnerable and impactful areas such as the Wildland Urban Interface (WUI), to ensure the most appropriate safety measures and best benefits for society-at-large.

Understanding the forest is also important in relation to the ecological conditions and forest vitality. Improving vitality and functioning of forest ecosystems is essential to increase fire resistance and lower pest risk. This requires well defined ecosystem restoration and forest management (incl. species diversification, improving ecological conditions). The EU Nature Restoration law can play here an important role in support this process.

Post-fire management: reducing impact and creating conditions for recovery

Implementing NbS after wildfires can lead to healthier, more resilient ecosystems that are better equipped to withstand future fires and climate-related challenges. They also provide additional benefits such as enhancing biodiversity, improving water quality, and supporting local communities through sustainable livelihoods related to grazing and tourism. However, it requires a case-by-case evaluation, as in some instances, rather than actively re-planting trees, it may be better to do nothing, and let nature take its course. Differences across Europe are important to include in decision making as fragile soils and intense rainfall may create the need to tailor the best NbS to the local conditions. The key leading objective in decision making about which NbS to use, should be the multi-faceted benefits of such a measure: i) avoiding soil threats such as erosion, ii) supporting biodiversity, both in terms of a diverse and resilient vegetation cover, as well as supporting fauna such as burrowing animals and pollinators and iii) supporting recovery of water resources (Vallejo et al., 2012).

Pests in European forests

The focus in forest pest management in Europe is shifting from controlling pests to protect timber production towards a more holistic approach that considers the entire forest ecosystem. Traditional pest control measures, such as intensive salvage logging and the use of pesticides, have adverse impacts on biodiversity. This highlights the need for a more sustainable approach that prioritizes forest ecosystem health as a whole. NbS in forest pest management include managing pests within the context of healthy, diverse forest ecosystems. This involves improving the ecological conditions of forests across Europe, which, among other things, includes considering the ecological roles of both target pests and beneficial insects. While classical biological control (introducing natural enemies of pests) has been successful, it requires careful risk assessment to avoid harming native species. There is a need for more research and cautious implementation. Planting diverse forests can enhance resilience to pests because different tree species may offer varying levels of resistance or attract beneficial insects. This approach aligns with broader conservation goals. Creating diverse landscapes that include patches of forest, grasslands, and other habitats can benefit both pest control and overall biodiversity. This encourages a wider range of beneficial insects and provides more complex foraging opportunities. Overall, integrated pest management strategies that consider ecological complexity, regional socio-economic aspects, promote biodiversity, and balance economic needs with long-term ecosystem health are needed. Such strategies, therefore, need to be sustainable, cost-effective, and align with biodiversity goals. In this framework, the adoption of NbS in forest pest management contributes to meeting the EU Biodiversity Strategy and the Sustainable Development Goals set by the UN 2030 Agenda for Sustainable Development.

Socio-economic and governance considerations for the use of NbS in European forests

The implementation of NbS for forest fire and pest management faces societal and financial challenges. NbS provide broad societal benefits, including the reduction of wildfire risks and pest outbreaks. Yet many of these ecosystem services are difficult to monetize and many private forest owners and commercial timber producer are not able or willing to support the costs of their implementation. An increased awareness of the benefits NbS can provide for wood production, for instance in terms of a reduction of risks of losses from fire and pest, and the recognition of societal services produced by healthy forests in terms of e.g. water and erosion management and carbon storage, could trigger higher investments from both private and public funders.

Along with financial incentives, guidance and (organizational) support for forest owners is key for the successful integration of NbS in forest management strategies. Such guidance and support can be combined with public subsidies and payments which implicitly or explicitly recognize the provision of ecosystem services for society. Support can also be organized as part of regional groups and communities of practice which share knowledge and create synergies with local and regional development strategies, for instance with the goal of countering land abandonment in rural areas.

To achieve such transformations in the forest sector, several enabling conditions are needed. However, NbS objectives can sometimes conflict, particularly in balancing wildfire resistance with conservation objectives and commercial timber use. First, finding balance between the multifaceted objectives and conflicting goals connected to timber production, biodiversity conservation, and regional development will require effective negotiation processes. NbS should aim to address their primary goals (e.g., wildfire risk reduction, pest management) while enhancing ecological diversity, and ensuring socio-economic viability. This requires alignment between large-scale legislative goals and localized land-use planning, with measures adapted to specific territorial needs. Efficient NbS requires setting clear, context-specific priorities that accommodate different needs through detailed risk assessments and cost-benefit analyses, avoiding one-size-fits-all approaches. Furthermore, NbS implementation requires dynamic strategies: they must evolve with changing environmental conditions and vulnerabilities. As mentioned above, this may include, after careful consideration of trade-offs, the inclusion of selected and site-adapted non-native species, which are better adapted to future climate conditions. The design of NbS should thus also lead to a careful consideration of nature conservation goals, as historically native vegetation may not be sufficiently resilient to changing future climate conditions and imply the risk of important future losses to drought, fire and pest.

The use of fire insurances for homeowners as a means of recognizing the benefits of implemented NbS for the reduction of risks from fires has been explored in some cases outside Europe (Martinez et al., 2021). Such forms of recognition of insurance values produced by NbS based management would require homogeneous strategies for wider areas to be able to substantially reduce the fire risk.

Consistent communication and community engagement are another key lever for success. In particular, engaging local communities living close to the forests, as well as recreational forest users can increase consensus, resilience, and thus facilitate the adoption of forest management strategies, in particular when visible landscape changes are involved (Berchtold, et al., 2023; Smeenk et al., 2024). For example, when prescribed burning is used for ecological management purposes, this approach must be characterized by preventive, integrated and sustainable solutions embedded in local knowledge and considerate of the needs of different land-use and management sectors (Ruane et al., 2020), and it requires a shift in the public mindset – from wildfires being perceived as a threat to society to an essential part of ecological processes.

Furthermore, coordination is important to create consistency across management plans. This consistency is needed to reduce fire risks and pest control not only at forest level, but also at a landscape level. Coordination can be governmentally steered, initiated by local authorities or through partnerships of (small) forest owners. In this proactive and committed leadership, it is important to solve identified barriers or obstacles (e.g. in regulations).

Ultimately, monitoring is another key element necessary for further integration of NbS within forest adaption and risk management strategies. NbS need to be integrated in forest monitoring systems in order to allow a better assessment of their impact in terms of wildfire and pest outbreak prevention and impact reduction. Linking the monitoring of NbS impact with national forest monitoring schemes would be a potential lever for better adoption of these solutions at scale.

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Annex 1: Case studies

This annex presents descriptions of eight case studies in various European forest ecosystems where NbS are implemented to mitigate the increasing risk of fire and pest outbreaks induced by climate change. For each case study, major challenges are described besides NbS used to address them. An analysis of the scaling potential of NbS is then proposed, making reference to biophysical factors, socio-economic factors and governance factors.

CASE 1: A COMMUNITY OF PRACTICE FOR THE SUSTAINABLE MANAGEMENT OF FORESTS SURROUNDING THE OCCHITO LAKE, ITALY

Introduction

The lake of Occhito marks the border between Molise and Apulia regions for about 12 km, in the South-eastern part of Italy. The lake, created along the Fortore river at the end of the 1950s through a dam and built as water reservoir for multiple water uses, is the largest artificial lake of Italy, with a capacity of about 250 million m3. In the 1970s, a large intervention of conifer reforestation was carried out in the area surrounding the lake with the aim of enhancing the hydrogeological protection of the area. Although the lake has been created by man, the environmental context has an exceptional ecological value and the area is protected under the EU Natura 2000 network (IT9110002 and IT7222248 sites).

The area is exposed to the risk of wildfire. In 2020, the Regional Environment Protection Agency of Puglia[11] recorded 398 fires in Apulia, with a total area covered by fire of almost 3,600 ha. Over 40 percent of this area (1,474 ha) was forested areas. The most affected province in Puglia region is Foggia (where the Occhito forest is located), both in terms of the number of fires and the area covered, with almost 1,200 ha. Since 2013, the average annual surface of individual fire events has always been less than 10 ha (with the exception of 2017), suggesting that prevention and active forest fire management becomes to be effective in the region.

Besides climate change (increasing warmer and drier conditions), other challenges are related to the agricultural land abandonment that leads to either the accumulation of unmanaged vegetation on the soil or the establishment of new urban settlements in the countryside. Both processes are increasing fire risk for people and assets located at the urban-forest interface, with increasing costs for civil protection, especially in summer.

NbS implemented

The PABLO (Environmental and forest planning of Occhito Lake) Project, funded by the Rural Development Programme of Puglia Region, aims to promote a participative process for innovation in the forestry sector by bringing together scientific, technical, political and private business partners (community of practice). The project aims to improve forest resilience, and the protective and environmental functions of forest stands of the surrounding landscape of the Occhito lake, through a combined approach that both considers the environmental aspects, the social aspects and economic production. Three types of solutions are being implemented: (i) preparation of forestry management plan for the area surrounding the Occhito lake; (ii) development of a public-private partnership for implementing the management plan (Forest Agreement); (iii) implementation of a pilot project for applying the technique of prescribed burn (also referred in the literature as prescribed fire, controlled fire/burn) to prevent wildfire.

The forestry management plan was developed to ensure long-term sustainability of forest management, focusing on the forest landscape surrounding to the Occhito Lake. The management plan includes the objectives, strategies and actions (silvicultural and non-silvicultural interventions) to be implemented in

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[11] ARPA Puglia website, https://www.arpa.puglia.it/pagina3269_entit-degli-incendi-boschivi.html

the next 10 years to enhance forest fire prevention and to mitigate the hydrogeological instability of the forested area, exacerbated by climate change. The preparation of the plan was preceded by a detailed forest inventory phase to better characterize forest structure and assess health, vitality and the current trend of management.

In order to facilitate the implementation of the plan, a public-private forest management model was proposed. It has taken the form of a voluntary “Forest Agreement” to which various entities operating and managing the area can sign up. Actions included in this agreement include projects to preserve and enhance the resilience of the forest ecosystems through nature-based solutions (close-to nature silviculture) aimed at consolidating slopes and at preventing fire risks and pest outbreaks that are worsening due to climate change.

Finally, a pilot project to test the applicability of prescribed burn to prevent fire risks was carried out in an area of 4.84 ha. The pilot project was implemented after the identification of suitable areas and the training of operators. Moreover, a shared pathway with local administrations has started to explore possibilities to fill in the current regional legislation gap, since the prescribed burn technique is still not regulated by specific regional operational guidelines. The ecological use of fire is a nature-based solution that makes it more difficult for forest fires to spread through the canopy and modifies fire behaviour fuel models. Through prescribed burn, fine and dead plant material, particularly susceptible to ignition, is removed or reduced, the vertical continuity of the fuel is interrupted and small open spaces located inside and at the edges of the forest are maintained or restored. It is also a silvicultural technique, as it can intervene in the selection of species and in the structure of populations, favouring the diametric growth and ensuring greater stability of the forest ecosystem.

Replication potential

The project activities focused on the Apulian side of the lake (eastern side), since the project received funding from the Puglia regional development programme. However, the forested area surrounding the Occhito lake also extends over the Molise region (western side of the lake), allowing high upscaling potential. The PABLO project made efforts to export its results to Molise, where several exchange activities are being done through the organisation of various meetings where stakeholders from both Puglia and Molise can participate. Main aspects that constrain replication and upscaling of the project are described in the following paragraphs.

Biophysical aspects

Lago di Occhito is a Mediterranean pine forest characterized by approximately 997 ha of structurally homogenous forests. Forest plantation is characterized by Aleppo pine (*Pinus halepensis*, 61%), which is the dominant species, and Arizona cypress (*Cupressus arizonica*, 20%), plus a limited number of other coniferous tree species (Alvites et al., 2024). Large reforestation interventions were carried out in the 1970s with the aim of enhancing the hydrogeological protection of the area, after the construction of the dam that originated the Occhito Lake in the 1950s. The forest extends over Apulia and Molise region, so that the project can be easily extended to cover a larger area than the one initially envisaged by the PABLO project.

Socio-economic aspects

Socio-economic characteristics are similar in the two regions that border the Occhito lake, with small, scattered villages, decreasing population and agricultural land abandonment. Silviculture is practiced through disorganised interventions based on local needs and without a management objective. The project is expected to generate social benefits, by overcoming general skepticism about the possibility to reconcile environmental protection with economic and societal aspects. Through the Forest Agreement, the project seeks to maximise the use of short supply chains for wood products that derive from routine operations (marketing of wood residues), with positive impact on local economies and rural development.

This will also contribute to the valorisation of abandoned or marginal rural areas. These manyfold socio-economic benefits are likely to encounter the interest of several municipalities, both in Apulia and Molise, paving the way to rural development and new and diversified economic activities, also including eco-tourism. The subscribers of the Forest Agreement are the beneficiaries of the interventions, that are performed to achieve a common objective. Subscribers are also asked to financially contribute with their resources and to actively seek public and private funding and support.

Governance aspects

The full-scale implementation of prescribed burn in Apulia region, tested in a pilot area of PABLO project, is still limited by a regional legislation gap, since a regulation for its implementation is still pending. A similar situation can be found in Molise region, although the technique is mentioned in the regional Forest Plan. This well reflects the situation of the Italian legislation about prescribed burn that is quite fragmented in national and regional laws and planning documents, with significant differences among various regions. The territory where the PABLO project is implemented is a mosaic of state, municipal and private properties. The lack of a forest management plan is a source of complaints from local administrations, with a similar situation also in Molise. The success of the project and its upscaling potential depend on the cooperation among different private and public entities that are encouraged to work with a common objective. In this regard, the project received the interest of several municipalities, located in Apulia and Molise. Some of them participated in the project events and expressed their interest in being partners of the Forest agreement, as an opportunity to contrast land abandonment and depopulation as well as to valorise the territory.

Source

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CASE 2: BUILDING FIRE RESILIENCE USING RECYCLED WATER IN RIBA-ROJA DE TÚRIA, SPAIN

Introduction

Riba-Roja de Túria is a municipality located in the National Park of Túria in Valencia (Spain) which represents one of the last remaining forestry lungs in its metropolitan area.

The area is subject to the growing risk of forest fires. These events are extremely exacerbated by different factors, such as climate change, agriculture abandonment, and insufficient forest management. Consequences are not only related to natural resources (loss of biodiversity, soil degradation) but also include risks for residents' life, damages to city infrastructures, and decrease in air quality, and have a negative overall effect on the local economy (e.g. tourism).

The Riba-Roja de Túria municipality led the GUARDIAN project (funded under the Urban Innovative Actions –UIA, 2019-2022), aimed to increase the resilience of Valencian municipalities to the risk of forest fires through the implementation of green urban and forestry actions. The area to be protected has an extension of 35 hectares and is populated by about 15,000 inhabitants that are potentially affected by fires. Activities have been then followed through the EU funded DesirMED project (2024-2028) that continues to work on fire prevention in the Valencian region. The focus of both projects is the so-called Wildland-Urban interface area (WUI), a transition zone between urban and forest area, to safeguard both the natural environment and the communities living there.

NbS implemented

A fire resilience strategy based on the use of recycled water was implemented in the Valencian region to prevent and protect the area from wildfires. The strategy is mainly based on building a hydraulic infrastructure to supply recycled water, from the city wastewater treatment plant to the WUI area. A monitoring system made of hundreds of wireless sensors has been set up to capture early signals of a possible wildfire (WUIProtect). The system is used to monitor meteorological conditions (temperature, humidity, wind), air quality conditions (particulate matter, nitrogen oxides) and biomass variables (fuel and soil moisture, etc.) together with eventual fire ignitions in real time. Based on these data, the local wildfire index is calculated and prescribed irrigations are performed through the WUIProtect sprinkler towers that propel water to a 40 m distance, increasing humidity in the surrounding vegetation.

NbS were integrated in the strategy, through designing, building and maintaining transitional 'green belts' around the urban area to act as green firebreaks. Green firebreaks are low flammability 50-60 m-wide strips of vegetation located in strategic areas of the territory to slow down or stop the progress of forest fires. The green fire breaks are made up of strategically planted fire-resistant trees (e.g. *Fraxinus ornus*, Celtis australis, Sorbus domestica). Shrub windbreak barriers made of species of low fire vulnerability (*Myrtus communis*, *Viburnum tinus*, *Pistacea lentiscus*) were also used at the windward edge of the firebreak to reduce surface wind speed. Green firebreaks get recycled water from the hydraulic infrastructure to moisten vegetation in the area and form a thick green wall facing the prevailing wind to block the ashes and heat. Plant species were selected based on the following characteristics: low flammability, structural properties to reduce wind speed, fuel load reduction, ability to generate the growth and maintenance of fungi to improve soil condition, and a combination of herbaceous plants to favour soil moisture.

Moreover, silvicultural treatments to reduce fuel load and continuity are continuously performed including thinning, pruning and clearing, especially in post-fire natural regenerated areas or in mature forest areas. Reforestation with fire resistant species and removal of alien species is also an important task for fire prevention while also improving its ecological conditions.

Replication potential

The GUARDIAN project has been conceived as a pilot of a sustainable and integrated fire management solution never tested before in the European Union on a real urban scale. The potential for scalability at the European level is estimated to be high, due to the large extension of interface areas vulnerable to forest fires that extend throughout the Mediterranean Basin. In any case, the implementation of this NbS requires a thorough parameterisation of the whole system according to the circumstances of each area in terms of vegetation, water cycle, meteorological conditions and expected fire behaviour.

Knowledge built with GUARDIAN and DesirMED projects will undoubtedly be a very valuable guide for other municipalities that want to face the challenge of wildfire risk in WUI areas and implement an integrated forest fire management solution for the benefit of both population and the natural environment.

The positive results of the GUARDIAN project have already contributed to trigger complementary projects. At least 11 municipalities in Spain demonstrated their interest in the project. In the area of Riba-Roja municipality, there is consideration to extend the project to “Valencia la Vella” with an anticipated investment of approximately €400,000, relying on municipal financing. Concurrently, Paterna is examining the protection of "la Cañada" settlement not covered by Guardian due to financial limitations. The municipality of Eliana (in the vicinity of GUARDIAN sites) has already acquired portable cannons similar to those developed in GUARDIAN to address fire risk. Other municipalities have also expressed interest. The Natural Park of "El Saler" near Valencia is currently adopting a system like the one developed in GUARDIAN. An improvement of the monitoring network and of the capability to detect most vulnerable areas to wildfire is performed within the DesirMED project.

Biophysical aspects

The forest where the wildfire prevention system was developed is typically Mediterranean, featuring a mix of conifers and broadleaved trees with pyrophytic characteristics, which are inherently adapted to dry and hot conditions but vulnerable to extreme weather events.
A key biophysical factor is the presence of a wildland-urban interface, i.e. areas of transition between forest and built areas. This is very common situation in Mediterranean countries that have experienced significant urban development, either in the form of housing developments or isolated houses (Font et al., 2016).

Green firebreaks are key for wildfire prevention. The need to maintain these firebreaks can be a challenge, especially in areas affected by water scarcity. Moisture is a key element for effective green firebreaks. In Riba-Roja, this has been addressed by re-using water coming from the municipal treatment plant. The complex landscape (with narrow roads close to wild areas) made it difficult to transport the sprinkler towers used for irrigation.

The solutions implemented in this project promote biodiversity through the removal of invasive species and the reforestation with native ones. The combination of all this entails the creation of high environmental and landscape value spaces and favours different ecosystem services (e.g. water preservation, greenhouse gas sequestration, protection against erosion, maintenance of biodiversity, etc.).

Socio-economic aspects

Locations where this NbS is implemented often include small villages and communities with economies largely dependent on forestry, agriculture, and, in some cases, tourism. These communities live within or close to forest land and, thus, they are directly dependent on forest health. Awareness raising about risk exposure is a crucial aspect of GUARDIAN and DesirMED projects. Training sessions were organised both for residents and schoolchildren living near the fire risk zones.
Funding for these projects often comes from government grants and EU funding.

The key socio-economic benefits of these projects include a significant reduction in wildfire vulnerability for local communities and the development of a circular water economy by repurposing water that has already been utilized in the residential areas being safeguarded.

Forest preservation can provide important ecosystem services, with possible economic return, including carbon sequestration (climate regulating service). The amount of CO2 that trees are capable of absorbing resulted to be 18,396 tons, considering an area of 400 hectares. Based on the average market value of CO2 emissions in 2021 and considering that the goods generated by environmental assets can last for a long period of time (e.g. 100 years), researchers calculated that the ecosystem service of carbon absorption and storage in Vallesa can be valued €32.8 million. The economic value of other ecosystem services provided by the forest (e.g., educational and research activities, cultural values, recreation and tourism) was quantified as well, suggesting a total value of €411.5 million, over a 100-year lifespan. Since the investment required to maintain the project's operation over a 100-year period was estimated around €6.2 million, the GUARDIAN project turned out to be cost-effective, having a highly favourable cost-benefit rate (Demonstrating GUARDIAN economic feasibility, 2023[12]). The cost of inaction if the project was not implemented was estimated at 31 million euros. This amount is the overall result of the quantification on the environmental and material consequences of wildfire in the GUARDIAN area, considering aspects such as the material and human resources necessary for its extinction, the forest mass affected, the CO2 emissions generated, and the costs associated with the damage to homes.

Governance aspects

The interest of local governments (especially manifested by Riba Roja municipality) was key to allow the implementation and long-term maintenance of the interventions. Proactive and committed leadership throughout the project lifecycle is a key asset to efficiently detect hazards and propose corrective measures to overcome them. Likewise, leadership and political commitment is necessary for a good dialogue with citizens and other stakeholders (regional and national administrations, risk and emergency managers, the media, etc.). Indeed, the ownership and management of forests usually involves a combination of private and public entities, including local and regional governments making governance for NbS quite complex.

Possible obstacles in the replication potential of the solution implemented in Riba-Roja can be found in the regulations of fire prevention that may not explicitly envisage the possibility to reuse water from wastewater treatment plants for fire prevention and to use green firebreaks. One of the most important achievements of the project was the amendment of the current regional legislation (legislation decree 1/2021) to include green firebreaks and the use of irrigation from hydraulic systems as valuable fire risk reduction measures.

Other governance aspects relate to possible restrictions in place in natural protected areas. The installation of the hydraulic infrastructure and the use of recycled water required several authorisations and increased the costs for creating the infrastructure. Moreover, complex public procurement and permitting processes can significantly compromise the successful implementation.

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CASE 3: SUSTAINABLE FORESTRY FOR INCREASING CLIMATE CHANGE RESILIENCE IN SORIA, SPAIN

Introduction

Soria Forest is located in the Iberian Mountain region of North-central Spain in the Castilla y Leon Autonomous Community. About 60% of the whole province of Soria (North-central Spain) is covered by forest (620,830 hectares). This includes various landscapes such as woodland, scrubland, and natural pastures. 447,546 ha is wooded forest area (43.45% of the whole province).

It is a large natural area that is also important for timber production and non-wood economic activities, including: resin production, mushrooms, truffles, hunting and extensive domestic livestock. It also offers a natural space for recreational activities.

Based on the historic climate trends in this area, the temperatures will continue to steadily increase, and temperature anomalies (much higher than normal) will become more frequent. Scenario-based projections have shown that in 50-100 years under current patterns of climate change (temperatures and precipitation changes), some of the main species will be outside of their adaptive ranges and cannot survive changes. In summer, minimum temperatures have increased, with prolonged periods of anomalies, and this is changing the growth patterns of trees: they go into dormancy when they should be growing. In addition, winters, which were historically cold enough to reduce many insect pest populations, are becoming warmer and shorter, increasing spring pest population growth and providing favourable conditions for spreading of tree diseases. Moreover, the hydrological changes such as droughts in summer and winter will affect the growth of forest stands. This situation compromises their resilience and can impact their long-term survival.

The forest proximity to arable agricultural lands is also becoming a fire threat. Spontaneous fires of agricultural machineries are becoming more common, and much more dangerous where the farms border the forest. Harvesting is always a time-sensitive activity that can come in conflict with the days of high fire-risks.

NbS implemented

Fire prevention strategies in Soria are based on a two-level system: the first level is the early detection of fires, based on 32 watchtowers with guards (people), and a detection system using thermal cameras (19), smoke detection (1) and visible cameras (2). The second level is the prevention of forest fire all year round. Fire crews are forestry workers who perform fire prevention activities, and, in addition, they are knowledgeable about forests. This system is the opposite of the majority of Spanish regions or autonomous communities, which have opted for an extinguishing system with urban firefighters who are very professional, but are not familiar with forests, their accesses, or the behaviour of forest fire.

Concerning pest management, the forest service includes several sites with pheromone traps to monitor the presence of the most important insect pests in the area, such as, for example, the pine processionary *Thaumetopoea pytiocampa*, a lepidopteran that defoliates pine trees in its larval stage.

Besides specific fire and pest prevention strategies, a nature-based approach to forestry is adopted in the Soria Forest. This is expected to generate a healthier ecosystem able to better contrast various effects of climate change and facilitate restoration:

- Establishing mixed forest with resilient species and ages. *Pinus halepensis* and *Pinus pinea* for example can be introduced in areas where drier conditions are expected. Making sure that logging and replanting is not done in large areas to create a diversity in tree age is important. This reduces the vulnerability of the stand to pest and disease pressure. This is also a national strategy, but it needs more evidence to determine its success as a solution also to forest fire increases.

- Introduction of broadleaved forest species into large coniferous forest stands. Local managers call this "broadleaved enrichment". This practice contributes to forest biodiversity and may have a role for fire risk reduction (Oliveira et al., 2023). These species include elms, ashes, birches, etc.
- Bringing forest back to agricultural areas. Landowners are supported by the government for planting trees with advice of species composition. National policies also support the land use change from agricultural land to forested land.
- Grazing through rotation of fenced-off areas. There is an abundance of both wild and domestic grazers in the area. These are kept away out of about 20% of the forest area at a time to allow for these areas to regrow naturally. There is also consideration for the timing of hunting or harvesting non-wood products, particularly important for the forest regeneration.

Replication potential

Biophysical factors

Most of the Soria Forest has a mixed tree composition of conifers and deciduous species and hosts 8 dominant species: *Pinus sylvestris* (Scots pine), *Pinus pinaster* (maritime pine)- from which resin is extracted as an important non-wood forest product, Pinus nigra (black pine) and *Juniperus thurifera* (Spanish juniper); *Fagus sylvatica* (European beech), *Quercus ilex* (holly oak), *Quercus faginea* (Portuguese oak), and *Quercus pyrenaica* (Pyrenean oak). Adaptation solutions (mainly based on mixed stands, uneven-aged stand structure, silviculture practices and managed grazing) are suitable to most types of forests. However, Soria Forest is vast and spans across a wide range of altitude (that determines a temperature gradient) and landscape variety. This imposes to adapt management strategies to the local conditions.

Socio-economic factors

Soria Forest includes a mosaic of private, public, industry and educational institutes that need to collaborate to make adaptation possible. The forest, despite being a natural area (it includes several Natura 2000 sites, that cover more than 22% of the province’s surface), has an important economic value (wood and non-wood products) and is commonly used for recreation. The flexible management of timing for grazing, hunting, and harvesting non-wood products is important for allowing forest regeneration. Moreover, the presence of agricultural areas bordering the forest creates further conflicts, due to possible competing interests that need to be considered. This is particularly relevant during harvest time, when the risk of fire is greater and the movement of agricultural machinery carries the risk of sparks, and the soil and forest are drier.

Governance factors

In Soria, like in many areas of Spain, forests are commonly owned by a group of owners. Denominations such as “Monte de la Sociedad de Vecinos”, “Montes del Común”, “Sociedad del Monte”, “Sociedad de Bardíos” are common forms of ownership throughout the national geography and are known as “Montes des socios”. They are special land tenure regimes for common property, which are co-owned by different natural or legal persons (in many cases several hundred), who do not own a parcel within the area, but a percentage of the overall area. Decisions about the management of the area follow joint decisions and jointly set rules. In many cases, these forests belong to a group of people who gradually have been left without formal organisation and therefore without a management body to make decisions and work for the health of these forests. On the other hand, nationwide 70% of the forests are privately owned, but only around 20% of the areas have forest management tools in place. In the Soria Forest, there are mature forests which cannot be managed because of the lack of jurisdiction in co-owned lands, thus there is no structural management to organise the necessary work or access to public aid to do so. The Association of Forest Owners of Soria (ASFOSO) seeks to save these mountains from abandonment and oblivion, offering solutions to recover the management capacity of their co-owners and to achieve their integral value. The role of this association is also essential in facilitating contact between private owners and the administration to manage aids and support management plans. The association promoted an initiative to recover the abandoned mountain lands of Soria, offering solutions to facilitate the collective management capacity and to achieve common goals.

Source

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CASE 4: PRESCRIBED FIRE AND GRAZING AS AN INTEGRATED APPROACH TO MAKE FORESTS MORE RESILIENT IN VISEU DÃO LAFÕES, PORTUGAL

Introduction

The Viseu Dão Lafões Intermunicipal Community (CIM) is an association of 14 municipalities part of Viseu district, in central Portugal. It includes a mountain landscape with forested areas and various pasture areas and extensive livestock farms. The area suffers from recurrent fires that are a severe threat for the population and for the ecosystems. Especially after the large event occurred in 2017, the urgency to adapt the territory to the increasing risks of climate change has become even more clear.

Between 1980 and 2020, there was an average of 19,202 forest fires per year, corresponding to 117,433 hectares of burnt area per year. Looking at the last decade (2011–2020), this average increases up to 130,706 ha. Considering the type of land cover burnt, from 2011 to 2020, 49% corresponded to forest stands, 44% corresponded to bushes and natural pastures, while 7% corresponded to agricultural land. Maritime pine and eucalyptus are the species which have suffered most severely, corresponding to 83% of the area of forest burnt in the aforementioned period (Casau et al., 2022). The Viseu district in Central Portugal is one of the most hit areas, with severe consequences for human and ecosystem health.

The abandonment of traditional livestock farming and its progressive industrialization, combined with the adverse effects of climate change, is a great challenge for the region. This made it also urgent to combine adaptation actions to fire risks with adaptation actions for extensive livestock farming.

NbS implemented

By participating in the LIFE Landscape fire project, the CIM Viseu Dão Lafões Intermunicipal Community investigated and started to implement the combined use of extensive grazing and prescribed fire to increase the forest resilience to fire.

The grazing technique was tested as a solution to help prevent fire risk in the region, while also preserving biodiversity (seed dispersal) and soil fertility. A total of 48 farms (2.931 sheep, 1.230 goats and 225 cows) were identified in the region, with a total area of grazing of 2900 ha. In summer 2023, based on the results of a financial and technical study about the need of infrastructure throughout the territory and on specific field visits to some of the farms, drinking fountains were installed in the Serra de São Macário, in São Pedro do Sul, and in Aguiar da Beira. Information panels about the project were also placed next to the infrastructure mentioned. These infrastructures were installed to favour the maintenance of extensive grazing in the region, as a means to reduce fire fuels more effectively than most mechanical methods. Grazing plans were developed for some of the livestock farms that agreed to take part in the project, with the objective of planning grazing actions in space and time for each of them. It also made it possible to identify the needs in terms of materials and equipment ("drinking stations") to be installed in strategic fuel management zones, so that the animals could feed in these areas.

In combination with grazing, several controlled fire pilot actions were carried out in the municipalities of São Pedro do Sul, Vila Nova de Paiva, Vouzela and Castro Daire, covering a total area of around 250 hectares. The selection of pilot areas to implement project activities was based on a study that identified strategic fuel management points in the region and that investigated fire behaviour during events from 1990 to 2017. Controlled fire (also referred to as prescribed fire/burn) is highly important for the prevention of fires, by maintaining forest fuel loads below critical levels. Controlled fire was applied in small patches of forest and scrublands in compatible weather conditions and far away from houses, to ensure the safety of people living in the nearby villages. Controlled fire consists of the use of fire in the management of forested areas spaces, under controlled conditions and specific procedures according to controlled fire plans. Controlled fire is always carried out under the responsibility of an accredited

technician, with technical training in the use of controlled fire, a factor of primary importance for its operational use.
Finally, by participating in LIFE NIEBLAS project, CIM Viseu Dão Lafões has been also carrying out the reforestation of some areas affected by fires with native species (*Quercus robur*, *Quercus pyrenaica* and *Quercus suber*). This is expected to allow the sustainable recovery of forests and aquifers, thus reinforcing the resilience of the ecosystems of Viseu Dão Lafões.

Replication potential

Besides Viseu Dão Lafões, the Life Landscape Fire Project also includes actions in Extremadura, Spain and is based on a methodology successfully implemented in other Spanish regions (Andalusia and Catalonia). This allowed to exchange experiences in the use of prescribed fire combined with controlled grazing between the two countries. The experience about grazing adapted to fire prevention achieved during the Mosaic Project in Extremadura was shared with the partners of Life Landscape Fire Project and opened new perspectives for replication in the Portuguese area.

Biophysical factors

The forest in the Viseu Dão Lafões region occupies around 60% of its territory. In terms of other occupations, 20% of the territory is occupied by agriculture and 16% by scrubland. It is mostly a production forest, with the dominant species being pine (*Pinus pinaster*) followed by eucalyptus (*Eucalyptus globolus*) and species of the *Quercus family*. There is also a considerable area of autochthonous forest in protected areas (nature network) (approximately 47,000 ha).

In the last decades, a progressive increase of Eucalyptus coverage has been observed, with a correspondent decline in pine species. A reduction in other resinous species has also been observed, with an increase of oaks and other species like lindens, ash, plane trees, acacias or poplars). The most important biophysical factor for implementing the solutions tested in the Landscape Fire project is the presence of a mixed rural landscape with both forest and pasture areas. The integrated use of prescribed fire and grazing helps preserving this typical landscape.

Socio-economic factors

The Viseu Dão Lafões intermunicipal community is characterized by heterogeneous socio-economic development (Rocha de Jesus Gomes Vieira, 2017), with areas evolving similarly to the most developed sub-regions and others with development close to that of the markedly rural areas.

Socio-economic conditions (including growing rural exodus, transformation of production from extensive to intensive models) were important triggers of solutions tested in the area during the Life Landscape Fire Project. Through encouraging grazing for fire prevention, extensive livestock farming can be preserved as an important form of sustainable food production with low carbon footprint. It is also an instrument for landscape management and conservation, with the capacity to transform areas that have been abandoned or having low agricultural productivity into areas capable of generating high-quality products and services. This is important for the local economy and for preserving local culture and traditions.

Governance factors

The role of local governments is key for the success of fire prevention. The role of the Intermunicipal Community was reinforced by the renovation of the legislative package for forestry reform, approved in Portugal in 2017, after the 2017 fires. It was approved with the aim of overcoming structural problems in territorial planning. These problems started to become more evident due to the increasing effects of climate change, with serious threats to the safety of populations and to the economic and social development of the region. As part of this new legal framework, a resolution of the Council of Ministers (no. 157A/2017) established the Forest Sappers Brigades that have the role to intervene in the installation and maintenance of the primary forest defence network against fires, in post-fire actions, as well as in emergency control actions. They promote action in line with the objectives defined in the National Strategy for Forests and the National Forest Defence Plan against Fires. Moreover, framed within this legislative package, the Intermunicipal Forestry Technical Offices were also established. Intermunicipal Communities (including the Viseu Dão Lafões CIM) started to assume an important role in defending the forest against fires, as well as promoting regional policies, bringing together local synergies.

In 2017, the Viseu Dão Lafões CIM also launched the Intermunicipal Climate Change Adaptation Plan, aimed to promote the integration of climate change adaptation into intermunicipal and municipal planning and, in this way, create a culture of adaptation across various sectors and actors, reinforcing territorial resilience and preparing the community for climate change challenges.

A key component of the project was training, especially considering that prescribed burn must be implemented by expert personnel in controlled conditions to avoid risks. A total of 100 people was trained during the project, from various firefighting teams operating in the territory. Training also involved people of "forest sappers" brigades, established by CIM Viseu Dão Lafões and operating in all the territory to reduce forest fuel. Data about the health effect of smoke exposure of firefighters during fire suppression operations were also collected by cooperating with the ArRiscO that formulated recommendations to reduce risks. Face-to-face and online sessions took place to introduce the topic of advanced Grazing Planning, Grazing Techniques and Pastoral Planning and Actions.

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CASE 5: WILDFIRE RISK REDUCTION IN DEURNSE PEEL BY LANDSCAPE DIVERSIFICATION, THE NETHERLANDS

Introduction

In the forest ecosystem of the Deurnse Peel, the vitality and resilience of the natural forest is declining due to climate change. The Deurnse Peel is part of Noord-Limburg region, in the Southern Netherlands. The landscape is diverse, with the peel remnants in the west around Nederweert and the former flow marshes on the border with Belgium in the Kempen-Broek. The influence of the Meuse can be seen in the terraces around, among others, Beesel on the east side and Geysteren on the west side. Dry areas with heather and reclamation forests alternate with alder swamp forests in the stream valleys. This causes higher risk for wildfires and pressure on biodiversity and calls for new choices in management of the region. The choice made here is based on the approach in the LIFE project Climate Forest (www.climateforest.eu). The main approach in this project is small-scale climate-smart forest management, as it offers the opportunity to tackle the problems and thus contribute to the emergence of resilient and vital forest ecosystems that are ready for the future.

NbS implemented

To create a more diverse and resilient landscape, corridors were formed with different more fire resilient species. 30 m wide corridors with deciduous/broadleaved forests were implemented in the whole area. These changes were made in collaboration with all stakeholders involved: the municipality, the safety region and with and the owners of forests and other natural areas. By creating a diverse mixed forests at landscape scale, more structure was created to the vegetation, both from a vertical and horizontal point of view. This new approach in forest management will generate a next generation forest that will have 2 or 3 tree species on each hectare. In the selection of the trees that are planted on a specific position in the landscape, the key issue is the suitability of the growing position in the landscape for that specific species. Creating a suitable composition of tree species on each position creates forested landscapes which are less susceptible to fire and to pest outbreaks, compared to less healthy stands. This transformation from mono-culture pine trees to a mixed forest started in the 1990's and is still ongoing, with results which are already visible in the region. The resulting landscape has not only a diverse species composition, but also has different tree ages and open areas as landscape elements. This creates a vital and resilient forest ecosystem which is better equipped to respond to climate change related risks such as fire and drought related pests. The landscape planning is done as part of different planning tools, such as the nature-fire management that are agreed on by all stakeholders in the region (www.brandweernederland.nl/wp-content/uploads/sites/2/2024/01/2023-09-25-Visie-Natuurbrandbeheersing.pdf).

Replication potential

The process of making a plan for prevention and management of forest fire with all involved partners and stakeholders is scalable, if economic pressures on forest productivity are relatively low. In the Netherlands, forests in densely urbanized areas are managed mainly for recreation purposes and for the increase of biodiversity. Harvesting wood is often a means for transforming forests, not a goal to gain income (although it is always part of the financial balance of ownership). Dutch forest policy aims at rehabilitation of at least 250.000 ha of forests on sandy soils and additional afforestation on 37.000 ha.

Biophysical aspects

In the Deurnse Peel the forest is mainly used for recreation and consists of Pine/Fir/Douglas/Lork and different species of broad-leaved deciduous trees. The landscape consists of sandy soil, with low nutrient levels and low water tables except for areas where due to peat formation there is stagnant water.

In the past these regions were used for pine timber production, but nowadays the area is mostly used for recreation and nature conservation. Climate change causes fire risks and biodiversity loss due to unsuitability of the vegetation stands according to the new climatic conditions. The approach of landscape diversification has benefits for biodiversity, such as insects, birds, mammals and different plant species. The landscape diversification creates a vital forest that is a resilient forest ecosystem ready to adapt to changes and continue to provide its ecosystem services, such as habitat for flora and fauna (and recreation for people) as well as ecosystem services related to regulation (climate mitigation, water and soil protection). This approach developed further as a tool in the climate forest project is ready to be used in other areas. Moreover, on a regional scale, water boards will benefit from improved hydrological conditions, while society as a whole will benefit from the improved water supply in dry periods, as well as reduced downstream flooding in case of heavy precipitation. The activities aim that by 2030, the forests' vitality and fire resilience on a landscape basis will be improved.

Socio-economic aspects

North Limburg is a region with about 125 members grouped in the Bosgroepen, with a very diverse background. Members of the Bosgroep are private individuals with small groves, estate owners with historic parks and castles, municipalities that own a large forest and nature reserves as well as care institutions with park forests. The Bosgroeps have a management agreement with some of these members. The forests have multiple owners: the national forest service (Staatsbosbeheer), the municipalities and private owners have forests ranging from 1-50 ha. A more diverse landscape will allow local communities (e.g. Horst and Oss) to benefit from enhanced economic activity in the recreational sector and from wood production, as well as from more pleasant living environments. Wood production is a minor income stream but does provide opportunities for investing in management changes towards more diverse, mosaic landscapes. In addition, the area will have a lower risk for large-scale fires due to the mosaic landscape, and the diverse species in the region makes it less prone to pest outbreaks.

Governance aspects

The owners and managers of the forest are municipalities, nature organisations, private forest owners. Bosgroep Zuid Nederland maintains many forests from municipalities.
The largest legislation gap that prevent the implementation of the measure at scale is that there is no funding for buying, selling or exchanging forest plots. There is no legislation which gives the possibility to transform forests without the consent of the owner. Therefore, currently all activities are on a voluntary basis.

In the Nature fire management plans the areas are analysed and measures are described. These plans are accorded by municipality, (large) owners and civil protection regions (Veiligheidsregios). Funding of the measures is lacking. Ownership represents a key challenge, as forest owners hold rights to influence functioning and structure of forests, and forest biodiversity. "The trade-offs between landowners' property rights and society's conservation interests are a cornerstone of what forest biodiversity policies seek to address" (Muys et al., 2022, p. 47).

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CASE 6: PEST MANAGEMENT IN NORTH RHINE-WESTPHALIA, GERMANY

Introduction

In North Rhine-Westphalia (NRW), since 2018, about 145,000 ha of spruce forest have been damaged by wind, drought, and subsequent European spruce bark beetle (*Ips typographus*) outbreaks (MLV NRW, 2023b). Spruce dieback is continuing and is actually expanding further into higher altitudes of the area. The large-scale forest dieback is a major challenge in NRW and restoring ecosystem services while increasing resilience of forests under changing climate conditions is seen as an imperative need.

In the context of the SUPERB project[13] seven study sites within NRW have been selected for testing strategies for the restoration of forest landscapes and improving adaptation to various challenges and stressors from climate change. The NRW demo sites are in the south-eastern and eastern hilly areas of the region and correspond to those areas which are most interested windfall and pest outbreaks. The German Forest legislation foresees a legal obligation for reforestation; these obligations are supported by public subventions for all types of reforestation activities. Reforestation efforts are facing challenges due to the dimension of the problem: the extent of forest dieback is so large that resource shortages (planting materials, skilled personnel, etc.) are challenging a full and timely reforestation. Furthermore, many forest owners are financially unable to manage reforestation without assistance, as their income base has been lost due to the large-scale calamity and the following collapse of timber market prices.

Spruce stands have dominated the forest landscape in NRW since in the 19th century, when the demand for pit timber increased in the neighbouring mining and iron industries of the Rhine-Ruhr industrial area. In this period, conifer stands consisting of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) replaced previously existing beech and mountain beech forests in which spruce stands occurred only in the higher altitudes. Impacts from a changing climate with altered temperature and precipitation regimes, as well as soil characteristics have contributed to weaken existing forests, and will make spruce forests no longer suitable for spruce on most sites under future climates.

NbS implemented

Restoration concepts for the sites were developed with owners and stakeholders, following the guidelines and indications provided by the NRW State Ministry in its concepts for forest management for reforestation (MLV NRW, 2023c, 2023a). Both concepts propose typical forest development typologies (*Waldentwicklungstypen*) which correspond to the specific site potential (climate, soil water, nutrient balance) under future climate scenarios, and proposes suitable compositions of tree species according to the "four tree species principle" within a forest stand to ensure more climate-resilient mixed forests. The site-specific species mixtures consist of ideal-typical combinations of deciduous and coniferous species, mixed with light and shade tree species, and include, for forests dedicated to timber production, also limited shares of the more drought resistant Douglas fir (*Pseudotsuga menziesii*) among the conifers, while for forests used for biodiversity protection and recreation, no exotic species are considered. Specific guidelines for reforesting of damaged forest areas issued by the same NRW ministry (MLV NRW, 2023c) furthermore provide a series of recommendations and rules for the restoration of large damaged stands.

The case study is based on forest areas with different types of property regimes, including small scale private owners and consortia of small-scale owners, forests managed as investment assets and public forests. In the case of forests managed as investment assets, the asset manager applies sustainability criteria for differentiating the investment option on the financial market.

[13] https://forest-restoration.eu/about/

Replication potential

Biophysical aspects

The interventions planned and implemented in the study sites were aimed at demonstrating replicable solutions for typical problems of reforestation provided by the public guidelines for forest management in the state. The guidelines distinguish between economically exploited and conservation forests. For forests managed for economic exploitation the guidelines propose, for instance, drought resilient non-autochthonous tree species, which ensure fast growth and high-quality timber as Douglasia are proposed alongside with region specific species.

Socio economic aspects

The interventions are implemented by public and private landowners, who have exclusive rights on the exploitation of one ecosystem service provided by the forests. Other ecosystem services provided, such as recreation and cultural services, have the characteristics of public goods (cultural and recreational values as well as carbon storage capacities).

The interventions have been defined and implemented in collaboration with the landowners and financed by the Superb project. The restoration costs consist of the direct cost of various restoration activities carried out on demo sites. The direct costs are divided into several categories such as site preparation (e.g. soil preparation - ploughing, topsoil removal), materials (e.g. wooden polls for fences, fence net), plants (e.g. cost of seeds, seedlings, saplings) and labour costs (e.g. person costs for soil preparation, planting, installing fences, maintenance like weeding).

Considering a plot of 10,000 m2, the costs for broadleaf dominated reforestation (Mixed-oak-forest) over a surface of 7,000 m2, leaving natural regeneration for the remaining 3,000 m2, range between EUR 13,000 to EUR 17,700 The costs for a conifer dominated reforestation (Mixed-Douglas-fir-forest) range between EUR 8,400 to EUR 13,100. Such costs include plant material, planting, tending and fencing for a timeframe of 10 years (Lindner, 2022). The SUPERB project financed a part of the activities. Besides this, the state of North Rhine Westphalia has set out a system of graduated subventions for different intensities of repair and reforestation, which offers reforestation primes between EUR 800 and EUR 12,700 per ha for projects which follow the public guidelines for forest development and should cover both costs of plants and maintenance for the first year. It should be noted that this subsidy is lower than what has been reported as reforestation costs by the SUPERB project.

The primary economic benefits from restoration in those stands which are economically exploited will become tangible in 30 more than years, when trees have reached a marketable size for timber. The establishment of a mixed forest is expected to yield a forest which is more resilient to large calamities and thus able to sustain continuous forest microclimates and avoiding reoccurrence of large, cleared areas, so will mitigate the risk of future important losses for forest owners.

Forest owners can derive further benefits from hunting and leasing of hunting rights, as those rights are connected to land ownership. In some areas of Germany, the lease of hunting rights represents a substantial market (Bösch et al., 2018) depending on the quantity and prestige of game available. The economic value of game hunted is estimated with almost EUR 200 million for the year 2022/23 (DJV, 2024). Game browsing is, on the other hand, a major cost factor in restoration works as additional protection measures are necessary to prevent browsing with costs for protection which can exceed costs of plants and planting. High deer populations causing heavy browsing of shots, leaves and buds and damage from fraying and bark can threaten forest restoration and require additional measures for protection measures. Therefore, it is important to integrate the hunting infrastructure in the reforestation plans and include silvicultural goals in agreements with owners and leaseholders of hunting rights. Challenges of reforestation due to sika deer were discussed with stakeholders: despite intense hunting of sika deer, in some areas it is not possible to establish tree species such as oak or silver fir, which are susceptible to browsing – if not protected by either fencing or growth shelters which create additional costs in the case of reforestation.

Other expected forest ecosystem services that will be enhanced through reforestation activities, though not specifically quantified, are climate regulation, water regulation and supply, erosion control, habitat provision and recreation.

Alternative forms of income from ecosystem services (carbon offset, etc.) as payments for ecosystem services, for instance for forests ensuring drinking water for nearby settlements are not part of the work plan.
Beyond such economic benefits, many of the forests have a high relevance for recreation. In particular, in Germany, free access to forests is granted by law to anybody, so benefits from the biodiversity, as cultural services and recreation values for citizens create public benefits. The same holds for carbon storage capacities.

Governance aspects
Besides the EU Nature Restoration Law adopted by the European Parliament in 2024, the Habitat Directive and the related requirements established by the EU Natura 2000 network, reforestation in NRW is regulated by federal and state forest and nature conservation legislation, e.g. the Federal forest act, the Federal forest strategy 2050 and the NRW forest law. According to this legal framework, forest owners are obliged to reforest or complement clear cuts and open areas of damaged forests for two years. The state authorities as well as national authorities provide subsidies for reforestation of areas destroyed by pest infestation, provided that public guidelines for species selection are respected.

Conflicting restoration objectives. The reforestation plan for a Natura2000 site among the study sites has been rejected by the conservation authority as the species composition included some tree species which had been introduced to address future climate condition, but did not correspond to the pristine habitat characteristics subject to the protection status of the site. Such conservation strategies refers to the (past) potential natural vegetation (see, for instance, Tüxen, 1957), while the principle for the development of climate resilient forests issued by the state authorities and adopted in the workplans developed in the SUPERB project (Lindner, 2022) propose a mix of different tree species in view of the future development of humidity conditions in the site, so as not to limit future adaption capacities of the forest. Climate adaptation in fact requires the establishment of mixed forests with species that are adapted to the new site conditions posed by climate change instead of one single dominating species. This issue needs to be further addressed for future restoration plans.

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CASE 7: PEST MANAGEMENT: BIOLOGICAL CONTROL AND USE OF MYCOLOGICAL RESOURCES TO REDUCE THE RISK OF TREE DISEASES IN A CHESTNUT FOREST, ITALY

Introduction

The San Godenzo site, situated near the village of Castagno d'Andrea (725 meters above sea level), lies in a fan-shaped valley below Mount Falterona, where the Arno River originates. This demonstration site is located on the border between Tuscany and Emilia-Romagna, approximately 7 km from the village of San Godenzo. The area receives an average annual rainfall of around 870 mm, and the local Mediterranean forest ecosystem faces several challenges exacerbated by climate change, including increased drought, pest outbreaks, and forest fires.

Two demonstration areas were selected in the San Godenzo site, each dealing with different phytopathological problems:

- Casale (11.1 ha): A young chestnut coppice affected by chestnut blight, a disease caused by the invasive pathogen *Cryphonectria parasitica*.
- Castellina-Le Casine (19 ha): A chestnut orchard affected by ink disease, caused by the soil-borne pathogen *Phytophthora cambivora*.

The forest's traditional management practices were focused on chestnut production for timber and fruit. However, these trees have become increasingly vulnerable to both biotic (pests and pathogens) and abiotic stressors (drought and fire) due to climate change. The introduction of innovative solutions was needed to protect the forest and improve its resilience in the face of these growing threats.

NbS implemented

To address the pest outbreaks and build resilience against climate change, LIFE Mycorestore implemented several key NbS in San Godenzo. The interventions focused on biological control and the use of mycological resources to aid forest recovery:

- Inoculation of Edible and Non-Edible Mycorrhizal Fungi: Mycorrhizal fungi form symbiotic relationships with tree roots, improving nutrient and water uptake while helping the trees resist stress caused by pests and pathogens. In this project, species like *Pisolithus tinctorius*, H*ebeloma spp.*, *Cortinarius spp.*, and *Tuber borchii* were inoculated into the soil around the chestnut trees. These fungi not only help improve soil health but also contribute to forest regeneration by supporting tree growth. The inoculation also has the potential to enhance biodiversity by fostering the establishment of fungal communities that play a crucial role in ecosystem functions. Additionally, the inclusion of *Tuber borchii* aims to support the production of valuable truffles, which can offer an economic benefit to local communities.

- Biological Control of Chestnut Blight: A major focus of the intervention was the use of hypovirulent strains of *Cryphonectria parasitica*, the fungus responsible for chestnut blight. Hypovirulence refers to a condition where the fungal pathogen is weakened by a virus, making it less aggressive and allowing infected trees to recover. By introducing these weakened strains, the project aimed to naturally spread this virus to more aggressive strains of the fungus. This reduced the severity of the disease, allowing the affected trees to recover and reducing the long-term damage caused by chestnut blight. This method of biological control has proven effective in maintaining tree health while minimizing the need for chemical treatments.

- Soil Inoculation with Biocontrol Agents (BCAs): To combat ink disease, a soil-borne pathogen (*Phytophthora cambivora*) that affects chestnut trees, the soil around diseased trees was inoculated with biocontrol agents (BCAs), specifically different species of Trichoderma fungi. These fungi have the ability to parasitize harmful pathogens, reducing their presence in the soil and improving tree health. *Trichoderma hamatum*, *T. koningiopsis*, and *T. koningii* were among the species used for this purpose. These fungi help control root diseases and improve the trees' overall resilience. By enhancing root health and reducing pathogen levels in the soil, these BCAs support the recovery of affected trees and contribute to forest stability and productivity. These measures have been implemented to reduce disease incidence, promote forest regeneration, and enhance ecosystem services while building resilience to the effects of climate change.

Replication potential

Biophysical aspects

The biophysical conditions of the San Godenzo site—such as deep, well-drained soils, moderate acidity, and the presence of chestnut and other Mediterranean tree species—make it ideal for implementing mycorrhizal and biocontrol-based solutions. These conditions, however, are not unique to San Godenzo. Similar Mediterranean and temperate forest ecosystems across Europe, especially those affected by pests, pathogens, and climate change-induced stress (e.g., drought and fire), offer great potential for replicating these NbS.

Replication is particularly feasible in regions with chestnut and oak forests, or areas that face similar phytopathological issues such as Phytophthora and Cryphonectria parasitica infections. The ability of mycorrhizal fungi to improve soil health and enhance forest resilience can be beneficial in various climates and soil types, especially where nutrient uptake or pathogen pressure is a concern.

The biodiversity benefits of these NbS are significant and can be replicated across similar ecosystems. Introducing mycorrhizal fungi supports the growth of a wide variety of fungal species that help improve nutrient cycling and soil health. Furthermore, by controlling pathogens like chestnut blight and ink disease through biological methods, the overall health of the forest is improved, reducing the need for chemical interventions that could harm non-target species. The promotion of biodiversity through these NbS can have a cascading effect, improving the resilience of the entire ecosystem, including plants, fungi, and wildlife.

Socio-economic aspects

The San Godenzo region is a rural area, with small villages like Castagno d'Andrea reliant on agroforestry activities, particularly chestnut production for both timber and fruit. Similar rural communities throughout southern Europe and other chestnut-growing regions could benefit from these NbS.

The main economic objective of replicating these NbS is to protect and enhance forest productivity, particularly in regions where chestnut production is economically important. By reducing the impact of diseases such as chestnut blight and ink disease, these interventions could maintain or even increase timber and chestnut yields, providing long-term economic benefits to forest owners, local producers, and broader rural economies. The use of truffle-producing mycorrhizal fungi (*Tuber borchii*), for example, could create new income streams for landowners and communities by diversifying forest products.

This particular project was funded by the LIFE program, with local stakeholders (such as smallholder chestnut producers) benefiting from the increased resilience of their forests. In terms of replication, funding for these NbS could be sourced through a combination of European Union programs (like LIFE or Horizon Europe), national government incentives for sustainable forestry, and private-sector partnerships, especially in areas where agroforestry plays a key role in the local economy. Local forest managers and rural communities stand to benefit directly from the increased forest resilience, while broader society benefits from the ecosystem services provided by healthier, more resilient forests.

Governance aspects

In the San Godenzo trial areas, the forests are managed by local landowners and stakeholders involved in the “Montagne Fiorentine Model Forest” initiative. This voluntary, non-profit association is dedicated to improving sustainable forest and land management in the region. The Montagne Fiorentine Model Forest integrates various local actors, including private landowners, public authorities, forest managers, and rural communities, to create a governance framework that promotes sustainability and biodiversity.

The demonstration areas at San Godenzo—specifically Casale (chestnut coppice) and Castellina-Le Casine (chestnut orchard)—are privately owned but fall under the broader management strategies promoted by this association. This governance structure ensures that forest management practices align with sustainable principles, balancing economic activity with environmental preservation.

In this case, the implementation of these NbS is supported by the Montagne Fiorentine Model Forest initiative, which promotes sustainable forestry practices in line with environmental conservation and climate resilience goals. In some regions, however, there might be barriers to scaling these interventions due to a lack of awareness, financial constraints, or regulatory gaps. Expanding these measures at scale would require legislation that encourages sustainable forest management and provides incentives for adopting nature-based solutions, particularly in rural or economically disadvantaged areas.

At the national level, Italy's forest management is aligned with broader European policies on sustainability and climate adaptation. The National Forestry Plan (Piano Forestale Nazionale) provides a framework for forest management that emphasizes the importance of sustainable practices, biodiversity conservation, and climate resilience. The plan supports the use of nature-based solutions (NbS) like those implemented at San Godenzo, especially in the context of mitigating climate change impacts such as increased drought and fire risks.

Programs such as the LIFE Program and Horizon Europe support research, innovation, and the replication of sustainable practices across Europe. However, scaling these solutions in rural or economically disadvantaged areas may require additional national incentives and clearer legislative frameworks to ensure widespread adoption.

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CASE 8: PEST MANAGEMENT: INTRODUCING MIXED SPECIES TO REDUCE THE RISK OF SPRUCE BARK BEETLES IN NORTH KARELIA, FINLAND

Introduction

The area of productive and poorly productive forest land in North Karelia (NK, Southeastern Finland) is 1.6 million ha. Protected forests covered 123,000 ha in 2022, representing 7.6% of the forest land. The main tree species are Norway spruce (Picea abies) and Scots pine (Pinus sylvestris) forming varying mixtures with birch (Betula sp.). Forestry in NK provides over 6,000 jobs and over 2 billion € in annual turnover. However, forests also have a large cultural importance through hiking, berry picking and hunting.
Climate change might have considerable impacts on the dynamics of the managed boreal forests. Due to climate change the major abiotic and biotic risks in the Northern boreal forests are snow loading, heatwaves and droughts, windstorms, forest fires, pathogens of trees and major insect pests. Climate change increases summer temperatures and the length of the growing season in North Karelia, enabling the completion of additional bark beetle generations during the season, with increased risk for insect outbreaks. Despite these vulnerabilities, forest growth projections for the region are notably higher compared to other regions in Finland.

NbS implemented

The North Karelia Living Lab in the Eco2Adapt project focuses on sustainable forest management practices and biodiversity enhancement, integrating silvicultural activities and ecosystem resilience strategies. Challenges include adapting to climate change impacts, integrating conservation and production goals, and enhancing forest resilience. Forest management practices in the region include soil scarification, prescribed burning, seeding, planting, improving young stands, root-rot disease prevention, forest fertilization and planning and maintenance of ditch networks and forest roads.

Mixed forests and shortened rotation periods have been identified as potential means to mitigate the risk of pest outbreaks in North Karelia. In addition, harvesting the damaged trees and thinning from above (i.e. removing the largest trees) reduce the availability of habitat for bark beetles. However, dead trees should be left on site because they are natural habitats for the spruce bark beetle predators.

Mixed forests maintain biodiversity better than monocultures. Especially old aspens (*Populus tremula L.*) and goat willows (*Salix caprea*) are important tree species for endangered forest species. Leaving the dead trees on site also increases biodiversity. Deciduous trees are known to improve soil fertility, further improving the resilience of forests. However, shortened rotation periods and harvesting the largest trees may have negative impacts on biodiversity which can be compensated by leaving retention trees on the regenerated sites.

Replication potential

Biophysical aspects

The silvicultural approaches could be scaled up to spruce monocultures growing on fertile site types in the boreal regions of Europe. Introducing species mixtures, especially aspen and willows, improves forest resilience and provides habitats for threatened forest species. Planting commercially valuable tree species, such as birch and noble broad-leaved trees, is seen as both expensive and very risk-prone due to the grazing of wild ungulates.

Socio-economic aspects

The earnings from the nature tourism destinations in North Karelia (i.e., Ruunaa, Koli, Patvinsuo, and Petkeljärvi) significantly contribute to income generation and employment opportunities. In 2019, the earnings from these four sites amounted to 25.5 million euros, providing direct employment for 204 individuals per year. Additionally, in 2017, the forestry and fisheries sector contributed approximately 6%

to the domestic production of the North Karelia region, creating around 2.5% of the employment opportunities. Furthermore, in 2018, the gross interest of total earnings reached about 211 million euros, with private forest owners accounting for 76% of these earnings.

The North Karelia region is a hub for forest activities, with diverse actors contributing to shaping the industry. Forest industry companies, such as forest machinery and wood logistics companies, pulp and paper mills and sawmills are dispersed throughout the North Karelia region. Major wood construction companies also play significant roles.

Moreover, various networking, digitalization, and wood research hubs and research institutes are active in the region. These entities contribute to research, innovation, and collaboration in the forestry sector.

Governance aspects

In North Karelia, commercial woodland comprises about 96% of the forest land, with private, state, other public owners, and companies accounting for 55%, 19%, 5% and 21%, respectively. The other public owner groups include, for example, cooperatives, foundations, parishes, and municipalities. The average forest estate size of Finnish private owners is about 30 ha, and the owners are on average about 60 years old.

The Finnish Forest Centre (FFC) serves as a crucial entity in forest governance, actively promoting the forestry sector and providing guidance to landowners. Forest owners' rights, Forest Damages Prevention Act, Animal Damages Act, Temporary Act on the Financing of Sustainable Forestry, Nature Conservation Act, Private Roads Act and other laws affecting forest use are governed by FFC. In contrast, Metsähallitus, Finland's state-owned forest administration body, established by a decree in 1921, is tasked with managing, overseeing, and promoting Finnish forestry. However, its responsibilities do not extend to private forestry areas.

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Annex 2: Main typologies of NbS suitable for fire risk and pest outbreaks

The following table presents main typologies of NbS discussed in this report, highlighting their relevance for fire and pest management. Corresponding case studies (Annex2) where these options were implemented are also indicated.

NbS	Description	Relevance for fire risk	Relevant for pest outbreaks	Case study
Rewilding	Allowing nature to return to a wilder landscape. It includes restoring natural biodiversity and (re-)introduction of large herbivores	*Fire risk reduction and management* Naturally diversified forests are more resilient to fire risks	Creating diverse stands with favourable habitat conditions for natural enemies (e.g. Birds, beetles, flies), Creating less favourable conditions for the insects	
Prioritizing fire-resistant vegetation	Planting (native) vegetation less prone to fire risk, e.g. introducing broadleaved into forests dominated by conifers. It may include planting fire-resistant crops and using hedgerows and other natural barriers to slow fire spread (agroecology and land stewardship)	*Fire risk reduction and management* *Post-fire restoration* Planting Fire-resistant vegetation halts or slows down the spread of wildfire		Riba-Roja, Valencian community, Spain Soria province, Central-northern Spain
Green infrastructure, green corridors and buffer zones	Natural vegetation buffers around urban areas and critical infrastructure	*Fire risk reduction and management* Fire risk reduction and management: These structures act as firebreaks, if they are strategically planted with low-flammability species		Riba-Roja, Valencian community, Spain Deurnse Peel, Southern Netherlands

NbS	Description	Relevance for fire risk	Relevant for pest outbreaks	Case study
Close to-nature and adaptive forestry (*Similar terms: Sustainable forest management, close-to nature silviculture, Adaptive forest management*)	Managing the establishment, growth, composition, health and quality of forests on a sustainable basis. It includes various measures like the conversion from monoculture (e.g. fire-prone eucalyptus) to polyculture, selective thinning, and favouring mixed stands of forests (diverse species and age composition)	*Fire risk reduction and management* Reduce fuel connectivity and create diversified forests more resilient to fire risks	Reduce the amount of available breeding substrate and decrease landscape-scale host connectivity, which helps prevent and mitigate the impact of future outbreaks	Occhito Lake, Puglia region, Southern Italy Deurnse Peel, Southern Netherlands Soria province, Central-northern Spain North Karelia, South-Eastern Finland Riba-Roja, Valencian community, Spain
Agroforestry	Land management strategy where trees, shrubs and hedges are planted in combination with either livestock, pasture or agricultural crop. It enhances soil quality, provides habitats for wildlife and helps increase yields.	*Fire risk reduction and management* Agroforestry creates barriers in forest landscapes and reduces the understory layer of biomass that is usually found in forests	Reduce the amount of available breeding substrate and decrease landscape-scale host connectivity	
Grazing management	Optimising wild and domestic grazing pressure of domestic animals (It can be part of combined with Agroforestry)	*Fire risk reduction and management* Grazing helps reduce vegetation density, lowering the amount of combustible material (fuel load) in fire-prone areas *Post-fire recovery* Fencing off forest regeneration areas helps forest recovery (linked to **natural and assisted natural regeneration**)	Increase diversity, making an ecosystem more resilient also against pests	Viseu Dão Lafões, Portugal Soria province, Central-northern Spain

NbS	Description	Relevance for fire risk	Relevant for pest outbreaks	Case study
Rewetting and Hydrological restoration	Various measures to restore the natural water yield and flow (rewetting dried wetlands, restoration of streams, wetlands and grasslands, building small dams or various water retention structures)	*Fire risk reduction and management* Rewetting help reduce peat oxidation and hence the risk of fire Restored ecosystems create natural firebreaks by creating moist areas *Post-fire restoration* Through restoration, aquatic habitats recover, water quality improves and soil erosion decreases		
Prescribed fire	Use of fire under specific controlled conditions	*Fire risk reduction and management* Prescribed fire reduces the occurrence of large uncontrolled fire events	Decrease landscape-scale host connectivity	Occhito Lake, Puglia region, Southern Italy Viseu Dão Lafões, Portugal
Reforestation and afforestation with native and diverse species	Planting native tree species in areas severely impacted by fires or storms to restore forest cover, stabilize soils, and promote biodiversity. In also include keeping control over alien species. Linked to **Prioritizing fire-resistant vegetation**	*Post-fire management* Planting native and diverse species help restore forest cover after damage has occurred. If fire-resistant species are planted, it can enhance future resilience	Forests more accustomed to local conditions and maintaining vitality. Less vulnerability to insect attacks.	Riba-Roja, Valencian community, Spain Viseu Dão Lafões, Portugal Deurnse Peel, Southern Netherlands North Rhine-Westphalia, Northwest German
Natural and Assisted Natural Regeneration	Protecting natural regrowth of native species, young seedlings and controlling invasive species to support the natural regrowth of forests affected by large damages. This may also include keeping ungulate population low during the initial recovery measures (linked to **grazing management**)	*Post-fire management* Preserving natural regeneration accelerate recovery of forests after large damage has occurred.	Preserving natural regeneration accelerate recovery of forests after large damage has occurred	North Rhine-Westphalia, Northwest German Soria province, Central-northern Spain

NbS	Description	Relevance for fire risk	Relevant for pest outbreaks	Case study
Soil erosion control and stabilisation	It includes Contour Log Terracing (placing logs or other natural barriers across slopes to slow water and sediment runoff to reduce landscape connectivity) and Mulching and Ground Cover (Applying organic materials like straw or wood chips to burned areas	*Post-fire management* These strategies protect the soil erosion and overland flow. Mulching and Ground Cover can also retain soil moisture and protect seedlings		
Soil microbial restoration	Biotechnological strategies by introducing native or external micro-organism Application of biochar for improving organic matter in soils	*Post-fire management* Microbial application creates a cohesive layer that covers the soil surface to protect fragile soil surfaces	Inoculation of Mycorrhizal fungi that form symbiotic relationships with tree roots, use of hypovirulent strains to increase the growing conditions and lower the sensitivity for insects	Tuscany region, Northern Italy
Dead biomass management	Optimising dead and residual biomass	*Fire risk reduction and management*	Removing freshly killed and infested trees reduces breeding substrate and maintain timber quality. In other cases, keeping some dead trees is useful preferred, to create diverse habitats for natural enemies of pest (see rewilding).	North Karelia, South-Eastern Finland
Pheromone traps	Trap that uses pheromones to attract insects		Pheromone traps are used to monitor the presence of insects and to inform control measures.	Soria province, Central-northern Spain

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