https://doi.org/10.17221/87/2025-JFS

Balancing conservation and intervention: Managing forest diebacks in Slovakia's Tatra National Park

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Citation: Puškárová P., Černota M., Slivinský J. (2026): Balancing conservation and intervention: Managing forest diebacks in Slovakia's Tatra National Park. J. For. Sci., 72: 119–135.

Abstract: Disturbance regimes in Central European mountain forests are changing under the ongoing climate change, raising questions about how protected areas should respond to increasingly frequent windthrow and bark beetle outbreaks. In Tatra National Park, a major windstorm in 2004 triggered a landscape-scale bark beetle eruption that challenged long-standing expectations that non-intervention alone could safeguard forest ecosystems. Using the Socio-Ecological Systems framework, we combined long-term field observations with archival sources and stakeholder interviews to examine how ecological dynamics, governance structures, and actor perspectives interacted during and after the outbreak. We show that warming, abundant post-storm breeding substrate, and legacy Norwegian spruce (*Picea abies*) monocultures reduced forest resilience and enabled successive beetle waves. Governance fragmentation led to delayed decision-making, allowing large volumes of wind-felled timber to remain untreated and facilitating its spread into high-naturalness stands. In contrast, evidence from other European countries suggests that timely, spatially focused measures can reduce outbreak duration without compromising conservation values. Our results indicate that in disturbance-prone, spruce-dominated forest systems experiencing climate change, a combination of strict protection in core areas and timely, selective measures in adjacent zones is more likely to maintain resilience and support conservation outcomes than strictly passive or fully interventionist approaches.

Keywords: climate change; forest disturbance; protected areas; socio-ecological systems

The recent discussion on the concept of sustainable and integrated management of forest protected areas (FPA) emphasises the need to reconcile biodiversity, climate, and socio-economic goals across landscapes (e.g. Gilmour 2016; Sotirov, Arts 2018; Wiersma et al. 2010; Palomo et al. 2014). This reflects the increasing recognition that protected forest areas cannot be treated in isolation from surrounding production forests, ecosystem service flows, and socio-economic governance contexts (Ezquerro et al. 2023; Konczal et al. 2023; Gregor et al. 2024; Jandl et al. 2024). Rather than treating FPAs as isolated units, current research suggests management models that integrate conserva-

Supported by the European Union's Horizon H2020 research and innovation programme (Grant agreement No. 692413) and VEGA (Project No. 1/0689/23).

https://doi.org/10.17221/87/2025-JFS

tion and production functions through landscape connectivity and multi-use strategies (Wiersma et al. 2010; Ezquerro et al. 2023; Gregor et al. 2024). Empirical studies demonstrate that integrated approaches can achieve comparable biodiversity outcomes to those of strict protection while enhancing ecosystem service delivery and rural viability (Konczal et al. 2023; Jandl et al. 2024; Seguin et al. 2024). Governance analyses further highlight the role of social-ecological factors, stakeholder engagement, and incentive mechanisms in facilitating such integration (Tiebel et al. 2021; Heshmatol Vaezin et al. 2022; Andriollo et al. 2024).

Climate change is reducing the capacity of European mountain forests to absorb and recover from extreme events and natural disturbances. Rising temperatures, prolonged drought, and shifts in precipitation weaken physiological resistance in trees, making them more vulnerable to windthrow, insect outbreaks, and disease (Anderegg et al. 2018, Sousa-Silva et al. 2018). Warmer conditions accelerate insect development and increase the likelihood of multiple bark beetle generations per year, thereby amplifying the extent and intensity of disturbance (Netherer, Schopf 2010; Mezei et al. 2017b). These changes interact with legacy management and structural simplification, particularly in spruce monocultures, reducing adaptive capacity and increasing the likelihood that systems will cross ecological thresholds (Reyer et al. 2015; Seidl, Rammer 2017). Lenton et al. (2008) describe how gradual warming can trigger tipping points in socio-ecological systems, leading to abrupt losses in resilience; in forests, such shifts manifest as cascading disturbances where storms create breeding substrate, fuelling beetle eruptions that then spread beyond initial damage (Jönsson et al. 2007; Potterf et al. 2019). As a result, disturbance regimes in Central Europe are increasingly exceeding historical variability, and forests are moving toward alternative ecological states characterised by higher mortality, altered species composition, and reduced ecosystem-service capacity (Sommerfeld et al. 2018; Hlásny et al. 2019). This indicates that climate change is transforming disturbance dynamics from episodic events into persistent pressures, diminishing forest resilience, particularly in high-elevation spruce systems.

Bark beetle outbreaks represent a complex socio-ecological challenge, where ecological disturbances interact with human management systems. The Socio-Ecological Systems (SES) framework (Ostrom 2007, 2009; Romagnoli et al. 2022) provides a structured approach to analysing these interactions, helping to identify key system components and pathways for FPA management. Applying the SES theory to protected areas can offer significant theoretical and practical insights into alleviating the contradiction between social development and ecological protection through an in-depth analysis of interactions within SES elements (Guerrero, Wilson 2017). It contains action situations in which human-nature interactions lead to specific outcomes related to sustainability and resilience. These interactions and outcomes are directly influenced by the properties of four SES subsystems: actors, governance system, resource system, and resource units (McGinnis, Ostrom 2014). This integrative approach enables us to conceptualise forests as complex adaptive systems, shaped by feedback between biophysical processes (e.g. climate change, insect infestations) and institutional arrangements (e.g. governance regimes, silvicultural strategies). By examining variables such as resource units (e.g. forest stands), governance systems (e.g. laissez-faire vs interventionist policies), and user interactions (e.g. forest stewards, conservation stakeholders), the SES framework provides a structured lens for assessing the resilience, adaptability, and transformability of forest ecosystems under socio-climatic pressures. Applying this framework enables us to explain how bark beetle outbreaks emerge at the intersection of natural disturbances and human decision-making, and how governance choices shaped by historical, political, and cultural contexts mediate ecological responses and recovery.

Central and Eastern Europe, including other mountain ranges such as the Alps, Apennines, Fennoscandian mountains, and Dinaric mountains, provide a particularly insightful region for studying forest resilience to wind- and insect-led diebacks, given the unique combination of nature conservation reserves adjacent to densely populated areas (Kulakowski et al. 2017). Moreover, in Central Europe, FPAs have been established around the concept of multi-purpose silviculture, where forest stewards are required to combine both conservation and interventionist approaches to mitigate the effects of natural disturbances and promote succession (Koreň 2015; Michalová et al. 2017). Our case study focuses on the ongoing debate between

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advocates of passive (laissez-faire) and active (interventionist) approaches to forest conservation. We aim to analyse the bark beetle outbreak in Slovakia's Tatra National Park (TANAP) using the SES framework.

Despite this growing body of research, few studies have explicitly applied the Socio-Ecological Systems framework to analyse bark beetle outbreaks in protected mountain forests. Existing work tends to examine either the ecological dynamics of disturbance or the institutional and policy responses in isolation, rarely integrating the two within a unified analytical model. As a result, the interactions between disturbance regimes, governance structures, and stakeholder perceptions remain less studied. This study, therefore, addresses this gap by applying the SES framework in a case study of High Tatras National Park in Slovakia (TANAP), where ecological resilience and policy responses are placed within the context of socio-political and biophysical interactions.

To analyse how forest silvicultural strategies (passive vs interventionist) mediated the bark beetle outbreaks in high conservation-value landscapes, we seek to answer the following research questions:

(*i*) How do climate-driven bark beetle disturbances affect forest resilience and ecosystem services in TANAP?

(*ii*) How did different forest governance approaches (passive vs interventionist) shape the outcomes of bark beetle outbreaks in TANAP?

(*iii*) How did actors and their actions shape the response to bark beetle outbreaks in TANAP?

The paper is structured as follows: We first situate the intervention–non-intervention debate and present the study area and data sources. We then structure the results through the SES lens, identifying the resource system and units, governance system, and actor dynamics, and synthesising cross-regional comparisons. Finally, we summarise our conclusions and provide policy recommendations.

MATERIAL AND METHOD

Study area

Tatra National Park, located in northern Slovakia, is one of the oldest transboundary protected areas in the world, established in 1949. It is a significant ecological hotspot and a popular tourist destination in the Central European region. Topographically, the park encompasses the highest part of the Carpathian Arc, with its peak at Gerlach Mountain (2 655 m a.s.l.). It serves as a refuge for key species of European biodiversity, including great predators such as wolves, brown bears, and European lynx. The park can attract up to 50 000 visitors daily during both summer and winter seasons. Additionally, the mountain range acts as a crucial water source, with numerous springs and underground freshwater reservoirs, and provides a range of provisioning, regulating, and cultural ecosystem services.

Tatra National Park covers a total area of over 74 118 ha, divided into intervention zones (approximately 49% of the total area) and non-intervention zones (approximately 51%). Approximately 96% of the park is forested (71 206 ha). The forests exhibit a high degree of naturalness at higher elevations, despite comprising only 3% of primaeval forest, 13% of natural forest, and 13% of semi-natural forest. The remaining areas are classified as slightly altered (23%), significantly altered (30%), and utterly altered forests (18%) (Fleischer et al. 2009).

Tatra National Park represents an important symbol of Slovak national identity as evidenced by the inclusion of the High Tatras in the Slovak national anthem, national emblem and national euro coins. Per se, the park is often the focus of Slovak media attention, research, as well as expert debate, particularly concerning conservation and regional development driven by either tourism or industry. High Tatras are also unique among Slovak mountain ranges in terms of international recognition. In 2019, High Tatras were named 'Best European Destination 2019' by Lonely Planet; in 2025, they received the Travelbook Award 2025 for the 'Best Hidden Gem Region in Europe'. Analysis of Google Trends data indicates that the interest in the High Tatras is consistently 2–3 times higher than that in the Low Tatras. While the interest in the Low Tatras has strong seasonal peaks associated with winter tourism in Jasná, the High Tatras maintain high interest all year-round. Other forest protected areas in Slovakia, such as Slovak Paradise or Malá Fatra, typically reach only 10–20% of the Google search volume compared to High Tatras.

Data collection

The overall research design underpinning the analysis aimed to capture long-term variability in climate conditions, forest ecosystem responses, and conservation approaches, and to examine the interlinkages among these dimensions. To achieve

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this, we adopted a three-step methodological framework combining: (*i*) scoping review of existing literature (*sensu* Peters et al. 2015), (*ii*) the analysis of both spatial and temporal data, and (*iii*) original qualitative research aimed at addressing gaps and blind spots identified in the literature and available data sources.

The integration of spatial and temporal dimensions represents a core element of the analytical framework. Given the strong spatial and temporal dependencies inherent in ecological data, explicit consideration of space–time variability was necessary to reduce potential bias arising from spatial and temporal autocorrelation, a well-documented issue particularly in quantitative forest and climate analyses. We deliberately refrained from conducting correlation analysis or quantitative modelling, as we understand that correlations provide only heuristic indications of association rather than causal explanation. In governance research, institutional outcomes emerge from historically contingent, multi-actor interactions and feedback loops that cannot be meaningfully isolated through statistical inference alone. Therefore, by combining long-term datasets with qualitative insights, the research design enables a more comprehensive understanding of forest–climate–conservation interactions across scales.

The data collection involved both a practitioner and academic representatives. Thus, a clear division of responsibilities was established to minimise potential bias in data collection. The practitioner author conducted field-based data collection on forest stands, including land imagery, spatial mapping of tree inventories, and assessments of biotic and abiotic factors (with primary contribution to Figure 1). The academic co-authors were responsible for respondent selection, ensuring adherence to principles of random sampling and methodological rigour. To further mitigate confirmation bias and interpretative asymmetries, the analysis drew not only on primary qualitative interviews but also on a broader corpus of publicly available interviews and independent scholarly and media sources.

Step 1: Literature search and scoping review strategy. This study draws on the currently available European scientific literature addressing windstorm impacts on governance and institutional dimensions linked to forest-related SES in Europe. Key aspects and main topics of interest were identified based on the currently available academic literature including review studies (Hanewinkel et al. 2011; Leverkus et al. 2021) and previous studies that have assessed impacts of climate change or extreme natural events on SES (Thom, Seidl 2016; Fleischer et al. 2017; Thonicke et al. 2020; Romagnoli et al. 2022).

A scoping review is commonly used to map the existing literature on a certain topic, clarifying concepts and eventually highlighting research gaps (Kerner, Thomas 2014). Further, scoping reviews provide better structure to map out existing literature summarising issues that have received high scientific attention on the one hand (Nakagawa et al. 2019) and on the other identifying current knowledge gaps and the need for more in-depth research (Arksey, O'Malley 2005).

Two rounds of paper searches were conducted using the Scopus database. The initial search was conducted in May 2019 and subsequently updated in January 2026. In both rounds, combinations of keyword strings were applied, including ('barkbeetle' AND 'High Tatras') and ('forest protected areas' AND 'barkbeetle'), and ('forest protected areas' AND 'management'). Studies addressing bark beetle disturbances in the High Tatras were comparatively scarce, with only two publications identified prior to 2002, 54 publications available by May 2019, and 132 publications identified by January 2026. In contrast, searches combining bark beetle disturbances and forest protected areas yielded 3 320 records, of which 1 229 were published between 2020 and 2026, while forest protected area management produced 125 442 records overall. Given the specific focus of this study, the primary body of literature reviewed consisted of publications addressing bark beetle disturbances in the High Tatras, complemented by broader European studies for contextual comparison.

Step 2: Data compilation across space and time. The data compilation and spatio-temporal data triangulation followed the SES framework. Data sources included previously published quantitative and qualitative datasets from scholarly literature, complemented by media-recorded stakeholder surveys, land imagery and institutional documents. Data processing included iterative spatial mapping of selected datasets and organisation of data in time. We identified two data collection phases crucial for long-term mapping of Elizabeth storm effects.

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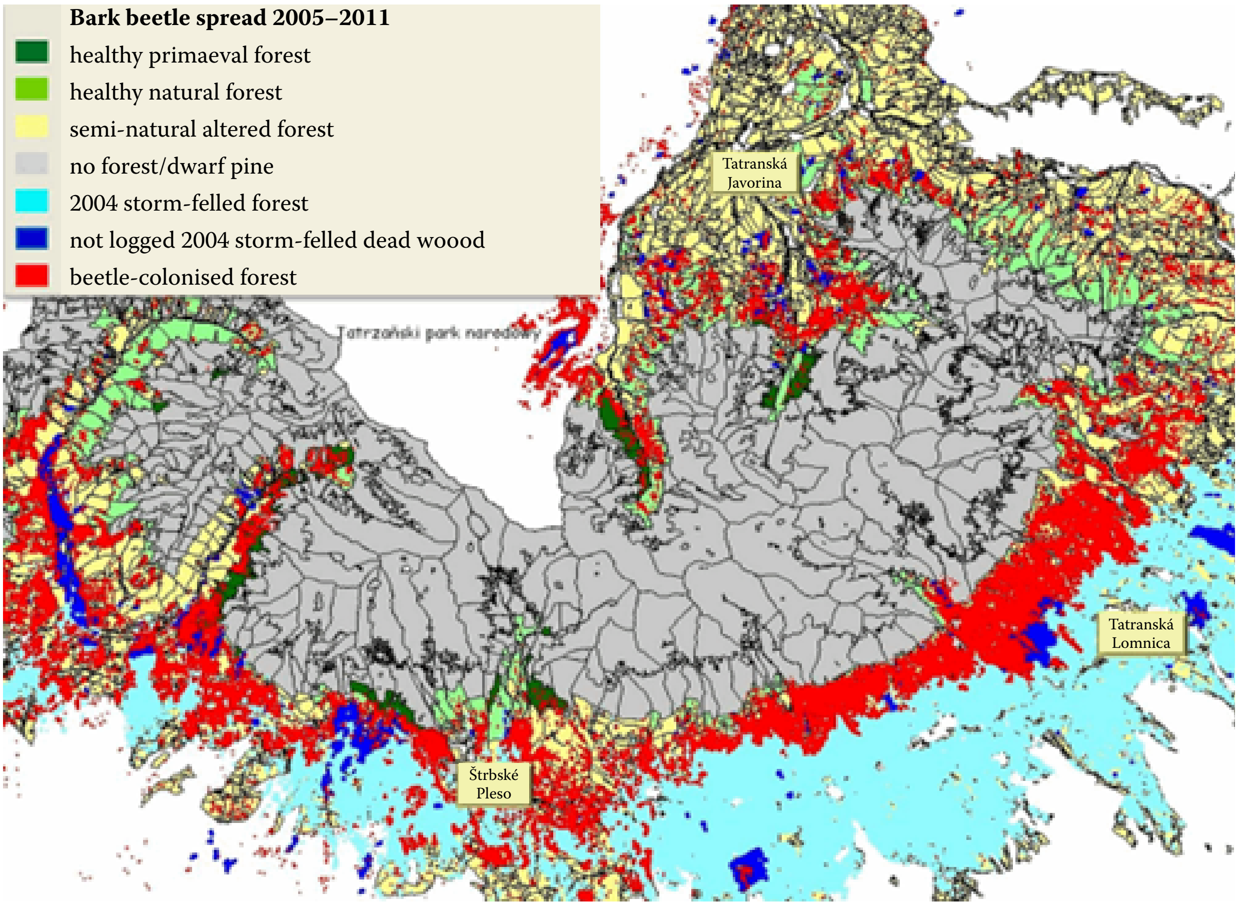

Figure 1. Bark beetle infestation in Tatra National Park, 2005–2011

Source: Authors' processing; data retrieved from the State Forests of TANAP (2019); degree of naturalness taken from Korpeľ (1988) and Fleischer et al. (2009)

The first data collection phase focused on the evolution of bark beetle infestation following the Elizabeth windstorm, covering the period from 2005 to 2014. This phase captured early post-disturbance dynamics, with particular emphasis on qualitative material from 2007, when management interventions and public debates intensified. The second phase addressed conditions approximately twenty years after the windstorm, using November 2024 as a reference point to assess longer-term ecological and institutional outcomes. The data is summarised in Table 1.

Step 3: Primary qualitative data collection and analysis. Step 3 complemented the spatio-temporal data compilation described in Step 2 by generating primary qualitative evidence to interpret ecological and institutional dynamics within the SES framework. Data collection focused on the same spatial extent (TANAP protection zones) and temporal phases identified in Step 2, thereby enabling cross-scale and cross-time triangulation.

Approximately 48 interviews were conducted with key stakeholders representing state, municipalities, public, NGOs, researchers, and experts (Table 2). Interviewees were identified using purposive and snowball sampling. Interviews generally lasted 20–60 minutes and were documented through written notes.

Primary qualitative data collection was structured to capture both post-disturbance dynamics following the Elizabeth windstorm (2005–2014) and longer-term institutional and management responses emerging thereafter. Particular emphasis was placed on the period around 2007, when bark beetle management interventions and public debate intensified, corresponding to the first analytical phase identified in Step 2. Longitudinal insights were further informed by repeated observations and interactions during professional meetings, workshops, and municipal gatherings across the TANAP region, which were re-

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Table 1. Data summary and description

Data type	Data description	Key respondents	Time	Data source
Qualitative	stakeholder perception survey airing in: – print media: SME, Tatranský korzár, Plus 1 deň; – radio: Expres, Okey, Viva, Slovensko; – TV: STV1, STV2, TA3, JOJ, Markíza	29 respondents: – 11 state employees (3 Ministry of Environment, 6 State Forests of TANAP, 1 State Environment Inspection, 1 Regional Environment Office), – 6 from NGOs (Vlk, Naše Tatry, WWF Slovakia, Klub stráže prírody), – 1 expert, 2 influencers, 8 randomly selected public respondents (1 forest steward, 6 protesters, 1 local resident)	Apr 11–30, 2007	Ministry of Environment (https://share.google/M0UsFOv4tfyxCQLY)
Qualitative	media monitoring/first 30 hits for (Tatry*20 rokov po)	State Forests of TANAP, mayor and ex-mayor of High Tatras, media: Korzár, TA3, Pravda, Hlavné správy, Spiš Gemer, Nový čas, Štandard, STVR (5 respondents)	Nov 2024	authors' own elaboration
Quantitative	degree of naturalness (%), tree mortality (m^3), sanitary logging (m^3), average temperature in High Tatras (°C)	State Forests of TANAP, Slovak Hydrometeorological Institute, National Forest Center in Zvolen, Slovak Academy of Sciences	1960–2024	Fleischer et al. 2009; Bičárová et al. 2014; Kunca et al. 2025; Sitková et al. 2025
Quantitative	land imagery – STALES application	National Forest Center in Zvolen	2005–2011	Barka et al. 2018

TANAP – Tatra National Park; source: authors' own elaboration

corded as field notes and used for contextual triangulation.

Field observations were carried out across all protection zones, both in infested and intact stands. Observations were documented through field notes, repeat site visits, GPS-tagged photographs, and tree-level imagery, and analysis of STALES (Satellite-based Forest Stand Identification and Change Detection) land images, capturing the progression of the outbreak. The photo documentation is available on demand and captures parts of TANAP, such as the Javorová Valley, before the outbreak and then in real-time over the years. For some parts, archived data from the State National Forest of TANAP (such as tree sanitation) were retrieved and matched against our own evidence. We followed appropriate ethical guidelines in our study, allowing the interviewees to speak freely, without any pressure, and in their native language, Slovak. We anonymised their responses and repeated the interviews to reduce the risk of possible data collection bias.

Interview notes, observational material, and archival documents were analysed using thematic coding. Initial open coding identified relevant topics, which were subsequently organised deductively according to the Socio-Ecological Systems (SES) framework, specifically the components of resource systems and units, governance system, and actors. Triangulation across interview statements, field observations, and documentary sources increased the consistency and credibility of the findings.

Coding the data into the SES framework followed a primarily deductive logic grounded in the tiered structure of the SES framework as formulated by Ostrom (2007, 2009). Tier 1 components (resource systems, resource units, governance systems, actors, interactions, outcomes, social–economic–political settings, and related ecosystems) served as overarching analytical categories while Tier 2 variables were operationalised as sub-codes where empirically applicable. Empirical material was systematically assigned to SES components through iterative cross-referencing between interview transcripts, documentary sources, and the SES variable definitions. For example, statements on policy instruments were coded under GS1, references to forest dieback under RS3/RS5. Forest resilience was conceptualised as an emergent outcome (O2) resulting from interactions (I) among actors (A) operating under specific governance arrangements (GS), within biophysical constraints of the resource system (RS).

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Table 2. Key respondent interviews – summary and description

Respondent type	Respondent description	Where?	When?	What data?
State	government outing, outing of the Slovak National Council: Environment Committee (3 respondents)	Belianske Tatras	Oct 23, 2018	perception of the role of conservation-intervention legislation in High Tatras
Municipality	regional association of Association of Towns and Communities of Slovakia (ZMOS) (3 respondents)	Monfort Hotel, High Tatras	2012	perceptions of the effects of community engagement on sanitary logging backlogs
General attorney	expert group led by Ms B (2 respondents)	Kôprová and Tichá valleys	Aug 2012	perceptions of the state failure for bark beetle outbreak after the storm
Researchers	National Forest Center in Zvolen expert group (8 respondents)	various TANAP protection zones	2007–2011, 2024	confrontation of other respondents' perceptions with the SES framework
Expert groups	State Forests of TANAP (10 respondents) + interns (4 respondents)	TANAP valleys (Kôprová, Tichá, Jamnícka, Bielovodská, Javorová)	2007–2013, 2024	experience with post-Elizabeth storm sanitary logging and links to bark beetle outbreak, role of stakeholders
Broad public	tourists (10 respondents), visitors of the '20 Years After' Conference at TANAP museum (8 respondents)	hiking trails in TANAP	2005–2007, Nov 9, 2024	experience with post-storm bark beetle outbreak, mapping of infestation, perceptions of long-term effects

SES – Socio-Ecological Systems framework; TANAP – Tatra National Park

Source: Authors' own elaboration

RESULTS AND DISCUSSION

The Results section is organised following the Socio-Ecological Systems framework, beginning with the characteristics and dynamics of the resource system and resource units, then examining governance arrangements and institutional change, and finally analysing actor interactions and their influence on management responses. One section is dedicated to a cross-European comparison.

Resource system and resource units: TANAP's high-mountain forest ecosystem under pressure

TANAP represents a high-elevation, climatically sensitive forest socio-ecological system that functions as both a conservation zone and a multifunctional landscape embedded within broader regional socio-economic structures. As a resource system, TANAP encompasses alpine and subalpine forest ecosystems, dominated by Norway spruce (*Picea abies*), and is subject to natural disturbances, including windthrows, drought, and increasingly frequent bark beetle outbreaks. Some scholars call the sub-Tatra region a 'risk zone' for wind disturbances due to the prevalence of a cold, falling wind known as the Tatra bora (Plesník 1979; Koreň 2015). These disturbances are intensified by climate variability and legacy management practices, making the system highly dynamic and responsive to external stressors. At the lower level, the specific resource units within this system comprise mature spruce trees, wind-felled logs, deadwood accumulations, and regenerating forest patches, which form the ecological substrates upon which both disturbance agents and management interventions operate. Justifying their combined treatment, the boundary between the system and its component units becomes blurred in this case. The bark beetle targets structurally vulnerable units such as ageing or damaged spruce trees. These units, in turn, have implications for the functioning of the wider forest system, including its hy-

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drological cycles, biodiversity patterns, and carbon sequestration. Moreover, management responses such as felling, salvage logging, or non-intervention typically occur at the unit level (e.g. tree stands or infestation zones) but accumulate in effect at the system level, influencing long-term forest structure and resilience. Therefore, in this context, we combined these two components.

The key disturbance event that has shaped the current image and socio-economic value of High Tatras was recorded on November 19th, 2004. At that time, bora winds Elizabeth of up to 230 km·h^{-1} at the timberline uprooted more than 12 600 ha of forest, equivalent to 2.8 million cubic meters of timber. This event marked the largest volume of uprooted tree stands in the park's history. The subsequent bark beetle eruption led to vast areas of tree mortality, particularly in the park's highest protection zones, which have a high degree of naturalness. For example, in the Javorová Valley, a core protection zone that includes old-growth forests up to 300 years old, spruce bark beetle-induced tree mortality increased 53-fold from 3.29 ha in 2002 to 175 ha in 2015. A similar situation was recorded in Tichá, Kôprová, Bielovodská and Jamnícka valleys. We retrieved the archived data on storm- and barkbeetle-led forest losses following the Elizabeth storm up to 2011 and in Figure 1, we spatially overlay these data with TANAP areas differentiated by degrees of forest naturalness. Figure 1 shows that the infestations hit not just the vast areas of spruce forests particularly in south-east part of TANAP, yet the bark beetle fed also in the areas of old-growth trees. The key message of Figure 1 is that regardless of the degree of naturalness, areas of infested and not-logged storm-felled trees overlap. Thus, 7 years after the storm, the effects of the bark beetle infestation were still present and continued to flourish in unlogged forest stands with dead wood. The area directly affected by sanitary loggings and bark beetle-led tree mortality accounted till 2011 for over 37.2% of the TANAP forest stands.

Vast amount of scholarly work supports this evidence. Bark beetle population eruptions are typically associated with large areas of wind-felled trees that serve as breeding grounds for beetle larvae. Mezei et al. (2017a) provide evidence that the bark beetle colonisation of Tatra National Park was subject to storm uprooting and subsequent sanitary loggings over decades.

Yet, the bark-beetle infestation cannot be seen as a mere consequence of belated sanitary logging. A positive correlation between bark beetle eruptions and temperature increases for various European countries (Netherer, Schopf 2010; Kulakowski et al. 2017). Longer warm seasons enable the spruce bark beetle to produce more generations per year, due to an earlier onset of swarming and faster development, which are direct effects of temperature rise. Furthermore, the links between wind and beetle disturbances have tightened, as post-windthrow conditions become more favourable for the development of beetle populations (Seidl, Rammer 2017). This is particularly evident in disturbance cascades indirect effects (Jönsson et al. 2007). Dobor et al. (2020) indicate that even relatively small amounts of wind felled Norway spruce trees remaining after high-intensity sanitation logging are sufficient to trigger the transition from endemic to epidemic conditions in bark beetle population dynamics.

In Figure 2, we reconcile the long-term storm-led sanitary loggings in TANAP with the temperature rise. The temperature has grown since the 1960s till 2014 (10 years after the Elizabeth storm) by a mere 0.6 °C, yet clearly it coincides with the rise of bark beetle infestation as well as windthrows. Our respondents supported this data and named climate change one of the key drivers of bark beetle population dynamics in Tatra National Park over the past few decades. To note, similar claims were derived from scholarly work (Zach 2008; Grodzki et al. 2006; Potterf et al. 2019). Our respondents also pointed out that over the past two decades, the pace of natural disturbances in Tatra National Park quickened. As also documented by Kunca et al. (2025), the storm Elizabeth in 2004 was followed by windstorm Sophia in 2014 and droughts in 2022 and 2024. All these disturbances led to waves of sanitary logging amidst heated public discussion on TANAP forest resilience under climate change.

Besides drought and windstorm vulnerability, our respondents name air pollution as another environmental factor exacerbating the adverse effects of climate change on TANAP forest stands. Again, we also find scholarly evidence to support these claims. For example, Koreň (2015) showed that since the 1970s TANAP forest stands have been gradually suffering necrosis as an effect of increased content of several foreign elements

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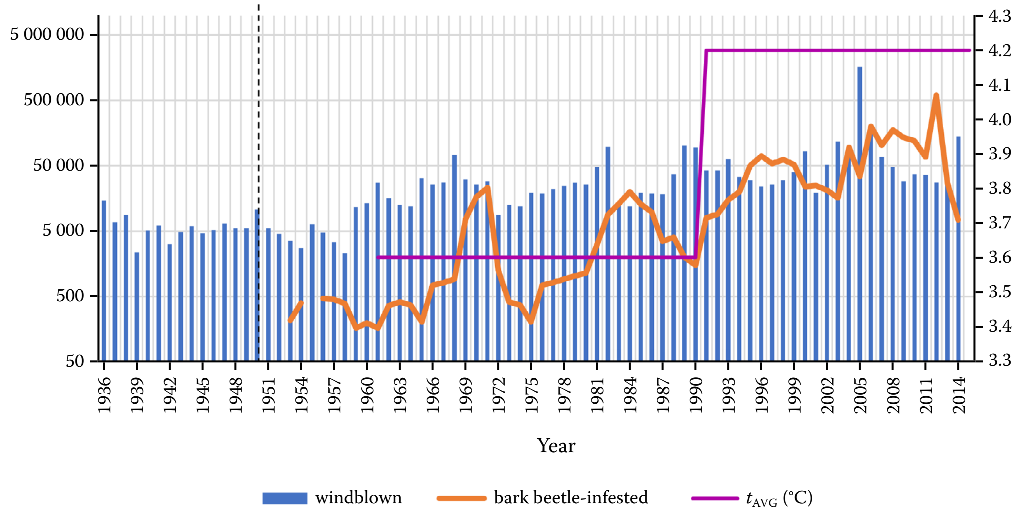

Figure 2. Windblown vs bark beetle infested tree volumes, $\log_{10}$ (m^3), TANAP 1936–2015

t_{AVG} – average temperature (°C)

Source: Authors' own elaboration based on data from Krajčovič (1996), Andráš (2015) and State Forests of TANAP (2019) bookkeeping records; t_{AVG} (°C) data from Bičárová et al. (2014)

in spruce needles (especially Pb, Cd, Hg), relatively high proton load in the area, high concentrations of SO_4 and NO_3 in precipitation, high concentrations of ozone in the air, and episodic smog emissions (particularly in Tatra Javorina).

Figure 2 is designed to feature not just temperature rise and forest stand disturbances, yet also legislative milestones in TANAP conservation. In the subsequent section, we explore further the governance element within the SES framework.

Governance systems – Overlapping mandates and institutional tensions

Historically, Tatra National Park (TANAP) has been subject to various human interventions. Prior to the 1950s, the area was subject to extensive alpine grazing and timber extraction. The declaration of High Tatra National Park in 1949 initiated a significant shift towards afforestation, aiming to restore previously degraded lands. Early afforestation efforts were influenced by the widespread 'spruce mania' of the 1900s, driven by the economic value, visual appeal, rapid growth, and commercial versatility of Norway spruce (*Picea abies*) timber. This led to the dominance of Norway spruce, particularly in subalpine regions, at the expense of a more diverse mix of species, including European larch (*Larix decidua*), Arolla pine (*Pinus cembra*), and various broadleaved trees (Koreň 2015; Zielonka, Malcher 2009).

The growth of tourism in the 1980s and rising pollution prompted a gradual diversification between strictly protected areas and areas open to public use. Until the establishment of the Slovak Republic in 1993 and the adoption of Act No. 287/1994 Coll., TANAP was managed using a multi-purpose management concept advocated by Papánek (1978), which justified timely and consistent pest intervention. After 1994, more intensive management techniques were implemented, including the use of trap trees and salvage loggings (Jakuš 1998). Some scholars linked these silvicultural practices to timely and effective containment of pest populations and the prevention of large-scale infestation dynamics.

A major turning point occurred after the 2004 Elizabeth windstorm, when conflicting legislative mandates introduced regulatory ambiguity into forest governance. Shortly before the 2004 Elizabeth storm, an amendment to the Act on Nature and Landscape Protection (No. 543/2002 Coll.) declared 41.6% of TANAP as strictly protected, thereby excluding these areas from active forest management. In the aftermath of the disturbance, the Forest Act (No. 326/2005 Coll.) was adopted, which obliged forest managers to take prompt measures to prevent and mitigate damage caused by wind and snow calamities or pest eruptions. However, substantial portions of the wind-affected forest were located within newly designated strictly

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protected zones, creating regulatory ambiguity between conservation and forest management obligations. According to respondents, administrative authorities frequently faced uncertainty regarding the proper legal interpretation, resulting in the protraction of sanitary logging and bark beetle expansion.

Institutional fragmentation further intensified governance complexity during this period. Act No. 287/1994 Coll. split the TANAP management between the State Forests of TANAP, reporting to the Ministry of Agriculture, and the TANAP Administration, subordinated to the Ministry of Environment. The TANAP Administration prioritised strict conservation and non-intervention, while the State Forest Enterprise remained legally responsible for active forest protection, including sanitation logging, pest control and timber value recovery. Respondents indicated that this institutional fragmentation led to inconsistent management practices and policy tensions, particularly in buffer and overlapping zones where competences were shared or contested. Following the Elizabeth windthrow, overlapping mandates reportedly prolonged administrative procedures, complicated day-to-day forest operations, and led to growing uncertainty among stakeholders regarding governance responsibilities.

To note, in response to these long-standing institutional tensions, substantial governance reforms were introduced only between 2021 and 2022. National Park administrations gained legal subjectivity, meaning they became independent legal entities capable of making management decisions and hiring staff. State forest land within national parks – especially in core zones – began to be transferred under their control. In the case of TANAP, the process involved merging the former TANAP Administration with the State Forests of TANAP, thereby ending the dual institutional structure that had historically divided authority between conservation and production forestry.

High Tatras protection zonation. The absence of clearly delineated protection zones represented a major governance deficiency in TANAP. Although the Act on Nature and Landscape Protection (No. 543/2002 Coll.) formally established five protection zones, the spatial demarcation of these zones was never fully implemented, and zoning remained provisional due to unresolved land ownership and institutional conflicts.

Competing visions of zoning further contributed to policy stagnation. For example, Moravčík et al. (2007) proposed expanding protected areas from 57.2% to 67% (approximately 50 000 ha) of TANAP in line with the IUCN (International Union for Conservation of Nature) category II, combining biodiversity conservation with education and recreation, while allocating smaller areas to categories IV (approximately 1 900 ha) and VI (approximately 22 000 ha) (State Forests of TANAP 2019). The IUCN management category II does not inherently prohibit human intervention but allows for core zones where such intervention is strictly prohibited, aligning with categories 1a (Strict Nature Reserve) and 1b (Wilderness Area). However, only small and fragmented parts of the TANAP approach the naturalness levels expected in these stricter categories. Topercer (2010) suggested aligning the zonation with ecological resilience principles. Koreň (2015) advocated for zonation based on historical delineation of original forests and adjacent grazed and afforested land parts. However, negotiations stalled as environmental stakeholders opposed limiting strict non-intervention to a few core zones, and private landowners demanded higher compensation for restrictions on land use.

A central dimension of the zoning debate concerned the degree of forest naturalness as a determinant of ecological resilience. As illustrated in Figure 1, TANAP encompasses forest stands that differ substantially in structural composition and historical alteration, implying varying capacities to withstand and recover from disturbance. We argue that naturalness should be treated as a key criterion in zoning decisions: forests with high structural integrity and near-primaeval characteristics demonstrate greater self-regulating potential and may therefore be suitable for strict non-intervention regimes. In contrast, structurally altered stands with reduced resilience may require adaptive management to prevent large-scale disturbance amplification.

Our findings suggest that non-intervention in already modified stands did not consistently enhance resilience. Respondents numerously claimed that these areas ceased to function as effective protective buffers for adjacent primaeval forests. Rather than containing disturbances, these areas often acted as sources of infestation, contributing to the amplification of bark beetle outbreaks. Zoning thus

https://doi.org/10.17221/87/2025-JFS

becomes not merely a legal or political exercise but an instrument for aligning management intensity with ecological condition. Determining the balance between strict protection and active intervention should therefore be grounded in the resilience capacity of specific forest types under projected climate change, rather than based solely on institutional preferences or normative conservation positions. These conclusions reinforce earlier empirical evidence (Mezei et al. 2017b; Brodrechtova et al. 2018).

Actor dynamics in bark beetle outbreak

In the aftermath of the Elizabeth windthrow, it appears that diverse actors shaped both the discourse and the practical responses to forest disturbance. Our respondents living in the neighbourhood – in small towns and villages – frequently expressed strong emotional, cultural and economic attachments to the forested landscapes. Many perceived the outbreak and the subsequent accumulation of deadwood as a threat not only to ecological health but also to local identity, tourism revenues, and quality of life. These concerns were frequently accompanied by frustration over what the locals perceived as a passive or ineffective response by conservation authorities, particularly where strict protection regimes constrained traditional economic activities such as timber harvesting, foraging, or tourism development.

In contrast, urban populations – geographically distant from the national park – tended not to share these views. They saw High Tatras as a 'sacred site' devastated by decades of human interventions and, per se, in need of strict protection. It appears that media portrayal played a critical role in amplifying this divide. Some media increasingly framed bark beetle outbreaks as evidence of natural self-regulation. Campaigns such as 'My sme les' ('We are the Forest') gained substantial traction on social media platforms, predominantly among urban audiences, and contributed to the polarisation of public opinion. These mediated narratives strengthened political sensitivity around intervention decisions and reinforced institutional risk aversion.

Scientific actors – ecologists, conservation biologists, and foresters – further shaped these dynamics by offering competing interpretations of disturbance. While some ecologists framed bark beetle outbreaks as natural components of forest succession (Morris et al. 2018), state foresters emphasised historical experience with active disturbance management and the risks posed to remaining primaeval stands (Mika et al. 2007). Conversely, environmental NGOs, backed by Křenová and Polak (2007), argued that Mika et al.'s (2007) arguments were strongly biased and ignored nature's supreme power to self-regulate and self-rejuvenate. Foresters opposed using the arguments of Holling and Meffe (1996) that human intervention reduces forest resilience and that High Tatras were 'managed by a man' for too long to be suddenly 'forced to take care of themselves'. This conflict between non-interventionists and foresters culminated in high-profile events such as the civil blockade in the Tichá Valley in 2007, further politicising forest management.

Civil society organisations played a dual role throughout this period. Environmental NGOs acted as watchdogs, challenging sanitation logging and mobilising public and international support for strict protection. In some cases, these groups have facilitated citizen science initiatives and organised educational campaigns, contributing to broader shifts in public understanding of ecological resilience and the natural role of disturbance regimes. At the same time, their success in shaping public discourse contributed to decision paralysis.

State authorities started to delay resolutions on sanitation logging permits. The standard 30-day resolution time was extended to 163, 182, 252, 290, and even more days. In one extreme case, a sanitation claim filed by the Department for Environment of the Presov Self-Governing Region on January 1, 2003, was resolved by the Minister for Environment 761 days later, on February 8, 2005. Ultimately, authorities rejected the sanitation of 419 395 m^3 of trees within the 3rd and 4th (restricted intervention) zones and 163 607 m^3 within the 5th (non-intervention) zone. Consequently, around 600 000 m^3 of timber remained at risk of bark beetle propagation within the state-governed TANAP area. This constituted a significant share of the total salvage logging. The storm-felled forest volume was estimated at 2.8 million m^3, with 2.036 million m^3 in the state-governed area of TANAP. By late May 2006, 1 447 463 m^3 of storm-felled trees had been cleared, leaving approximately 28.9% of the uprooted trees to natural processes, according to data from the State Forest Enterprise of TANAP. To compare, after the massive January 2008 storm

https://doi.org/10.17221/87/2025-JFS

in Sweden, the Swedish Forest Agency ordered the clearance of about 90% of the total 2 million m^3 of storm-felled forest (Långström et al. 2009).

Transboundary learning further influenced actor positioning. Experiences from Šumava, Bayerischer Wald, and Białowieża entered the Slovak debate through academic networks, media reporting, and advocacy coalitions. These external references were selectively mobilised by different actor groups to legitimise either interventionist or non-interventionist strategies, reinforcing existing divides rather than fostering convergence. The subsequent part summarises the European discourse around pest infestation.

Cross-Central European comparison

The situation observed in TANAP reflects broader patterns across Central Europe, where bark beetle outbreaks have intensified over the past two decades, revealing structural vulnerabilities in spruce-dominated mountain forests and the limitations of passive management under rapid climatic change (Hlásny et al. 2019).

Historically, droughts and heatwaves have repeatedly stressed Norway spruce, creating favourable conditions for bark beetle population growth. In the 1970s, Norway and Sweden experienced severe droughts, resulting in extensive tree vulnerability; subsequent interventions, particularly sanitary logging, demonstrated that active management can reduce recovery time (Eidmann 1983; Bakke 1989; Långström et al. 2009). In the 1990s, southern Germany, especially Baden-Württemberg, faced similar outbreaks, where timely intervention mitigated damage, whereas delays exacerbated losses (Schröter et al. 2004; Senf, Seidl 2021; Müller et al. 2019).

Since 2017, the Czech Republic has experienced a dramatic rise in bark beetle-induced tree mortality. Cross-border national parks – the Bavarian Forest in Germany and Šumava Forest in the Czech Republic – were heavily affected by Hurricane Kyrill in 2007, leading to the loss of approximately 700 000 m^3 of trees (Křenová, Kindlmann 2017). Efforts to manage the aftermath through sanitary logging were delayed by public conservation campaigns, resulting in an estimated 30 million m^3 of dead trees by 2019 (Lopatka 2019a, b; Zýval et al. 2016).

A similar management conflict occurred in Białowieża National Park, Poland, a lowland mixed forest, where bark beetle diebacks mainly affected Norway spruce over 3 000 km^2 in Poland and Belarus. By 2019, around 7 500 ha of spruce in the Polish sector had died. Disputes between interventionists and conservationists escalated to the European Court of Justice, with NGOs advocating for complete non-intervention (Stokstad 2017; Blicharska et al. 2020).

Comparisons of bark beetle-induced tree mortality across Europe (Table 3) suggest that strictly passive or conservationist approaches alone are unlikely to mitigate outbreaks effectively. Evidence from Western and Northern Europe, where interventionist strategies dominate, indicates that removing infested trees promptly reduces cumulative losses, although a semi-active approach combining conservation and timely intervention is gradually being adopted. Protected areas permitting sustainable forest use have often been better conserved than strictly protected ones (World Bank 2013). Norway spruce remains particularly vulnerable to large-scale disturbances, highlighting the need for more resilient tree compositions and adaptive management (Hlásny, Turčáni 2013; Sommerfeld et al. 2018).

These widespread infestations underline the urgency for European countries to develop robust, adaptive, and coordinated forest management strategies. Lessons from cross-national experiences can guide policies that integrate scientific knowledge, practical interventions, and flexible conservation principles to enhance forest resilience in the face of climate change.

To summarise, Table S1 in the Electronic Supplementary Material (ESM) conceptualises TANAP as a coupled socio-ecological system in which climate warming and wind disturbances act as external drivers that interact with forest structure, governance arrangements, and stakeholder responses to shape bark beetle outbreak dynamics. Spruce-dominated forest stands (resource units) embedded within a high-elevation mountain forest system (resource system) exhibit declining resilience. Governance choices create two divergent SES pathways. Under a laissez-faire (conservation) approach, delayed or absent post-disturbance action allows large volumes of wind-felled timber to persist, reinforcing positive feedback loops that promote bark beetle population growth. In contrast, intervention management dampens disturbance cascades by limiting beetle population

https://doi.org/10.17221/87/2025-JFS

Table 3. Bark beetle-led tree mortality across Europe, historical perspective

Region	Data for	Storm-felled trees	Bark beetle-led tree mortality	Time to mute the bark beetle	Policy response	Source
TANAP Slovakia Javorina	1968–1971	158 837 m^3	48 523 m^3	3 years	active, 5 days	Krajčovič (1996)
TANAP Slovakia Javorina	1994–1997	3 000 m^3*	72 041 m^3	3 years	active, 5 days	Kunca, Zúbrik (2006)
TANAP Slovakia	2004–2019	2.8 mio m^3	2.1 mio m^3	ongoing	passive, 725 days	State Forests of TANAP (2019)
Swiss Alps	1999–2007	5.6 mio m^3	1.0 mio m^3	6 years	active	Meier et al. (2009)
Austria	1944–1991	1.6 mio m^3	0.2 mio m^3	2 years	active	Steyrer et al. (2011)
Austrian Alps	2002–2010	1.9 mio m^3	1.3 mio m^3	6 years	semi-active	Thom et al. (2013)
Aosta/ Italian Alps	1990–2010	55 $ha \cdot yr^{-1}$	840 $ha \cdot yr^{-1}$	6 years	semi-active	Vacchiano et al. (2016)
Czech Šumava	2007–2019	0.7 mio m^3	2.9 mio m^3	ongoing	passive	Šumava Park Administration
Polish Bialowieza	2012–2019	n/a*	1.1 mio m^3	ongoing	passive	www.lasy.gov.pl

*bark beetle-led tree mortality was not led by a storm, but by bark beetle invasion from Poland; TANAP – Tatra National Park

amplification and maintaining the resilience system. Feedback from ecological outcomes to governance and actor behaviour further influences adaptive capacity.

This study has several limitations. First, although we triangulated field observations, archival records, and interviews, long-term disturbance data, particularly historical salvage operations and early post-storm interventions, were partly reconstructed from institutional documents and respondent testimony, which may contain reporting gaps or retrospective bias. Second, detailed spatial data on bark beetle spread and post-disturbance management were not available for all years, and our time series therefore combines sources of varying resolution. Third, while interviews captured diverse stakeholder perspectives, these were not representative views and are limited to stakeholders attending events organised by the TANAP administration. Fourth, although the SES framework enabled us to analyse interactions between natural processes and governance structures, our qualitative approach relies on published literature rather than standardised quantitative indicators. Finally, because TANAP combines unique biophysical and institutional features, generalisations to other protected areas should be viewed with caution; however, the mechanisms we identify may also apply to other high-elevation spruce forests in Central Europe.

CONCLUSION

This study demonstrates that the post-Elizabeth windthrow dynamics in the High Tatras cannot be understood solely as an ecological disturbance but must be interpreted as the outcome of a governance trap in which contested knowledge, politicised media narratives, and institutional fragmentation mutually reinforced delayed decision-making within a highly sensitive protected-area context. Rather than enabling adaptive responses, interactions among state institutions, scientific communities, civil society actors, and media amplified uncertainty, prolonged administrative procedures, and constrained timely intervention, thereby weakening the system's capacity to respond to cascading disturbances.

Our findings show that the assumption that forest intervention can be suspended in the short run in favour of protection is problematic in landscapes that have been intensively shaped by human activity over decades. Once forests have been structurally altered through grazing, selective harvesting, and large-scale monocultural afforestation – particularly with Norway spruce – cessation of intervention does not equate to a return to 'natural' conditions. In the High Tatras, strict protection applied to already transformed forest stands failed to enhance resilience and, in some cases, facilitated

https://doi.org/10.17221/87/2025-JFS

the spread of bark beetles into remnant primaeval forests. This highlights that non-intervention itself constitutes a form of human decision-making with ecological consequences, rather than the absence of management.

The analysis further underscores that forest resilience in the High Tatras is strongly linked to tree species composition. Homogeneous spruce-dominated stands, many of which were established during past management regimes, exhibited heightened vulnerability to windthrow and subsequent pest outbreaks. In contrast, structural and species diversity emerged as critical attributes for buffering disturbance impacts. These findings point to the need for a strategic reorientation of forest governance away from rigid dichotomies between intervention and conservation, and towards adaptive management approaches that explicitly account for historical land-use legacies and future climate risks.

Looking forward, enhancing forest resilience in the Tatra Mountains requires a long-term strategy that increases tree species variability and finalises park protection zonation while respecting historic legacies. Such an approach would support both biodiversity conservation and disturbance resistance under changing climatic conditions. Crucially, this strategy must be embedded within a governance framework capable of integrating scientific and local knowledge, and institutional coordination, rather than allowing polarised narratives and fragmented mandates to paralyse action.

The High Tatras thus illustrate how protected-area governance, when shaped by unresolved actor conflicts and politicised interpretations of nature, can inadvertently reduce ecological resilience. Avoiding similar governance traps elsewhere will require not only ecological insight, but also institutional designs that enable timely, context-sensitive, and adaptive decision-making in human-modified forest landscapes.

Acknowledgement: The authors thank the two anonymous reviewers for their valuable insights.

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Received: November 28, 2025
Accepted: February 24, 2026