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LONG-TERM ECOSYSTEM, CRITICAL ZONE AND
SOCIO-ECOLOGICAL
RESEARCH INFRASTRUCTURE

Forests at Risk: Measuring and Building Resilience Against Extreme Climate Events

The Message in Brief

Europe's forests are increasingly exposed to climate extremes, yet their resilience can be strengthened if it becomes a central management objective: forest resilience needs to be **systematically monitored, assessed, and forecasted**. Long-term ecological observation and large-scale Research Infrastructures such as **eLTER** provide the empirical foundation to detect early warning signals, quantify resilience, and evaluate management outcomes. Science-based strategies including **Closer-to-Nature** and **Climate-Smart Forestry**, **assisted migration**, and **biodiversity-based diversification** enhance forests' adaptive capacity. Emerging **ecosystem service payment schemes** create incentives to invest in resilience. Embedding **quantitative resilience indicators and targets** in national forest and climate strategies enables informed, evidence-based decision-making across Europe's forest landscapes.

Challenges and Current Status

Disturbance regimes are intensifying

In Europe, forest disturbance rates have more than doubled over the past three decades, with increases in frequency, size, and severity of events such as storms, droughts, fires, and insect outbreaks ([1-3], see Figure 1). Climate extremes are increasingly pushing forests outside the conditions they evolved to withstand, thereby reducing their ability to recover and increasing the risk of regime shifts.

The forest carbon sink is shrinking

Forests currently sequester around 360 $MtCO_2$ per year in Europe [4], but this sink has been declining due to ageing stands, intensified harvesting, and more frequent disturbances. Projections show that without adaptation, the EU's land sector may fall short of the 310 $MtCO_2$ annual removal target for 2030, undermining national Climate and Energy Plans [5].

Economic and social costs are mounting

Climate-driven forest disturbances already generate multi-billion-euro annual damages in Europe, from timber loss to increased firefighting and restoration costs. Compound events—such as drought followed by fire or pests—could triple damage by mid-century if warming continues unchecked [6]. Beyond financial losses, extreme events jeopardize rural livelihoods, threaten cultural identity, and heighten hydrogeological risks such as floods and landslides.

Policy and monitoring gaps persist

Most national forest strategies and monitoring systems still lack quantitative resilience indicators. Current reporting focuses on area and biomass, overlooking key measures of recovery capacity, structural diversity, or regeneration. Forest management plans are rarely informed by climate scenarios and forest dynamics projections. This hampers policymakers' ability to anticipate tipping points and integrate resilience explicitly into National Forest Strategies, Adaptation Plans, and Nature Restoration Plans.

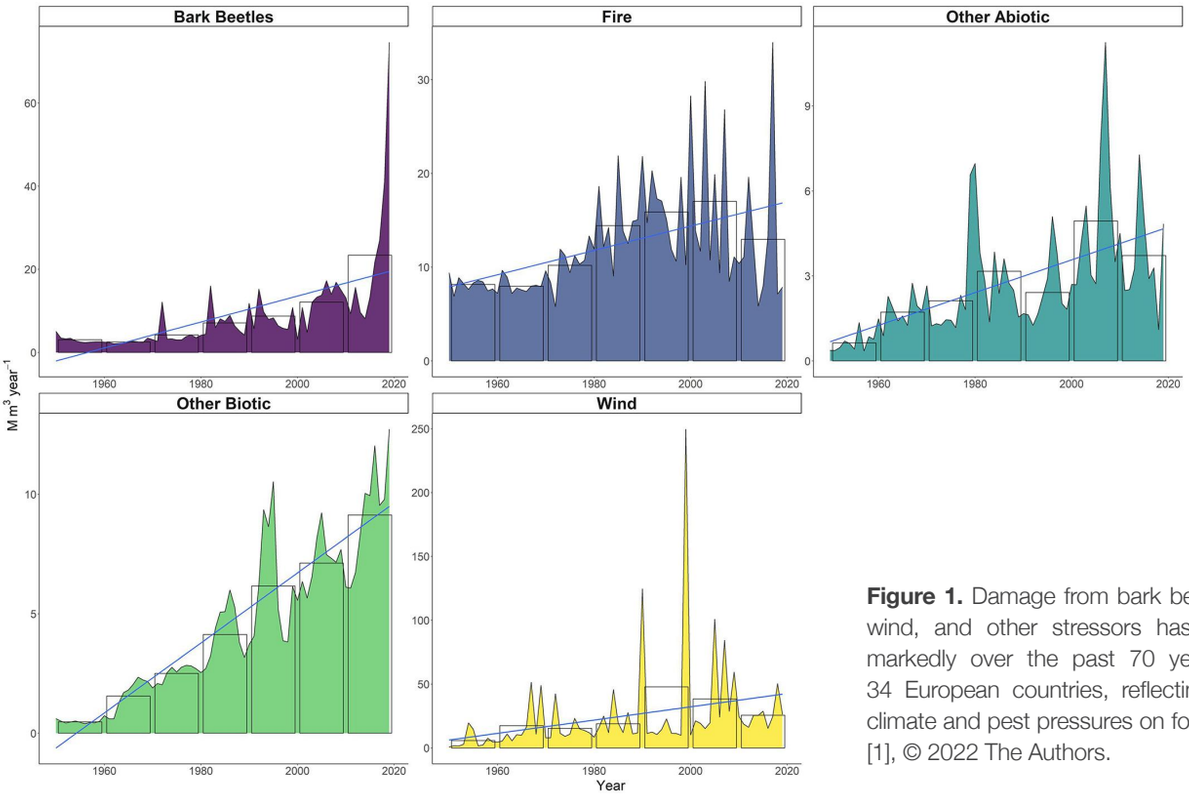


Figure 1. Damage from bark beetles, fires, wind, and other stressors has increased markedly over the past 70 years across 34 European countries, reflecting growing climate and pest pressures on forests. From [1], © 2022 The Authors.

Solutions and Opportunities

Strengthening the resilience of Europe's forests to extreme events is possible with the right tools and timely policies [7]. Science provides a robust foundation to set a Safe Operating Space for forests, by combining long-term observation, novel indicators, and scenario-based planning.

Novel indicators of forest resilience

Forestry requires new and more comprehensive indicators of resilience. What makes these indicators 'novel' is that they measure not only past impacts, but also how close forests are to losing stability. In doing so, they better capture the *multidimensionality* of forest resilience [8].

Early-warning indicators are one example. Signals such as *critical slowing down* [9] detect increasing variability in photosynthetic activity over time—visible in satellite data—which can point to an impending collapse in growth or vitality.

New hazard indicators should also account for *compound disturbances* (e.g., drought combined with fire, or storms followed by bark-beetle outbreaks) that are becoming more frequent under climate change but remain largely invisible to conventional monitoring [2].

In addition, resilience assessment should include landscape-scale metrics such as fragmentation and connectivity, as well as indicators of forests' adaptive potential. These include functional diversity (the range of ecological strategies and traits), functional redundancy and complementarity (the degree to which species can compensate for one another or provide stabilising roles), and species migration potential (the capacity of tree populations or introduced provenances to track shifting climates through genetic diversity, assisted migration, or natural range shifts).

Forecasting disturbances and forest responses

Resilience planning requires anticipating how climate extremes may affect forests. Risks can be assessed as the product of hazard × vulnerability × adaptability:

- **Hazards** are projected climate pressures (heatwaves, droughts, storms, fires) derived from downscaled scenarios and extreme event indices.
- **Vulnerability** reflects forest sensitivity to these hazards, depending on species composition, structure, and condition.
- **Adaptability** describes the capacity to adjust, through natural regeneration, assisted migration, or management interventions.

Simulation models at stand to landscape scales can combine these components to forecast disturbance regimes and forest trajectories under future climates, supporting "what-if" scenario analysis and preparing for intensified and novel risks.

Management strategies

Key options include Closer-to-Nature and Climate-Smart Forestry [10, 11], assisted migration of suitable species and provenances, diversification of forest structure, and restoration of hydrological functions. Enhancing biodiversity ensures the "insurance effect", buffering forests against uncertainty while reconciling commercial forestry with conservation and carbon storage [12].

Policy and economic opportunities

Resilience can be operationalized by embedding quantitative indicators and forecasts into National Forest Strategies, Adaptation Plans, Climate and Energy Plans, and Nature Restoration Plans. Local, catchment, and regional forest management plans can integrate climate and resilience forecasts to prioritize interventions where risks are highest. Economic incentives—such as EU nature credits, biodiversity credits, and payments for hydrogeological protection—can mobilize finance for resilience-based management.

How eLTER can help

As a European Research Infrastructure with hundreds of long-term research Sites and socio-ecological Platforms, eLTER can make invaluable contributions to forest monitoring by:

- **Tracking tree growth and mortality over decades to detect changes in resistance and recovery.**
- **Monitoring soil moisture, carbon pools, and water balance to assess drought vulnerability.**
- **Using remote sensing time series (NDVI, canopy mortality) to detect early-warning signals such as critical slowing down.**
- **Calibrating simulation models integrating hazards, vulnerability, and adaptability.**
- **Delivering case studies across Europe that link adaptive practices (e.g. assisted regeneration, mixed-species management) to resilience outcomes.**

Ways Forward and Recommendations

Building resilience into Europe's forests requires a climate-smart planning framework that explicitly incorporates resilience indicators and scenario-based modelling at all scales.

At the EU and national levels, policymakers should integrate quantitative resilience targets into National Forest Strategies, Adaptation Plans, Climate and Energy Plans, and Nature Restoration Plans. These targets must be supported by standardized monitoring frameworks and long-term data from Research Infrastructures like eLTER.

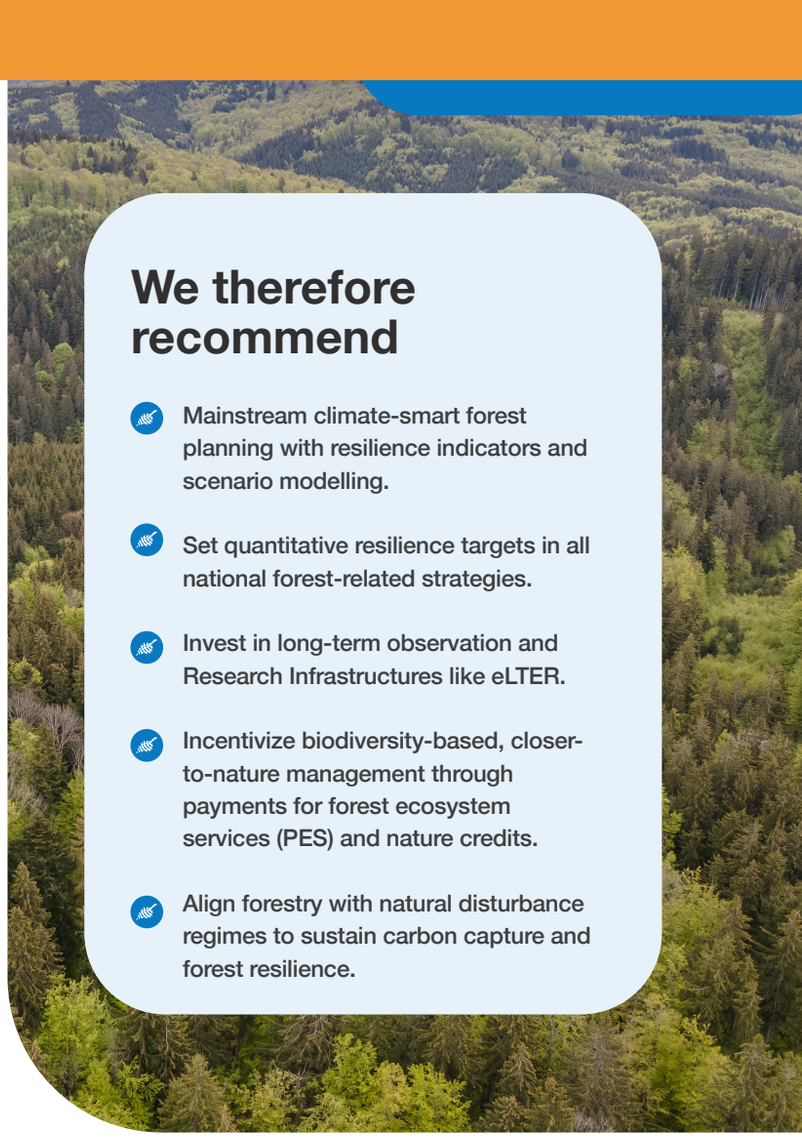
At the regional and catchment levels, management plans should embed "what-if" scenarios to anticipate extreme climate events and their ecological and socio-economic consequences. This means calibrating simulation models with long-term observations to assess hazards, vulnerabilities, and adaptive capacity, providing a realistic view of risks and trade-offs.

At the local scale, operational planning must become risk-based and forward-looking. For example, fire prevention plans in Tuscany and Lombardy already integrate climate projections, vegetation dynamics, and fire behavior models to prioritize interventions. Extending such approaches across Europe can reduce damage costs and strengthen forest resilience.

Investing in resilience pays off: forests that are better adapted to extremes protect biodiversity, store carbon, regulate water, and safeguard communities. By mainstreaming resilience forecasting in planning, policymakers can turn today's challenges into opportunities for a safer and more sustainable future.

Key Messages

- Intensifying climate-driven disturbances are pushing European forests outside the conditions they evolved to withstand, thereby weakening their resilience and capacity for recovery.
- The forest carbon sink is declining, undermining national climate and energy targets.
- Resilience can be strengthened through Closer-to-Nature and Climate-Smart Forestry, assisted migration, biodiversity enhancement, and hydrological restoration.
- Quantitative resilience indicators and forecasts should be embedded in National Forest Strategies, Adaptation Plans, Climate and Energy Plans, and Nature Restoration Plans.
- eLTER's long-term data helps to calibrate models, detect early warning signals, and track the success of resilience-oriented policies and management.



We therefore recommend

- **Mainstream climate-smart forest planning with resilience indicators and scenario modelling.**
- **Set quantitative resilience targets in all national forest-related strategies.**
- **Invest in long-term observation and Research Infrastructures like eLTER.**
- **Incentivize biodiversity-based, closer-to-nature management through payments for forest ecosystem services (PES) and nature credits.**
- **Align forestry with natural disturbance regimes to sustain carbon capture and forest resilience.**

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