communications earth & environment

A Nature Portfolio journal

Article

https://doi.org/10.1038/s43247-025-02284-3

Finnish forest-related laws need to acknowledge climate change risks and integrate adaptive strategies to enhance resiliency

Check for updates

Tahamina Khanam [1], Marina Peris-Llopis [2], Xiaoqian Xu [3], Blas Mola-Yudego [2,4], Leena Leskinen [5] & Frank Berninger [1]

Forests provide critical ecosystem services, including soil protection, water regulation, biodiversity conservation, and absorbing carbon dioxide emissions. Forest resilience to climate change is crucial to sustaining these ecosystems. Here, we aim to review to what extent current forest legislation in Finland supports the adaptation of forests to climate change. We also reviewed non-binding legal documents such as forest strategies and government guidelines. Finnish forest laws addressed selection of genetic material for forest regeneration as well as the management of forest after abiotic damages. Climate change was not clearly mentioned in the laws. Current strategic documents assume that continuing existing forest management practices is sufficient to cope with climate change effects on forests. Overall, the present Finnish forest norms predominantly rely on a perception of low climate risk and business-as-usual management approach can sufficiently address the challenges posed by climate change. We strongly suggest that the Finnish forest norms need to adopt a comprehensive approach that acknowledges the potential risks of climate change and integrates adaptive strategies into forestry practices to enhance climate resilience.

Forests cover approximately 30% of the global land surface and 33% of Europe's land area[1,2]. They are vital to global resilience against climate change, absorbing approximately one-third of anthropogenic carbon emissions and mitigating climate change. Forests also provide critical ecosystem services, including soil protection, water regulation, and biodiversity conservation[3].

Within Europe, the study of forest resilience has gained prominence, particularly in the context of climate-induced stressors such as drought. Key factors influencing resilience include improved water relations and inter-specific competition in mixed forests, which enhance resistance and recovery following drought events. Such dynamics have been observed in the recovery of post-drought forests in Central and Southern Europe[4–6]. A 2018 study across multiple European sites underscored the susceptibility of conifer species like Norway spruce and Scots pine to heatwaves and drought, highlighting significant challenges to their resilience[7].

Between 2018 and 2022, average summer air temperatures in Europe exceeded long-term averages by 0.9 °C to 1.4 °C[8]. These elevated temperatures have contributed to increased forest mortality in Central Europe[9] and amplified forest damage in Southern Fenno-Scandinavia, alongside heightened risks of bark beetle outbreaks due to warming climates.

Forest resilience to various stressors—biotic, abiotic, and anthropogenic—is critical to sustaining these ecosystems. Loss of resilience can be driven by factors such as mismanagement or climatic extremes[10]. In response, forest scientists have explored strategies to enhance resilience. For example, Filotas et al.[11] proposed incorporating principles of ecosystem self-organization and uncertainty into forest management, while Dhital et al.[12] demonstrated how complex landscape structures arising from ecosystem-based management secure wood provision under climate change in Canadian boreal forests. Diversification of forest management has also been suggested as a means of mitigating risks, with Knoke et al.[13] advocating portfolio-theory-based approaches to reduce vulnerability.

In the European Union, forest management is governed by national legislation supplemented by various non-binding guidelines, including

[1]Department of Environmental and Biological Sciences, University of Eastern Finland, Joensuu, Finland. [2]School of Forest Sciences, University of Eastern Finland, Joensuu, Finland. [3]College of Forestry, Northwest A&F University (NWAFU), Yangling, China. [4]Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden. [5]Finnish Forest Center-Metsäkeskus, Joensuu, Finland. e-mail: tahamina.khanam@uef.fi

Table 1 | Major threats and damages of the national and regional Finnish forest

Wind-storms Name (Year): Primary Damage Mm^3	Fires Year: Damage (x 1000 ha)	Heavy snow damage area	Heatwaves & Drought stress	Forest disease	Total damage (x 1000 ha)
Aila (2020): 0.4–0.7[84] Rauli (2019): 0.1–0.2[84] Rauli (2016): 0.15[85] Lyyli (2015): 0.1–0.2[84] Valio (2015): 0.8[85] Eino (2013): 1.5[84] Seija (2013): 1[84] Antti (2012): 0.3[85] Hannu (2011): 0.5[85] Tapani/Dagmar (2011): 3[84] Lahja, Asta and Veera (2010): 8.1a[86] Pyry and Janika (2001): 7.3a[86]	Total: 2021: 2793[28] 1996–2016: 11.46[28,92] North Karelia: 2003: 67[91,92]	Western Finland (South and Central Ostrobothnia, 2014–2015): 150 000 m^3 of timber[88] North Karelia: 2014–2018: 20 188 ha[32]	Damage by drought in forests sites (% of sites affected, 2005–2008)[90]: Pine 65.5%; Spruce 20.7%; Broad-leaved 13.8% Helsinki city forest park damage (2003): 25 ha[89]	Insects: NFI 12/13 (2017–2021): 0.4[87] Fungi: NFI 12/13 (2017–2021): 3.2[87]	Total[87]: NFI 12/13 (2017–2021): 23.7 NFI 12 (2014–2018): 24.1 NFI 10 (2004–2008):25.1 NFI 9 (1996–2003):21.8 North Karelia: 2017–2021: 17.6%[83] 2001–2021: 350.6[92]

private and governmental norms. These regulations have historically focused on sustainable timber production but have evolved to address broader ecosystem services. Legal scholars, such as Fischman[14], argue that climate change adaptation is intrinsically linked to resilience. Laws, therefore, should prepare societies for uncertain futures and acknowledge that adaptation may incur costs and trade-offs, including the loss of ecosystem functions. Craig[15] proposed five principles for climate adaptation laws: (1) continuous monitoring; (2) reduction of non-climatic stressors and promotion of resilience; (3) long-term, multi-stakeholder planning; (4) flexibility in regulatory goals and resource management; and (5) acceptance of adaptation costs and losses. These principles align with other frameworks for adaptive governance, such as those highlighted by Driessen and van Rijswick[16].

The interplay between legal norms and forest resilience continues to be a topic of interest[15]. Garmestani et al.[17] emphasized the role of laws in fostering resilience, while Seidl et al.[18] argued for a dynamic interpretation of resilience beyond normative definitions. Cañizares et al.[19] highlighted the utility of resilience as a guiding concept for designing ecosystems and setting management goals. Moreover, Newton[20] advocated for integrating resilience into large-scale policymaking, while emphasizing the need to assess its broader implications.

This study aims to analyse how current Finnish forest regulations support the adaptation and resilience of forests to climate change, with a specific focus on adaptation rather than mitigation. To our knowledge, this is the first review of Finnish forest policies from an adaptation perspective, addressing a critical gap in the literature. Specifically, we explore two research questions: (1) How are climate risks to Finnish forests addressed in forest legislation? (2) How does Finland's normative framework compare to theoretical studies on climate adaptation laws?

The Finnish context offers a unique case study due to its substantial forest resources, extensive forest legislation, and the challenges posed by climate change. While Finland's regulations historically emphasized forest growth and yield, many of these provisions may inadvertently support climate adaptation through sustainable forest management practices. By examining these dynamics, we aim to provide insights into how systemic change and adaptation can be better integrated into forest laws and governance frameworks.

Results

Challenges for resilience and adaptation

Finland's forest area, which constitutes 86% of its total land area, spans 26.247 million hectares and is primarily located in the Northern and Southern boreal zones[21]. The boreal forests in Finland experience an average annual temperature range of +5 °C to −2 °C[22]. However, due to climate change, Finland faces increasing extreme weather events, including heavy snowfall in winter, hot and dry summers, and intense rainfall.

The effects of climate change are particularly pronounced in boreal forests compared to other forest types. Kellomäki et al.[23] highlighted the main impacts of climate change on the dynamics of managed boreal forests in northern Europe. According to Venäläinen et al.[24], the primary abiotic and biotic risks in boreal forests due to climate change include heavy snow loads, windstorms, heatwaves, droughts, forest fires, pathogens affecting trees, and major insect pests (Table 1).

Mäkinen et al.[25] reported growth reductions in spruce stands following summer droughts in the 1990s. Simulations by Ikonen et al.[26] predicted escalating risks of wind damage in Southern Finland between 2010 and 2099, due to the region's higher proportion of Norway spruce. Luoranen et al.[27] identified high drought stress risks for newly planted Norway spruce seedlings in Nordic boreal forests, particularly those planted in early or mid-summer. Furthermore, increasing summer droughts heighten the likelihood of large-scale forest fires[24].

In Northern Finland, the peak fire alert season begins in early May and lasts 12 weeks. As of 2021, the cumulative burned area in the region was 2793 ha[28]. The most important year for burned areas in recent history was 2003, with approximately 67 hectares affected, primarily in agricultural zones. Despite these events, the overall threat of forest fires in Finnish boreal forests is considered mild compared to other regions.

Climate change also amplifies the risk of snow damage in Finland. Fluctuations around 0 °C may cause ice accumulation on tree crowns, leading to breakage[29,30]. A study by the University of Eastern Finland and the Finnish Meteorological Institute found that climate change increases snow damage risks, particularly in eastern and northern Finland, where trees are better adapted to heavy snow loads than those in other parts of the country[30]. Snow damage often precedes other serious risks, such as damage from insects or fungi.

The National Forest Inventory (2014–18) identified snow damage as the most severe cause of forest damage in regions like North Karelia, North Savo, Kainuu, and Lapland[31]. For instance, in 2018, forest damages were valued at 170 million EUR, affecting 52,000 hectares, with 70 million in Kainuu and 66 million EUR in North Karelia[32].

Predictive analyses revealed that wind damage varies depending on forest management and species regeneration under different climate scenarios[26]. While southern Finland faces higher wind damage risks, the northern boreal zone experiences lower wind risks but higher snow damage due to forest structure and prolonged frost periods[24,33]. Forest damages predominantly affect pine-dominated forests in Finland, with 87% of abiotic damage caused by snow, soil nutrient imbalances, and wind[21].

Rising CO_2 levels and enhanced photosynthesis from increasing temperatures have accelerated forest growth globally, provided water supply is sufficient[34]. However, during periods of rapid climate change, forest growth responses vary substantially between northern and southern Finland[24,35]. While northern Finland sees increased forest growth, its unique features may be at risk of decline. Vulnerability to climate change is higher for Norway spruce and birch but lower for Scots pine in northern regions[33].

Appropriate tree species selection and reduced forest rotation lengths could increase forest growth in Finland by up to 44%[23]. Moreover, promoting biodiversity through species selection can reduce pest damage[36,37], lower wind damage risks[33], and enhance ecosystem service provision[38].

As a result of the analysis, we identified six pivotal factors, that were the basis for the normative analysis: i) preventing pathogens, ii) increasing the presence of native tree species in forests, iii) practicing adaptive silviculture, iv) promoting tree species diversity, v) managing fire and water and vi) implementing flexible management systems to addresses challenges in resilience and adaptation.

Normative frameworks and forest laws to increase resilience

Numerous laws in Finland, such as the Forest Act 1093/1996[39], govern its forests. The aim of this act is 'to promote economically, ecologically and socially sustainable management and utilisation of forests in order that the forests produce a good output in a sustainable way while their biological diversity is being preserved' (ch. 1, § 1 Forest Act 1093/1996[39]). Other acts, including the Financing Act for Sustainable Forestry 34/2015[40], also aim to promote ecologically, economically, and socially sustainable management and use of forests. These laws focus primarily on felling practices that enhance the growth of remaining tree stands, with artificial regeneration through clear-cutting being the principal approach.

The Amendments Act of 2014 introduced greater freedom of choice for forest owners in forest management decisions[41]. Under the Act of 34/2015 (§ 37 & 39)[40], the Forest Centre terminated the obligation to manage and maintain areas or forest roads financed by state resources and to monitor conditions for granting, paying, and using subsidies. Moreover, if ownership agreements change, the new owner can terminate the agreement by notifying the Forest Centre (§ 43 & 43a Financing Act for Sustainable Forestry 34/2015[40]). However, after December 2023, the Financing Act for Sustainable Forestry 34/2015[40] was replaced by the Incentive System for Forestry 71/2023[42], which emphasizes the maintenance of forestry road networks.

The forest acts stipulate that while forest owners have the freedom to manage their forests, they cannot damage them, and reforestation is mandatory after tree removal (ch. 2, § 5 Forest Act 1093/1996[39]). The Government Decree on Sustainable Forest Management (1308/2013)[43] primarily addresses forest damage related to logging activities in Sections 4, 5, 9, 10, and 13 but lacks specific instructions for managing abiotic forest damage. However, the Act (§ 8 and 11 Forest Act 1308/2013)[43] includes essential guidance for promoting species diversity, particularly by emphasizing the use of native tree species for natural regeneration and sustainable forest management practices.

According to the Forest Damages Prevention Act[44] (1087/2013) § 2, 'Forest damage means diseases and deterioration of tree growth or quality caused by invertebrates, fungi, bacteria, or viruses to trees growing in forest which cause economic damage, and damaged tree means a damaged pine or spruce tree from which insects causing forest damage may spread.' This act emphasizes the removal of damaged conifers to prevent infestation and ensure forest health. It also supports the subsidization and construction of forest roads[45].

Forest legislation, directly and indirectly, supports the prevention and control of forest damage. Finnish forests experience fewer forest fires, partly due to natural factors, such as lakes that act as fire breaks and provide resources for fire suppression, and partly due to forest laws. For instance, the extensive forest road network, funded by the state (§ 1, 9, and 16 Financing Act for Sustainable Forestry 34/2015[40]; ch. 3, § 17 Act on the Incentive System for Forestry 71/2023[42]), facilitates forest connectivity, restrains fire spread, and assists firefighting efforts. Additionally, an aerial surveillance system helps prevent fires from becoming large-scale disasters.

The Forest Damages Prevention Act[44] mandates that felled timber, such as spruce or pine, must be removed, or substitute actions, such as covering, irrigating, or debarking, should be taken to prevent damage to surrounding forests. In cases of exceptional forest damage, the Ministry of Agriculture and Forestry requires landowners and Metsäkeskus to take preventive action (§ 9 Forest Damages Prevention Act 1087/2013)[44].

The European Council Directive (Council Directive 1999/105/EC, implemented as Finnish law 241/2002) mandates that forest seeds should be adapted to the local climate[46]. The directive provides rules for transferring forest genetic material across geographical regions. According to the Finnish Food Authority, seed transfers are permissible for certain spruce and pine sources, with specific temperature sum differences or geographic limits suggested for different seed types[47,48].

The Act on the Incentive Scheme for Forestry 71/2023[42] and the FSC guidelines (principle 6) emphasize water protection measures in forests. These measures mitigate erosion, soil degradation, and water pollution while supporting ecosystem health. By regulating hydrological processes and maintaining water cycles, these measures reduce forest damage risks from extreme weather events, such as floods, landslides, and drought stress[49]. Water protection is crucial for addressing nutrient loss from increased rainfall[50]. However, while the Incentive Scheme 71/2023 (§ 15, ch. 1)[42] highlights sustainable forest management and adaptation, it lacks detailed guidelines on achieving climate change mitigation. Moreover, these measures are voluntary, with forest owners needing to apply for financial support to implement them.

Finally, the Act on the Finnish Forestry Center (418/2011)[51] does not specifically address climate adaptation, forest damage, or climate change risks. Instead, it focuses on forest management and sustainable use, defining Metsäkeskus' roles and responsibilities, administrative functions, and state aid monitoring (Table 2).

Non-binding and technical frameworks and actions for increasing resilience

The Tapio guidelines for good forest management[47] are recommendations for the management of private forests. The guidelines consider a set of measures. The premises of the guidelines is that the climate will warm by between 3 and 6 °C before 2100. They estimate that as a result, the growth of spruce will decline 'to some extent in Southern Finland' and that there will be an increase in forest damage. The guidelines emphasise the use of genetically adapted material (especially genetically improved material) for forest regeneration. The guide also provides a list of the positive effects of climate change. As adaptation measures, the guide proposes intensifying the management of damages and using appropriate silviculture, without delving into the details.

The 'Instructions for Silviculture'[52] that are used in state owned forests are more concrete than those proposed by Äijälä et al.[47] and make direct suggestions about the establishment of mixed forests, the use of genetically improved seeds, the use of continuous cover silviculture as well as restricting the use of spruce on dry sites. We note that the paper combines measures for climate adaptation and climate mitigation, and we attempted to restrict our analysis to adaptation measures.

In our evaluation of the Forest Management PEFC FI 2022 standard series[53] (including documents such as PEFC FI 1006:2019[54] and PEFC FI 1002:2022[55]), we concentrated on multiple facets associated with PEFC FI. Although these documents cover a broad spectrum of topics, we noted that there is no specific section explicitly addressing forest damage, risk, snow damage or climate adaptation.

Notably, the 'Sustainable Forest Management—Requirements PEFC FI 1002:2022'[55] document emphasises the importance of climate change and adaptability. However, it does not provide specific suggestions or guidelines for combating these situations.

The FSC guidelines are based on the FSC-STD-FIN-02-2023[56]. Amongst the FSC's 10 principles, Principles 1.1, 6.3, 9 and 10 specifically focus on forest management plans that include preserving decaying wood, conserving habitat and protecting water, which are relevant to mitigating the risk of fire, disease and major insect outbreaks[57,58]. Additionally, criterion 4.4 highlights the necessity of incorporating measures in the forest management

Table 2 | Finnish Forest Laws' Climate-Resilient Management Actions

Climate threat/Damage	Laws	Section	Instructions
Manage option: preventive			
Forest disease	Plant Health Act 1110/2019[93]	4, 5, 6	Preventing dangerous plant pests in forest trees and their spreading.
	Forest Damages Prevention Act 1087/2013[44]	8a, 17	• The feller should take care of root rot and weevil control in the risk area between the beginning of May and the end of November. • FFC prepare control plan and Ministry of Agriculture and Forestry approve a forest damages control plan in order that the control is cost-efficient, effective, and preventive damages.
		4, 8	Prevent significant spread of insects causing forest damage from the timber in storage.
Tree species	Decree on the Sustainable management and use of Forests 1308/2013[43]	8, 11	A diverse range of native tree species for natural regeneration and sustainable forest management should be practiced.
	Alien Species Act 1709/2015[94]	1, 3, 4,11, Annex B	Preventing and mitigating the spread and adverse impacts of invasive alien species, respectively.
	Plant Health Act 1110/2019 (Ch 3)[93]	8	Use or import the native species
Wind-storms, Forest fires, Heavy snow, Forest disease	Forest Damages Prevention Act 1087/2013[44]	9	The Finnish Forest Centre (FFC) hear and collect information of the occurrence of forest damage time, area and the contact information of landowners to measures within 14 days.
		10	Compensating for the costs associated with the actions taken to prevent forest damages
	Act on the incentive system for forestry 71/2023 (Ch 1)[42]	15	• Advancement of sustainable forest management and measures to promote adaptation of forests to climate change. • Water protection measures, climate change mitigation, and biodiversity conservation.
Wind-storms, Forest fires, Heavy snow	Act on the incentive system for forestry 71/2023 (Ch 3)[42]	2, 10, 12, 16, 17, 19	Making a forest road, renovation of a private road and construction of a new forest road.
Wind-storms, Heavy snow, Forest disease	Climate Act 423/2022 (Ch 1,2)[95]	2, 10	Make and approve a National Climate Adaptation plan with climate risk management and sustainability measures
	Forest Damages Prevention Act 1087/2013[44]	4, 8	• If the owner of timber does not remove the timber as laid down shall: cover, sprinkle water; debark, treat plant protection product, pile away sufficient distance of the same species forest stand. • When storing pine or spruce timber in a terminal or industrial storage site the owner of the timber is obliged to undertake reasonable measures. • Cover the surface layer of a pine and spruce timber pile.
Manage option: corrective			
Wind-storms, Forest fires, Heavy snow, Forest disease	Act on the incentive system for forestry 71/2023 (Ch 6)[42]	40	Regeneration felling is conceded only if natural damage to the forest has occurred and necessitates it.
	Forest Damages Prevention Act 1087/2013[44]	3-4	Removal of timber from a felling and intermediate timing, location and distance of the storage.
		5,14	Removal of parts of trunk and stumps of pine and spruce from a forest stand and intermediate storage site.
		6	• Removal of damaged trees from a forest stand and intermediate storage site. • If the landowner does not remove the timber shall notify that to FFC.
		20	Landowner Liability for damages: • If a landowner damages another landowner's trees (as per section 6(6)) or causes a decrease in the tree stand growth of more than 20 solid cubic metres per hectare over five years, they are obligated to compensate the damaged owner. • The landowner is obliged to compensate if damage from their own forest spreads to a terminal or industrial storage. Otherwise, the provisions laid down in the apply to Tort Liability Act (412/1974).
		21	State's liability for damages: • Forest damages from State-owned reserves or protected areas are managed by Metsähallitus based on safety decisions. • Compensation can be reduced if the same party suffers and contributes to the damage. • Landowners apply to the damage occurring regional unit (FFC) to receive compensation from the Ministry of the Environment.
		25	Violating the provisions intentionally or through gross negligence according to the Forest Damages Prevention Act laid down in Section 3–6 shall be sentenced or fined.
Manage option: preventing & corrective deforestation	Income Tax Act on Agriculture and Forestry 543/1967[96]	5	The taxable income (referred to in § 4), among other things: Transfer prices and other considerations from machines, equipment and devices as well as damage, insurance and other compensations, deducted the acquisition costs as depreciation.

Forest disease = Forest health + Pathogens.

Table 3 | Non-binding Climate-Resilient Management Actions in Finnish Forest

Climate threat/Damage	Non-binding guidelines	Instructions
Manage options: preventive		
Forest disease	FSC-STD-FIN-02-2023[56]: P 10.7.6[b] PEFC FI 1002:2024: Annex 2[97]	Chemical pesticides should not pose environmental, or health risks & associated any drawbacks should be addressed promptly.
	PEFC FI 1002:2024: 8.5.1[97]	Ensure tree health by preventing fungal spread, minimizing damage during harvesting, protecting against insects.
	PEFC FI 1002:2024: 8.9.1[97]	Only approved plant protection products shall be used in forest management and harvesting.
Tree species	FSC-STD-FIN-02-2023[56]: P 6.6.1.1.2	Preserve biological diversity during felling by retaining specific tree species. • For Oaks, minimum diameter *is* 20 cm in the hemiboreal zone and 10 cm elsewhere in Finland. • For other Southern Broadleaved Trees, minimum diameter is 10 cm or more measured at breast height.
	FSC-STD-FIN-02-2023[56]: 6.6.1.4.1 & 6.6.1.4.2	Maintain at least 10% of the total number of deciduous trees within seedling stands.
	PEFC FI 1002:2024: 8.7.1[97]	Native tree species shall be used in forest regeneration, except in special cases.
	PEFC FI 1002:2024: 8.13.1[97]	The biodiversity of forest species shall be promoted with prescribed burning excluding Åland and areas under 200,000 hectares.
Wind-storms, Forest fires, Heavy snow, Forest disease	FSC-STD-FIN-02-2023[82]: P 6.5.7[a]	Conducted forestry operations, drainage, and road construction without compromising conservation values of protected areas.
Wind-storms, Heavy snow, Forest disease	FSC-STD-FIN-02-2023[56]: P 6.5.1.6[b]	Dangerous trees can be cut, blocked trees cleared, and access routes established to protect site conservation goals while minimizing damage to natural values.
Manage options: corrective		
Wind-storms, Forest fires, Heavy snow, Forest disease	FSC-STD-FIN-02-2023[56]: P 6.6.1.2	• Retention trees must include the main tree species (excluding alien species, except larch) and grouped within a 1 km diameter • In regeneration felling, at least 10 trees/hectare with specified diameters (20 cm and 15 cm in Southern and Northern Finland, respectively) must be retained. • A minimum of 10 cm diameter are required if larger retention trees are not available.
	FSC-STD-FIN-02-2023[56]: P 6.6.1.3[a]	• Retention of dead trees over 10 cm in diameter at breast height in forestry operations. • If freshly formed deadwood in decay class 1 exceeds 20 m3/ha, it can be removed on the site, irrespective of the Forest Pests Act threshold. In Class 2 forests, excess fresh dead wood in decay class 1 over 10 m3/ha can be removed.
	PEFC FI 1002:2024: 8.14.1[97]	• The minimum average number of retention trees left permanently in fellings is 10/ha; • The combined minimum number of damaged, live, and dead trees to be retained is 20/ha.
Wind-storms, Heavy snow, Forest disease	FSC-STD-FIN-02-2023[56]: N 1-36.6.1.3	The indicator does not impede legal wood harvesting, when there is a threat of fungal and insect damage and forestry operations should be carefully executed to minimize the risk to workers and trunk rot damage.

Forest disease = Forest health + Pathogens.
N Note, *P* Principle.
[a]Amended.
[b]New.

plan to maintain and enhance the resilience of forest ecosystems, including adapting to climate change.

Both the PEFC FI and FSC FI share overarching principles and criteria that emphasise the importance of forest management in the context of climate change adaptation and resilience. However, their suggestions and guidelines do not specifically address effective strategies for adapting to climate change (Table 3).

Discussion and conclusion

Our analysis demonstrates that normative rules for climate change adaptation are distributed across all legal levels (from the EU to non-binding legal frameworks). Subnational rules for climate change adaptation in Finland are absent because forest legislation in Finland is regulated at the national level.

In Finland, the Forest Act of 1093/1996[39] delineates the framework for the principles of the Finnish Forest Act and establishes four key principles: multiple use and sustainability (explicitly in §2, 3, 10 a), the protection of biodiversity and natural habitats (explicitly in §10 a, 10 b and 12), forest regeneration and tending (explicitly in § 6, 7, 8 and 14, 20) and forest owners' right to decide (implicitly in various section, e.g. §11, 15 and 20).

The Finnish Forest Act prioritises 'sustainability' to combat climate change and its impacts. The Finnish Forest Act of 1093/1996[39] also emphasises 'forest owners' decision-making rights'. However, there is an ongoing discussion regarding how the burdens of climate change will be shared in Finland. The role of forest harvests in climate change mitigation has received particular attention in political discussions. In the forest planning process within Finnish government-owned forest areas, a consultation procedure engages the public, as highlighted by Metsähallitus[59] and Kaukonen et al.[60].

Overall, the major principles of the Finnish Act are intended to encourage sustainable forest management and balance the social, economic and ecological aspects of forestry. For example, the principles of biodiversity and natural habitats promote and protect forest ecosystems to contribute to climate mitigation and adaptation, forest regeneration and tend to ensure the long-term productivity of forests and ecosystem services to promote sustainable development.

Thus, most forest operators and management-related personnel emphasise the dominant nature of protection and sustainability due to the long-term horizons used in forestry. For instance, simulations of forest dynamics for Finland (e.g., Kalliokoski et al.[61]) present scenarios for the upcoming 100 years to ensure sustainability. Forest management plans in Finland usually contain background simulations to ensure sustainability for several decades, although forest management is proposed for ten years. Forest operators and management-related personnel clearly distinguish between long-term strategic planning and short-term tactical planning. The Finnish Forest Strategy 2025[62] emphasises the positive effects of climate change on the productivity of Finnish forests while also mentioning the dangers of increased damage. The main instructions to increase adaptation are to 'perform silvicultural treatments in time'. Furthermore, the strategy mentions that treatments against decay of roots should be intensified.

The long-term nature of forestry means that specific silviculture measures reduce future management options for decades. For example, tree species selection in plantations may be costly to change. Changes in tree species could reduce the area of vulnerable tree species and thus create more resilient forests for several decades. For example, spruce is considered to be the most vulnerable tree species in Finland[23]. Conversely, birches are supposed to benefit from climate change[23]. Another option is to shift the origins of seeds used for regeneration to more southern areas or to introduce new, better-adapted tree species[63].

These scientific recommendations have not been reflected in practical guidelines for forestry. The laws on forestry do not address tree species selection, and there are no references to climate change for tree species selection in the 'Guidelines for Forest Management'[47]. The selection of seed sources for planting is regulated in the law about the 'trade in forest reproductive material' and their interpretations by the Finnish Food Authority, which implements a European law that recommends the transfer of seeds within 100 km north or south. The accompanying text does not mention climate change as a criterion for selecting seed sources, and there are no provisions for a longer-distance transfer of seeds to create climate-adapted future forests.

A second philosophy for adaptation to climate change accepts that climate change causes severe and unforeseeable changes in forests. In response, many forest ecologists[64] recommend that forest management be inspired by complex science and embrace the concept that forest management outcomes cannot be predicted during periods of rapid climate transition[10]. Thus, in a nutshell, challenges arise when attempting to build resilience within the forest ecosystem and incorporate it into environmental law to address social and ecological complexities[65]. Dhital et al.[12] suggested, based on a simulation, that ecosystem-based management approaches lead to more resilient forestry under climate and fire risks. However, this approach is based on emulating the natural disturbance regime. Therefore, it may not be suited for Finland, where forest ownership is fragmented, and most of the forest is held by smallholders.

To overcome these challenges, several authors[66–70] argue that resilience in forest ecosystems necessitates a co-management approach, involving stakeholder collaboration, communication and transparency, to address the complexity and interconnectedness of ecosystems and foster adaptive management practices. Benson and Garmestani[71] emphasise the importance of a policy framework and collaborative approach, along with investments in research, data collection and training for natural resource managers on resilience thinking and practical applications. Messier et al.[10] propose holistic approaches to tackle these challenges, which involve adopting diverse and adaptable objectives, tools and forest structures. A study by Triviño et al.[72] summarises the principal management approaches that can enhance forest resilience—landscape functional zoning, functional complex networks, natural disturbance emulation and climate-smart forestry.

Craig[15] notably examines the same issues from a legal standpoint. He claims that climate change law cannot be 'preservationist' and should strive toward maintaining ecosystem functions rather than ecosystems. Craig[15] further suggests reducing ecosystem stress and establishing sustainable production goals to withstand climate change. He emphasises the importance of flexibility in future climate change directives. Abrams et al.[67] advocate for a proactive approach to forest management employing the planning perspective of the United States National Forest. Forest managers should actively promote resilience rather than reacting to disturbances such as climate change.

The Finnish climate change regulations do not embrace uncertainty and complexity, as proposed by Messier et al.[10]. Instead, the critical tools for adaptation to climate change appear to intensify silviculture and to make silvicultural treatments in time to avoid future damages (Suomen metsästrategia[62], *Metsänhoitoohjeet*). Additionally, Fischman[14] highlights critical aspects of incorporating resilience into forest law, such as focusing on entire ecosystems rather than individual species or habitats and recognising the value of indigenous and local knowledge in ecosystem management. However, together, these perspectives stress the need for complexity-based diverse approaches to building resilience against social, ecological and climate change challenges in forests.

Notably, neither the forest law nor the forest guidance materials reference multiple outcomes. They also do not explicitly try to increase ecosystem-level resilience through admixtures. Nevertheless, the forest guidance[47] suggests that maintaining forest mixtures increases forest resistance against damage. Although the Finnish forest law delineates clear guidelines for the conservation of biological diversity by defining a large array of ecosystems to be protected, it does not explicitly promote the adoption of ecosystem-based adaptation approaches. These approaches prioritise the maintenance and restoration of healthy ecosystems as a means to enhance their resilience against climate impacts.

Altogether, we think the present Finnish forest norm is essentially based on a perception of 'low climate risk' (Suomen metsästrategia 2025)[62] and the idea that an improved business-as-usual management approach can address the problems arising from climate change. Furthermore, Driessen and van Rijswick[16] added that climate change adaptation policies should not only focus on reducing vulnerability and increasing resilience to future impacts but should also consider normative values and principles such as justice, equity and responsibility. Fischman[14] and Fiack[68] argue that resilience and adaptation should be a guiding principle for environmental governance and that legal frameworks should be designed to enhance the resilience of ecosystems and communities.

The legislation we reviewed concerns changes in tactical forest management, specifically short-term adjustments to forestry as a reaction to disturbances. This is especially true of the desire to limit forest damage caused by bark beetles (Forest Damages Prevention Act (1087/2013)[44]). Bark beetles usually breed in recently killed dead wood with intact bark and attack older living conifers. The law clearly defines the obligations of forest owners to store harvested wood or to remove wood from natural damage. This includes guidelines for litigation and provisions for force-majeure situations in the case of widespread forest damage. In addition, government agencies have an obligation to monitor forest damage under the law. Day and Perez[73] analysed management strategies in response to the mountain pine beetle outbreak in British Columbia. They stress the importance of precautionary management (i.e. harvesting stands at risk before they become infected).

The Forest Damages Prevention Act[44] includes provisions for several diseases, in which measures are prescribed to prevent diseases. Measures linked to the storage of harvested wood are precautionary but most of the measures are reactive and associated with forest management. Other forest acts include measures for loss and damage as well as options. In essence, the Finnish forest legislation provides tools to react to forest damage a posteriori and several tools to protect stands from damage. Furthermore, there are concerns regarding the law's effective enforcement and implementation.

Another set of important documents is the standards of FSC FI and PEFC FI which are developed based on the broader framework of Sustainable Forest Management (SFM) and include practices that promote long-term health and vitality of forests. These practices involve preventing, monitoring and mitigating forest damage caused by pests, diseases and extreme weather events. However, it is essential to note that neither FSC FI nor PEFC FI has specific guidelines exclusively dedicated to addressing adaptation, forest damage and resilience.

However, the current legislation assumes that Finnish forests are optimally managed under climate change using a business-as-usual approach. Consequently, Finnish normative documents do not provide tools for a systemic transformation of forestry through a more extensive spread of silvicultural options or by more carefully matching site-specific risks with silviculture. As a result, the law must adequately address the impacts of climate change on forests and prioritise climate resilience and adaptation in forest management practices. Furthermore, it should require monitoring and reporting of adaptation measures to assess their effectiveness and to inform ongoing adaptation efforts. Additionally, specific incentives or support should be provided for forest owners or managers who adopt climate-friendly forestry practices or implement adaptation measures.

The conservative approach to adaptation, as devised by Finnish forest policymakers, may be efficient if the effects of climate change turn out to be mild. However, legislation encouraging more transformative changes in forest management may be more adequate if climate change causes sustained damage. The recent events in Central Europe inspire fear of severe climate change effects. For example, Germany experienced a loss of 9% of its coniferous forest cover due to heat in drought from 2018 to 2020[74]. If large-scale losses of forests are shifting north, the present legislation will fail to push forest owners toward the creation of more resilient forests. In other words, the present regulations do not provide incentives to transform forests to be more resilient. The high-temperature increases and the occurrence of many extreme climate events during the past three years suggest that it might be worthwhile to prepare more actively for transformative changes in forest management. The present normative framework is not ready for these transformations.

Methods

Definition of key concepts

This analysis begins by examining climate change-related risks affecting Finnish forests. According to the IPCC[75], risks are defined as the 'potential for adverse consequences for human or natural systems,' which depend on forests' exposure to a hazard and their vulnerability to it. We identified major risks based on forest statistics and scientific literature, focusing on climate change-induced hazards such as wind damage and bark beetle outbreaks. Less emphasis was placed on non-climate-related risks, such as root rot, as our primary focus is on climate-driven challenges. Vulnerability, as described by the IPCC[76], reflects a system's lack of functioning, while the broader term 'threat' encompasses both immediate and long-term dangers arising from the interplay of risks and vulnerabilities.

Adaptation to climate change is defined by the IPCC[75] as 'human interventions' in natural systems that 'facilitate adjustment to future climate change and its effects.' In this study, adaptation actions are operationalized as measures that reduce exposure to hazards or decrease vulnerability. These actions are categorized as preventive (e.g., measures taken to avoid damage before it occurs) or corrective (e.g., measures aimed at reducing the impact of damage). Additionally, actions that mitigate the socio-economic burden after damage, such as cleanup efforts or compensation schemes, are also discussed.

We also distinguish between two forms of adaptation: transformational adaptation and incremental adaptation. The IPCC defines transformational adaptation as 'adaptation that changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts'[75]. Examples include the introduction of new tree species, altered forest compositions, innovative genotypes, or novel silvicultural systems to respond to climate change. Incremental adaptation, in contrast, involves implementing existing guidelines more stringently without fundamentally altering management practices.

Forest resilience, as defined by Reyer et al.[77] and Scheffer[78], refers to a forest's ability to absorb disturbances and restructure itself while maintaining functionality. From an ecological perspective, resilience reflects an ecosystem's capacity to persist, recover, and reorganize after natural or anthropogenic disturbances[79–81]. These mechanisms (persistence, recovery, and reorganization) form the foundation of resilience, which is the ultimate goal of adaptation measures.

Review methodology

This study comprises two interconnected components: a review of threats to Finnish forests and an analysis of regulatory frameworks. In the first component, we examined forest statistics and scientific literature to identify the primary challenges facing forests in adapting to and building resilience against climate change. This literature-based review highlighted key threats such as climate-induced hazards, including wind damage and bark beetle outbreaks, and their implications for forest ecosystems. The second component involved a detailed review of relevant legislation and significant non-binding (soft) regulations addressing climate change adaptation in forestry.

Our analysis focused on Finnish laws and regulations that explicitly reference forests or climate change. Each paragraph within these laws was examined to determine its contribution to the resilience of Finnish forests or its role in supporting adaptation and acclimation to climate change. In cases where explicit references to climate adaptation were absent, we interpreted provisions addressing forest damage prevention and the environmental impacts of forestry as indirect contributions to resilience.

This legal review was supplemented by an analysis of non-binding normative texts that hold significant practical importance in Finnish forestry. These included the National Forest Strategy of Finland, Tapio's Guidelines for Good Silviculture[47], and the Instructions for Silviculture for both private and government-owned forests. The certification systems PEFC (*Programme for the Endorsement of Forest Certification*) and FSC

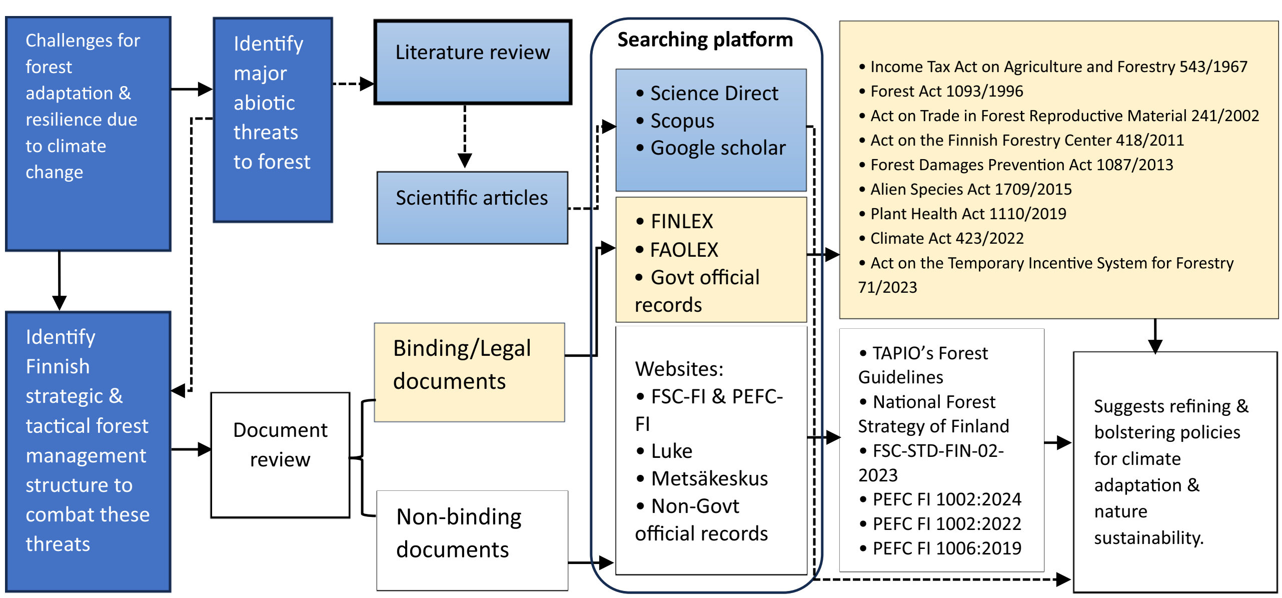

Fig. 1 | Conceptualization of the methodological steps followed. FSC—Forest Stewardship Council, PEFC—Programme for the Endorsement of Forest Certification.

(*Forest Stewardship Council*) were also examined, as they encompass nearly all managed forests in Finland.

Tapio, a state-owned company offering forestry advisory services, provides guidelines widely used by forest advisors working with private forest owners. Similarly, state-owned forest silvicultural practices are governed by the Instructions for Silviculture[52]. The certification systems provide an additional layer of guidance. FSC Finland, an independent, non-profit organization, promotes environmentally friendly, socially beneficial, and economically viable forest management. We analysed the most recent version of the FSC standard (FSC-STD-FIN-02-2023)[56], which incorporates updated provisions addressing forest risks, damages, adaptation, and climate change. Notably, revisions in the latest version have replaced older terms like 'damage' with concepts such as 'conservation values' to better reflect modern forestry priorities.

Similarly, the PEFC Finland Certification Council governs PEFC certification, which sets standards for sustainable forest management through a collaborative, transparent process. Endorsed by the international PEFC since 2000, the Finnish PEFC system is detailed in documents such as PEFC FI 1006:2019[53] and PEFC FI 1002:2022[55]. These internationally recognized standards, created collaboratively by diverse stakeholders, outline guidelines for sustainable forestry practices that address adaptation and resilience challenges. It is worth noting that we contacted Tapio Oy, FSC FI and PEFC FI to inform them about the study; however, we did not receive any response

To further support this analysis, we conducted an expert-driven literature review, where keywords such as *adaptation*, *adaptive silviculture*, *forest damages*, *climate change*, and *threats* to forests were used to identify relevant studies and regulations. Only literature and regulatory texts that aligned with the thematic scope of this study were included. By integrating binding legal provisions with non-binding standards and guidelines, this analysis evaluates how these frameworks support forest owners in adapting to climate change risks and, furthermore, we offer recommendations for enhancing existing policy measures (see Fig. 1).

Received: 16 October 2023; Accepted: 9 April 2025;
Published online: 30 April 2025

References

1. Senf, C. & Seidl, R. Mapping the forest disturbance regimes of Europe. *Nat. Sustain.* **4**, 63–70 (2021).
2. Mauri, A. et al. EU-Forest, a high-resolution tree occurrence dataset for Europe. *Sci. Data* **4**, 160123 (2017).
3. Joint Research Centre. *Climate variability drives global decline of forest resilience* (2022). https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/climate-variability-drives-global-decline-forest-resilience-2022-07-13_en Available at.
4. Zamora-Pereira, J. C. et al. Magnitude and timing of density reduction are key for the resilience to severe drought in conifer-broadleaf mixed forests in Central Europe. *Ann. For. Sci.* **78**, 1–28 (2021).
5. Forzieri, G. et al. Emerging signals of declining forest resilience under climate change. *Nature* **608**, 534–539 (2022).
6. Haberstroh, S. & Werner, C. The role of species interactions for forest resilience to drought. *Plant Biol.* **24**, 1098–1107 (2022).
7. Salomón, R. L. et al. The 2018 European heatwave led to stem dehydration but not to consistent growth reductions in forests. *Nat. Commun.* **13**, 28 (2022).
8. Copernicus Climate Change Service (C3S). European State of the Climate 2022, Summary: https://doi.org/10.24381/gvaf-h066 (2023).
9. Schuldt, B. et al. A first assessment of the impact of the extreme 2018 summer drought on Central European forests. *Basic Appl. Ecol.* **45**, 86–103 (2020).
10. Messier, C. et al. The functional complex network approach to foster forest resilience to global changes. *For. Ecosyst.* **6**, 1–16 (2019).
11. Filotas, E. et al. Viewing forests through the lens of complex systems science. *Ecosphere* **5**, 1–23 (2014).
12. Dhital, N. et al. Adaptation potential of ecosystem-based management to climate change in the eastern Canadian boreal forest. *J. Environ. Plan. Manag.* **58**, 2228–2249 (2015).
13. Knoke, T. et al. The role of economic diversification in forest ecosystem management. *Curr. For. Rep.* **3**, 93–106 (2017).
14. Fischman, R. L. Letting go of stability: resilience and environmental law. *Indiana Law J.* **94**, 689 (2019).
15. Craig, R. K. Stationarity is dead-long live transformation: five principles for climate change adaptation law. *Harv. Environ. Law Rev.* **34**, 9 (2010).
16. Driessen, P. P. & van Rijswick, H. F. Normative aspects of climate adaptation policies. *Clim. Law* **2**, 559–581 (2011).
17. Garmestani, A. S. et al. Can law foster social-ecological resilience?. *Ecol. Soc.* **18**, 37 (2013).
18. Seidl, R. et al. Searching for resilience: addressing the impacts of changing disturbance regimes on forest ecosystem services. *J. Appl. Ecol.* **53**, 120–129 (2016).
19. Cañizares, J. C. et al. Making sense of resilience. *Sustainability* **13**, 8538 (2021).
20. Newton, A. C. Biodiversity risks of adopting resilience as a policy goal. *Conserv. Lett.* **9**, 369–376 (2016).
21. Korhonen, K. T. et al. Forests of Finland 2014–2018 and their development 1921–2018. *Silva Fennica* **55**, 10662 (2021).
22. Pirinen, P. et al. Tilastoja suomen ilmastosta 1981-2010. raportteja rappoter reports 2012:1. Available at: https://helda.helsinki.fi/server/api/core/bitstreams/17a2b5c8-f148-4baf-9ce8-4b74d18b6456/content (2012).
23. Kellomäki, S. et al. Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. *Philos. Trans. R. Soc. B Biol. Sci.* **363**, 2339–2349 (2008).
24. Venäläinen, A. et al. Climate change induces multiple risks to boreal forests and forestry in Finland: a literature review. *Glob. change Biol.* **26**, 4178–4196 (2020).
25. Mäkinen, H. et al. Climatic signal in annual growth variation in damaged and healthy stands of Norway spruce [Picea abies (L.) Karst.] in Southern Finland. *Trees* **15**, 177–185 (2001).
26. Ikonen, V. P. et al. Regional risks of wind damage in boreal forests under changing management and climate projections. *Can. J. For. Res.* **47**, 1632–1645 (2017).
27. Luoranen, J. et al. Damage caused by an exceptionally warm and dry early summer on newly planted Norway spruce container seedlings in Nordic boreal forests. *For. Ecol. Manag*. **528**, 120649 (2023).
28. San-Miguel-Ayanz, J. et al. Forest Fires in Europe, Middle East and North Africa 2021 EUR 31269 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-58585-5. https://doi.org/10.2760/34094, JRC130846 (2023).
29. Nykänen, M. L. et al. Factors affecting snow damage of trees with particular reference to European conditions. *Silva Fennica* **31**, 193–213 (1997).
30. Lehtonen, I. et al. Heavy snow loads in Finnish forests respond regionally asymmetrically to projected climate change. *Nat. Hazards Earth Syst. Sci.* **16**, 2259–2271 (2016).
31. Lampela, E. MT Forest. Lumituhojen riskiä voi parhaiten ehkäistä huolehtimalla puiden hyvästä kasvusta –"Metsiä ei pidä päästää ylitiheiksi, jotta puut eivät riukuunnu". Available at: https://www.maaseuduntulevaisuus.fi/metsa/00394872-3fa3-5328-95a0-41954dba28fb (2022).
32. Lumituhohakkuut vuonna 2018. Suomen metsäkeskus. PDF-dokumentti. Saatavissa: https://www.metsakeskus.fi/sites/default/files/tiedote-liite/lumituhohakkuut.pdf [viitattu 8.2.2019]. Matti Iivonen. 2019. Metsätalousinsinööri (AMK) Toukokuu 2019 (2018).
33. Ikonen, V. P. et al. Effects of using certain tree species in forest regeneration on regional wind damage risks in Finnish boreal forests

under different CMIP5 projections. *Eur. J. For. Res.* **139**, 685–707 (2020).
34. Boisvenue, C. & Running, S. W. Impacts of climate change on natural forest productivity–evidence since the middle of the 20th century. *Glob. Change Biol.* **12**, 862–882 (2006).
35. Kellomäki, S. et al. Temporal and spatial change in diameter growth of boreal Scots pine, Norway spruce, and birch under recent-generation (CMIP5) global climate model projections for the 21st century. *Forests* **9**, 118 (2018).
36. Vehviläinen, H. et al. Effects of tree stand species composition on insect herbivory of silver birch in boreal forests. *Basic Appl. Ecol.* **7**, 1–11 (2006).
37. Guyot, V. et al. Tree diversity reduces pest damage in mature forests across Europe. *Biol. Lett.* **12**, 20151037 (2016).
38. Pukkala, T. Effect of species composition on ecosystem services in European boreal forest. *J. For. Res.* **29**, 261–272 (2018).
39. FINLEX. Metsälaki (Forest Act) 1093/1996. https://www.finlex.fi/fi/laki/smur/1996/19961093?search%5Btype%5D=pika&search%5Bpika%5D=Mets%C3%A4laki.
40. FINLEX. Kestävän metsätalouden määräaikainen rahoituslaki (Temporary Act on the Financing of Sustainable Forestry) 23.1.2015/34. https://www.finlex.fi/fi/laki/smur/2015/20150034?search%5Btype%5D=pika&search%5Bpika%5D=34%2F2015.
41. Nordic Forest Research. 2021. Forest fires in the Nordic region. Available at: https://nordicforestresearch.org/wp-content/uploads/2021/10/rapport-210928-2.pdf.
42. FINLEX. Act on the Fixed-Term Incentive System for Forestry 71/2023. https://finlex.fi/eli?uri=http://data.finlex.fi/eli/sd/2023/71/ajantasa/2024-12-05/fin.
43. FINLEX. Valtioneuvoston asetusmetsien kestävästä hoidosta ja käytöstä 1308/2013 (Decree on Sustainable Forest Management). https://www.finlex.fi/fi/laki/smur/2013/20131308?search%5Btype%5D=pika&search%5Bpika%5D=1308%2F2013%20.
44. FINLEX. Forest Damages Prevention Act 1087/2013. https://www.finlex.fi/fi/laki/smur/2013/20131087?search%5Btype%5D=pika&search%5Bpika%5D=1087%2F2013.
45. Lindberg, H. (2019). Why there are so few forest fires in Finland? EWWF Wildfire conference, Cardiff. Available at https://www.southwales-fire.gov.uk/app/uploads/2019/11/Wildfire2019_bookofabstracts.pdf.
46. FINLEX. 2002/2002. https://finlex.fi/fi/lainsaadanto/2002/241?language=fin.
47. Äijälä, O. et al. (toim.) 2019. Metsänhoidon suositukset. Tapion julkaisuja. https://tapio.fi/wp-content/uploads/2020/09/Metsanhoidon_suositukset_Tapio_2019.pdf.
48. Berlin M. E. et al. Scots pine transfer effect models for growth and survival in Sweden and Finland. *Silva Fennica*, *50*, *article id 1562.* (2016). https://doi.org/10.14214/sf.1562.
49. Ferreira, A. J. D. et al. Strategies to prevent forest fires and techniques to reverse degradation processes in burned areas. *Catena* **128**, 224–237 (2015).
50. Climate-ADAPT. (2016). Available at: https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/water-sensitive-forest-management/#source.
51. FINLEX. Laki Suomen metsäkeskuksesta (Act on the Finnish Forestry Center) 418/2011. https://www.finlex.fi/fi/laki/smur/2011/20110418?search%5Btype%5D=pika&search%5Bpika%5D=418%2F2011.
52. Metsähallitus. (2023). Metsänhoitoohje ("Silvicultural instructions"). 85pp. Available at: https://www.metsa.fi/wp-content/uploads/2023/01/mh-ohje_mtjr20230105.pdf.
53. PEFC Finland. Forest management PEFC FI 2022 standard series. (2022). Available at: https://kestavametsa.fi/pefc-standardit/.
54. PEFC Finland. Metsien kestävän hoidon ja käytön PEFC-standardin asettaminen (Setting the standard for sustainable management and use of forests) PEFC FI 1006:2019. (2019). Available at: https://kestavametsa.fi/wp-content/uploads/2022/12/Metsien-kestavan-hoidon-ja-kayton-PEFC-standardin-asettaminen.pdf.
55. PEFC Finland. PEFC FI 1002:2022 Sustainable Forest management-Requirements. (2022). Available at: https://kestavametsa.fi/wp-content/uploads/2022/12/metsien-kestavan-hoidon-ja-kayton-standardi-2022.pdf.
56. FSC Finland. The FSC Forest Stewardship Standard for Finland (FSC-STD-FIN-02-2023) (2023). Available at: https://connect.fsc.org/document-centre/documents/resource/296.
57. Češljar, G. & Stević, S. Small reservoirs and their sustainable role in fires protection of forest resources. *Renew. Sustain. Energy Rev.* **47**, 496–503 (2015).
58. Sturrock, R. N. et al. Climate change and forest diseases. *Plant Pathol.* **60**, 133–149 (2011).
59. Metsähallitus. Alue-ekologisen tarkastelun menetelmäkuvaus (Description of the methods for landscape ecological evaluations). 15pp. (2015). Available at: https://www.metsa.fi/wp-content/uploads/2020/05/AE-menetelmakuvaus_2015.pdf.
60. Kaukonen, M. et al. (edt.) 2023: Metsähallitus Metsätalous Oy:n ympäristöopas. 136pp. ISBN 978-952-377-079-9.
61. Kalliokoski, T. et al. Mitigation impact of different harvest scenarios of Finnish forests that account for albedo, aerosols, and trade-offs of carbon sequestration and avoided emissions. *Front. For. Glob. Change* **3**, 562044 (2020).
62. Ministry of Agriculture and Forestry of Finland. The National Forest Strategy 2025 ("Suomen metsästrategia 2025")—Government Resolution of 12 February 2015. Ministry of Agriculture and Forestry 6b/2015. 56pp.(2015). Available at: https://mmm.fi/documents/1410837/2000444/National%20Forest%20Strategy%202025/197e0aa4-2b6c-426c-b0d0-f8b0f277f332.
63. Kolström, M. et al. Reviewing the science and implementation of climate change adaptation measures in European forestry. *Forests* **2**, 961–982 (2011).
64. Puettmann, K. J. et al. Managing forests as complex adaptive systems. *Managing forests as complex adaptive systems: Building resilience to the challenge of global change*. C. Messier, KJ Puettmann, DK Coates (Eds.) 3-16 (Routledge, 2013).
65. Steen-Adams, M. M. et al. Historical perspective on the influence of wildfire policy, law, and informal institutions on management and forest resilience in a multi ownership, frequent-fire, coupled human and natural system in Oregon, USA. *Ecol. Soc.* **22** (2017).
66. Hoddy, E. et al. Legal culture and climate change adaptation: An agenda for research. *Wiley Interdiscip. Rev. Clim. Change* **14**, e825 (2023).
67. Abrams, J. et al. Can forest managers plan for resilient landscapes? Lessons from the United States national forest plan revision process. *Environ. Manag.* **67**, 574–588 (2021).
68. Fiack, D. Governing for resilience: a new epoch in US environmental policy and politics?. *J. Environ. Stud. Sci.* **12**, 43–80 (2021).
69. Unay-Gailhard, İ & Bojnec, Š Public support effect on natural disaster management: a case study of ice storms in forests in Slovenia. *Land Use Policy* **95**, 103811 (2020).
70. Olsson, P. et al. Adaptive comanagement for building resilience in social–ecological systems. *Environ. Manag.* **34**, 75–90 (2004).
71. Benson, M. H. & Garmestani, A. S. Can we manage for resilience? The integration of resilience thinking into natural resource management in the United States. *Environ. Manag.* **48**, 392–399 (2011).
72. Triviño, M. et al. Enhancing resilience of boreal forests through management under global change: a review. *Curr. Landsc. Ecol. Rep.* **8**, 103–118 (2023).
73. Day, J. K. & Pérez, D. M. Reducing uncertainty and risk through forest management planning in British Columbia. *For. Ecol. Manag.* **300**, 117–124 (2013).
74. Thonfeld, F. et al. First assessment of canopy cover loss in Germany's forests after the 2018–2020 drought years. *Remote Sens.* **14**, 562 (2022).
75. IPCC glossary. Available at: https://apps.ipcc.ch/glossary/ (22.3.2024) (2024).
76. IPCC. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of

the Intergovernmental Panel on Climate Change. Parry, M. L., et al., eds. 976 (Cambridge University Press, Cambridge, 2007).

77. Reyer, C. P. et al. Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges. *J. Ecol.* **103**, 5–15 (2015).
78. Scheffer, M. Critical Transitions in Nature and Society. (Princeton University Press, Princeton, USA, 2009).
79. Holling, C. S. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* **4**, 1–23 (1973).
80. Thompson, I. et al. Forest resilience, biodiversity, and climate change. In *A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series* (Vol. 43, pp. 1-67). (2009). https://www.srs.fs.usda.gov/pubs/ja/2009/ja_2009_thompson_002.pdf.
81. Falk, D. A. et al. Mechanisms of forest resilience. *For. Ecol. Manag.* **512**, 120129 (2022).
82. Global Forest Watch. North Karelia, Eastern Finland, Finland. Available at: https://www.globalforestwatch.org/ (2022).
83. Luke statistics database. Occurrence of damaging agents reducing silvicultural quality on forest land available for wood production (%). (2022). Available at: http://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE__04%20Metsa__06%20Metsavarat/2.15_Metsikon_laatua_alentavien_metsatu_ai.px/table/tableViewLayout2/.
84. Láng, I. et al. Windstorm Aila 2020: societal impacts. *FMI's Clim. Bull. Res. Lett.* (2021). https://doi.org/10.35614/ISSN-2341-6408-IK-2021-05-RL.
85. Valta, H. et al. Communicating the amount of windstorm induced forest damage by the maximum wind gust speed in Finland. *Adv. Sci. Res.* **16**, 31–37 (2019).
86. Metsäkeskus. Forests damage. (2023). Available at: https://www.metsakeskus.fi/en/forest-use-and-ownership/forest-management-and-fellings/forest-damage.
87. LUKE. Degree of forest damage on forest land available for wood production. Available at: https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/LUKE__04%20Metsa__06%20Metsavarat/2.13_Eriasteiset_metsatuhot_puuntuotannon.px/table/tableViewLayout2/?rxid=dc711a9e-de6d-454b-82c2-74ff79a3a5e0 (2023).
88. Forest.fi. Snow damages trees especially in Ostrobothnia. (2015). Available at: https://forest.fi/article/snow-damages-trees-especially-in-ostrobothnia/#f2201951.
89. Holopainen, M. et al. Drought damage in the park forests of the city of Helsinki. *Urban For. Urban Green.* **4**, 75–83 (2006).
90. Muukkonen, P. et al. Spatial occurrence of drought-associated damages in Finnish boreal forests: results from forest condition monitoring and GIS analysis. *Boreal Environ. Res.* **2**, 172–180 (2015). http://urn.fi/URN:NBN:fi-fe2016082623052.
91. European Commission. Fire Database in the European Forest Fire Information System (version 2-3-1). European Commission, Joint Research Centre (JRC) [Dataset]. (2018). PID: http://data.europa.eu/89h/678deb39-e35f-4236-a984-42d69bf95dec.
92. San-Miguel-Ayanz, J. et al. Forest fires in Europe, Middle East and North Africa 2016. Publications Office of the European Union, Luxembourg, 2017. ISBN 978-92-79-71292-0. (2016). https://doi.org/10.2760/17690.
93. FINLEX. Plant Health Act 1110/2019. Available at: https://www.finlex.fi/fi/laki/alkup/2019/20191110.
94. FINLEX. Laki vieraslajeista aiheutuvien riskien hallinnasta 1709/2015 https://www.finlex.fi/en/legislation/2015/1709.
95. FINLEX. Ilmastolaki (Climate Act) 423/2022. https://www.finlex.fi/fi/laki/smur/2022/20220423?search%5Btype%5D=pika&search%5Bpika%5D=Ilmastolaki.
96. FINLEX. Maatilatalouden tuloverolaki (Income Tax Act on Agriculture and Forestry) 543/1967. https://www.finlex.fi/fi/laki/smur/1967/19670543?search%5Btype%5D=pika&search%5Bpika%5D=543%2F1967.
97. PEFC Finland. (2024). PEFC FI 1002:2024 Sustainable Forest management- Requirements. Available at: https://cdn.pefc.org/pefc.fi/media/2024-01/8e225aa9-ca4c-4336-bc51-292d148395c9/9fbf7460-fcdc-58b9-a2c4-74b5b013141b.pdf.

Acknowledgements
The authors extend their sincere gratitude to the eco2adapt project, titled 'Ecosystem-based Adaptation and Changemaking to Shape, Protect, and Sustain the Resilience of Tomorrow's Forests,' for its invaluable financial support that facilitated the completion of this manuscript. This project, generously funded by the European Union through the Horizon Europe Grant (Grant No. 101059498), has played a pivotal role in bringing this work to fruition. Finally, the authors would like to express their sincere gratitude to the esteemed reviewers for generously providing valuable suggestions aimed at enhancing the quality of this paper. The authors also ensure that this paper adheres to ethical standards, ensuring proper citation and acknowledgment of all sources used.

Author contributions
Tahamina KHANAM: Conceived and developed the methodology, conducted writing and analysing, and authored the original draft of the manuscript. Marina PERIS-LLOPIS: Contributed to writing and editing throughout the manuscript. Xiaoqian XU: Contributed to writing the introduction section. Blas MOLA-YUDEGO: Contributed to writing and editing the manuscript. Leena LESKINEN: Engaged in providing valuable editorial input. Frank BERNINGER: Contributed to writing, editing, and provided overall supervision and guidance throughout the manuscript's development.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-025-02284-3.

Correspondence and requests for materials should be addressed to Tahamina Khanam.

Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editors: Martina Grecequet. A peer review file is available.