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ASSESSMENT OF CLIMATE RISKS AND ADAPTATION OPTIONS FOR CARPATHIAN FOREST ECOSYSTEMS AND THEIR SERVICES

Virgin forest in Ukrainian Carpathians © *Mariia-Varvara*

Suggested citation: United Nations Environment Programme; Carpathian Convention Secretariat (2023). Assessment of climate risks and adaptation options for Carpathian forest ecosystems and their services. Nairobi: United Nations Environment Programme.

Layout: [TO BE ADDED FOR PUBLICATION]

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Acknowledgements

We authors are grateful to the Carpathian Convention National Focal Points, members of the Workings Groups Forest and Climate Change, Science for the Carpathians, Trust for Mutual Understanding (New York, NY), and the United States Fulbright Scholars Program for supporting development of this assessment.

LIST OF ABBREVIATIONS AND ACRONYMS

CARPATCLIM	Climate in the Carpathian Region
CC	Carpathian Convention
CLIMAFORCEELIFE	Climate-Smart Forest Management for Central and Eastern Europe
COP	Conference of the Parties
CO2	Carbon dioxide
EbA	Ecosystem based Adaptation
EC	European Commission
EEA	European Environment Agency
EFI	European Forest Institute
EU	European Union
ETC-ULS	European Topic Centre on Urban, Land, and Soil Systems
FAO	Food and Agriculture Organization of the United Nations
FLAM	Wildfire Climate Impacts and Adaptation Model
FoRISK	Pan-European Forest risk knowledge mechanism
GEDI	Global Ecosystem Dynamics Investigation
GEOSS	Global Earth Observation System of Systems
IIASA	International Institute for Applied Systems Analysis
IPCC	The Intergovernmental Panel on Climate Change
NbS	Nature-based Solutions
NCS	Natural Climate Solutions NCS
N/A	Not applicable
SAFERS	Forest Fire Emergencies in Resilient Societies
SUPERB	Systemic solutions for upscaling of urgent ecosystem restoration for forest-related biodiversity and ecosystem services
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
WWF	World Wildlife Fund

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KEY MESSAGES

- *Forest ecosystems represent a **precious resource in the Carpathians**, harbouring a wealth of ecological, economic and cultural values and Europe's largest concentration of virgin, quasi-virgin and natural forests. Over 200 species of plants are endemic only to this region and large, uninterrupted expanses of forests and inaccessibility provide refuge for populations of large European mammal species, such as the lynx, river otter, grey wolf, woodland bison, red deer, moose, and brown bear.*

- *Yet, Carpathian forests bear the **legacy of a long history of intensive production-driven management** dating to the Austro-Hungarian period in the 19th century and more significantly during the World Wars and the subsequent communist era, where large-scale timber extraction and clearing for agriculture were common, resulting in extensive deforestation. Even-aged, plantation style forest management practices with homogenized forest structure and composition **tended to make Carpathian forests more vulnerable** to large-scale tree mortality and dieback.*

- *This sets the stage for **climate change**, which **superimposes** both **additional stresses** through direct effects on plant physiology, phenology, and reproductive success as well as indirect effects through altered and often increased disturbance frequencies and severities. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events already present significant challenges to the forests' health and functioning. These **interlinked changes** can **disrupt ecological processes, species interactions, and overall ecosystem dynamics**.*

- *A **Carpathian-wide survey identified several key climate change related risks and impacts** of greatest concern to experts in the region, posing significant threats to forest ecosystems and their crucial ecosystem services. These include:*

  - ***Altered disturbance regimes**:*
    Increased disturbance risks will accelerate overall rates of forest change, exacerbating other threats such as the spread of invasive species, species range shifts, and loss of important habitats for biodiversity. Disturbance impacts also create feedback loops that diminish the provisioning of critical ecosystem services, including timber and non-timber resource production, carbon storage, and hydrologic regulation.

  - ***Drought and wildfires:***
    Drought events and associated disturbance risks in the Carpathian forests have become increasingly common and severe in recent years. The assessment found drought to be a primary mechanism of concern negatively impacting forest productivity and timber resources, susceptibility to disturbances, biodiversity and habitats, and the climate regulating functions of Carpathian forests.
    Drought conditions can elevate the risk of forest fires in the Carpathians not only causing immediate damage and loss of vegetation but also contributing to long-term ecological disturbances and changes in forest structure.

  - ***Changes in hydrologic regimes:***
    Changes in hydrologic regimes are perceived a major vulnerability within the region and one that interacts with drought, disturbance risks and human impairment of watershed functioning.
    While shifts in precipitation patterns vary across the region, some areas may experience altered timing, intensity, and distribution of rainfall. This can result in more frequent and intense rainfall events or prolonged droughts leading to decreased soil moisture levels, impacting the water supply for vegetation and affecting forest productivity. Conversely, intense rainfall events can result in

rapid runoff, severe soil erosion, and possibly chemical loading. There is a risk of increased flood frequency although predictions carry high uncertainty and vary spatially throughout the region. Large-scale disturbances, such as fire, bark beetle outbreaks, and defoliating insects, will reduce water uptake by trees and reduce infiltration into soils, thereby increasing peak flows in rivers associated with high precipitation events.
Poorly designed forest roads, development, and imperious surfaces are adding an additional risk factor through changing the form of the hydrograph, meaning that water after precipitation events is delivered more rapidly and at greater volumes directly to streams, rivers, and other surface waters. This increases peak flows and flood vulnerability after high precipitation events.

- *Various **adaptation response options** can be employed to enhance the resilience and sustainability of forest ecosystems in the Carpathians addressing and coping with interlinked impacts and risks. With reference to the Carpathian Convention Protocol on Sustainable Forest Management[1] recommended **key pathways** to further consider **for climate-resilient forest management practices** include:*

    - ***Forest restoration and reforestation**, i.e. restoring and replanting degraded forest areas, converting non-endemic monocultures to site-specific endemic species compositions, broader use of close-to nature silvicultural practices, promoting natural regeneration of forests, and protecting and reintroducing rare native tree species in their natural ecosystem, following single or a combination of adaptation response options for adaptive management (cf. Forest Protocol Article 13 - Promotion of restoration of close to nature forests, Forest Protocol Article 8 - Maintaining and enlarging forest cover).*

    - ***Protecting and conserving virgin and natural forests**, i.e. establishing and effectively managing protected areas, national parks, and nature reserves to preserve intact forest ecosystems, maintain biodiversity, and provide refuges for species. These protected areas also contribute to carbon sequestration and storage. In this respect, further developing of the Carpathian virgin and natural forest (cf. Forest Protocol Article 10 - Identification and protection of natural, especially virgin forests).*

    - ***Enhancing forest landscape connectivity,** i.e. creation of ecological corridors, which connect fragmented forest patches, enabling species movement and facilitating gene flow. Conserving and restoring riparian zones can also enhance connectivity and provide climate refugia for species (cf. Forest Protocol Article 16 - Forestry, wildlife and ecological networks).*

    - ***Forest fire management, prevention, and restoration** i.e. developing national and regional early warning systems, improving fire suppression capabilities, and promoting community-based fire management approaches. Encouraging the broader use of prescribing burning to restore stand structures capable of supporting low intensity fire where this was historically operative in maintaining forest health. Ensuring adequate resources and training for forest fire management is essential to mitigate the impacts of wildfires on forests and communities (cf. Forest Protocol Article 14 – Forestry and climate change lit.3).*

    - *Promoting **sustainable wood utilization and developing value chains for forest products,** i.e. encouraging responsible harvesting practices, supporting local processing industries, and promoting the use of sustainably sourced wood products (cf. Forest Protocol Article 9 - Ensuring the productive functions of the forest and their role in rural development).*

    - *Adopting **ecosystem-based adaptation,** i.e. recognizing and harnessing the benefits provided by intact ecosystems and promoting sustainable livelihoods in an inclusive approach (cf. Forest*

[1] http://www.carpathianconvention.org/protocol-on-sustainable-forest-management/

Protocol Article 12 - Improvement of the protective forest functions, Forest Protocol Article 14 – Forestry and climate change and Article 15 - Social function of forests).

- *Incorporating* ***traditional and local knowledge*** *in adaptation planning to gain valuable insights into forest dynamics, species behavior, and ecosystem responses to climate change.* ***Community involvement*** *also promotes local ownership, improves livelihoods, and fosters sustainable forest practices (cf. Forest Protocol Article 15 - Social function of forests).*

- ***Education and capacity building****: i.e. providing training, education, and awareness campaigns for forest managers, policymakers, local communities, and relevant stakeholders to enhance understanding of climate change impacts, adaptation strategies, and the importance of sustainable forest management (cf. Forest Protocol Article 15 - Social function of forests).*

- *Strengthening* ***research and closing knowledge gaps*** *around climate-resilient pathways will enhance evidence-based decision-making for adaptation in the Carpathian forestry sector. Related topics include:*

  - *Developing capacity for* ***improved regional-scale forest monitoring*** *(cf. Forest Protocol Article 17 - Compatible monitoring and information systems). Harmonizing monitoring programs and sharing data across borders would facilitate both coordinated adaptation, such as multilateral plans for assisted species migration, and enable comparison of research results across within the region. Forest monitoring could also include an additional layer for forest ecosystem dynamics under climate change, including changes in forest structure, species distribution patterns, and ecosystem functioning. Furthermore, forest ecosystems can exhibit ecological thresholds, beyond which they may experience rapid and irreversible changes in structure and function.*

  - *Another area for additional knowledge generation concerns the importance of* ***genetic diversity in forest ecosystems*** *for adaptation, i.e. studying the genetic characteristics of tree species, assessing the adaptive potential of different genetic lineages, and investigating how genetic diversity influences ecosystem resilience and productivity.*

  - *Further research would also be needed for* ***assessing the effectiveness of various adaptive silviculture practices*** *in Carpathian forests, i.e. evaluating the effects of different adaptation approaches on forest resilience, productivity, biodiversity and socio-economic factors. Long-term monitoring of adaptive practices will also be important to continuously (re-)evaluate their success. Research is further needed to investigate the interactions and synergies among different adaptation options. Understanding how different approaches can complement or conflict with each other is crucial for optimizing adaptation strategies and avoiding unintended consequences (cf. Forest Protocol Article 18 - Coordinated scientific research and exchange of information).*

  - *Another critical knowledge gap relates to* ***understanding the socio-economic dimensions of adaptation in forestry****. This includes assessing the economic viability and costs associated with different adaptation approaches, understanding the social acceptability and equity implications of adaptation interventions, and considering the impacts of adaptation on local communities and livelihoods.*

Fostering **collaboration and transboundary cooperation** among the Carpathian countries will be vital for effective climate change adaptation in forestry, especially through sharing knowledge and experiences with various approaches as well as developing and implementing pathways for addressing common challenges.

EXECUTIVE SUMMARY

The **Carpathian Mountain region** touches eight European countries and encompasses natural ecosystems **considered of global ecological and cultural value**. Carpathian forests harbor high levels of endemic biodiversity, contribute to local and national economies through both timber and non-timber products, generate life sustaining ecosystem services including climate regulation and flood control, and are central to the rural character and cultural heritage that have defined the region for centuries.

Yet these resources and services are **vulnerable to the effects of climate change, exacerbated by forest management practices** that have simplified forest structure and composition across vast areas. The resulting landscape conditions are interacting with climatic trends of temperature increase, particularly during summer and in western portions of the region, and increasingly variable seasonal precipitation. The latter has become more variable year to year, exhibiting an overall increase in winter and autumn rainfall and a decline in summer precipitation. Perceptions of increasing risk have been confirmed by several recent pan-European assessments. These have identified **specific vulnerabilities facing forest resources in Carpathian countries**, including climate induced physiological and reproductive stresses in trees, making them susceptive to diseases, spread of invasive species, sensitivity to extreme climate events like heavy rainfall and floods, heatwaves, drought and wildfires, and altered natural disturbance regimes.

In response, the Carpathian Convention Conference of the Parties at its 6th meeting (COP6, held in 2020) called for an **assessment of the impacts of climate change on the Carpathian forests and their ecosystems services** by relevant Carpathian Convention Working Groups and partners and with support of the Convention Secretariat. Through a series of workshops, conference sessions, online discussions, and a survey sent to focal experts nominated by the National Focal Points[2], the Secretariat obtained **detailed information on key risks, climate impacts, and adaptation options of greatest concern within environmental and forest sectors** in Carpathian countries. Those data points form the basis for the information presented in this assessment.

More specifically, the survey was organized around seven themes identified by the Working Group on Sustainable Forest Management-- in an iterative discussion process -- as important topic areas. To evaluate the qualitative response data and rank the specific risks, a triangulation method was used to identify the number of mentions by the focal experts and their specific remarks for each theme. A similar process was used to extract and collate priority adaptation options from narratives submitted by survey respondents. This process resulted in the **synthesis of priority risks and adaptation approaches** presented in this assessment. Synthesized survey responses were supplemented with information from the scientific literature and obtained through interviews with key research groups at institutions located both within Carpathian countries and elsewhere in Europe. The risks and impacts articulated by focal experts echo those identified by peer-reviewed scientific literature. These are also the subject of on-going investigations at research institutions throughout both the Carpathian region and Europe generally.

The **most frequently mentioned risk** to all key themes (forest growth, biomass, tree mortality, etc.) was the **increasing frequency and severity of natural disturbances**, particularly insect outbreaks, fungal pathogens, and windstorms. Alteration of disturbance regimes caused by the interaction of climate change and human modified forest landscape conditions (i.e. that increase vulnerability) will have cascading effects on ecosystem services, including timber and non-timber resource production, carbon storage, and hydrologic regulation. **Drought and related forest fire risks were also ranked as of great regional importance**, especially given recent climate trends and severe drought events. Drought was frequently cited by national experts as posing grave consequences for forest growth and productivity,

[2] http://www.carpathianconvention.org/contracting-parties/

regional tree mortality rates, biodiversity, future shifts in species composition and the climate regulating functions of Carpathian forests.

No single theme emerged with a clear tertiary ranking. Rather, responses varied with respect to a variety of **additional risks and impacts** identified by national experts. These included **flood risks** and their connection to forest cover, forest roads, and forest management; **spread of invasive insect pests**, tree pathogens, and noxious plants; **range shifts in the distribution of biodiversity**; and concerns **over increased land-use pressures on forest ecosystems**. Focal experts had different views on some issues, such as restoration of older forests, the carbon sequestration and storage value of older forests, and whether forest management intensity should be increased or decreased to mitigate disturbance risks.

The assessment identifies **several key pathways for climate-resilient forest management practices in the Carpathians**. Adaptation approaches for enhancing the resilience and sustainability of forest ecosystems in the face of climate impacts and risks include forest restoration, afforestation and reforestation, silviculture practices that reduce drought stress, and conversion cutting to restore endemic species composition and to create more heterogeneous landscapes with enhanced resilience to disturbance and drought. Restoration as a key path of adaptation represented a recurrent theme, with frequent mention of the need for climate-adapted regeneration practices as well. There is high agreement both among regional experts and in the scientific literature regarding the adaptive value to be gained from broader use of close to nature silviculture, continuous cover forestry, riparian buffers and upgraded forest road engineering, expansion of protected areas networks generally, and protection of remaining virgin forests specifically.

And finally, the assessment describes **on-going initiatives** that complement the above-mentioned climate adaptation pathways. These include pan-European initiatives to map, monitor, and better predict current and future forest disturbance risks, recently published databases on European primary forests, initiatives individual Carpathian countries have taken to protect natural and virgin forests, growing interest in and demonstration of “climate-smart” forestry practices, and wide-scale tree planting programs. Together with regional harmonization of climate risk monitoring and forecasting, accelerated investment in climate adaptation pathways would offer great promise for sustaining Carpathian forest ecosystems and their vital services into the future.

1. INTRODUCTION

1.0 RATIONALE

The Carpathian Mountains are the backbone of Central and Eastern Europe, forming an arc of about 1,500 km and covering an area of about 209,000 km². Stretching across seven countries, the mountain range begins in the north-west of Austria, passing through the Czech Republic, Hungary, Poland, Serbia, Slovakia and Ukraine all the way to the Iron Gate Dam in Romania's south. Partly because of their history as the frontier between shifting geopolitical boundaries, the Carpathians harbour biological and cultural resources found nowhere else in Europe, a wealth of natural habitats and Europe's largest concentration of "natural forests" (FAO definition[3]) outside of Fennoscandia (see Sabatini et al. 2018).

Figure 1. The Carpathian region territory covering seven countries. (GRID-Arendal, 2014)[4]

For this reason, the Carpathian region is recognized as having global cultural and ecological significance by the United Nations Educational, Scientific and Cultural Organization (UNESCO). Large, uninterrupted expanses of forests and inaccessibility provide refuge for populations of large European mammal species, such as the lynx, river otter, grey wolf, woodland bison, red deer, moose, and brown bear. Over 200 species of plants are endemic only to this region and stands of virgin [i.e., synonymous with "primary", see Sabatini et al. (2018)] European beech forests with

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[3] Forest is determined both by the presence of trees and the absence of other predominant land uses. The trees should be able to reach a minimum height of 5 meters *in situ*. Source: Global Forest Resources Assessment 2020. @ FRA 2023.

[4] Reprinted with permission from Werners et al. (2014). TBD

areas larger than 10,000 ha are found only here. Sub-ranges like the Făgăraș in Romania encompass the largest areas of virgin or primary (never cleared) montane forest left in temperate Europe.

And yet, Carpathian forests have been profoundly altered by centuries of intensive production-driven management. Much of this originated in the 19th century and even earlier but includes forest management systems introduced during the communist period. Lowland temperate forests were extensively logged under the Austro-Hungarian regime, while much of the native beech (*Fagus sylvatica*) and mixed species forests were converted to Norway spruce (*Picea abies*) plantations managed using even-aged silvicultural systems (Keeton et al. 2013). Spruce is native to the Carpathians but was planted far and wide on sites where it was not endemic historically, often using genetic varieties from outside the region. These practices homogenized the structure and composition of forest stands, and they simplified landscape level diversity, pattern, and patch mosaics, creating the spruce dominated expanses we see in many areas today (Stoyko 1998). These changes have tended to make Carpathian forests more vulnerable to large-scale tree mortality and dieback – from insects, fungal diseases, mistletoe, drought, and in some cases interactions with other disturbances, such as wind and forest fire (Koral et al. 2022). This sets the stage for climate change, which superimposes both additional stresses through direct effects on plant physiology, phenology, and reproductive success as well as indirect effects through altered and often increased disturbance frequencies and severities.

Several recent pan-European assessments have mapped and identified vulnerabilities to climate change across a wide range of environmental infrastructures and natural resources. In many cases these include specific risks facing forest resources in Carpathian countries. From previous assessments (see chapter 1.1), forest ecosystems in the Carpathians will continue to change into the future as compounded stresses from climate disruption, invasive species, land use pressures, and other factors increase. With changes in ecosystem dynamics will come alterations in the mix of ecosystem goods and services those forests provide. Foresters, scientists, and policy makers alike are challenged to integrate knowledge from multiple disciplines in addressing questions of climate change. Differentiating between natural climate variability and human-caused climate change, and of course their interactions, will be as essential here as in any assessment of this nature.

More than half of the Carpathians are forested, with a stable or slightly increasing forest cover mainly as a result of strict prescription and control of forest regeneration in all countries, prohibition of deforestation and spontaneous afforestation of formerly used pasturelands. They provide a set of ecosystem services that contribute to societal well-being, such as regulation of water flows, protection of soils and conservation of biodiversity. Unfortunately, forest ecosystems are increasingly endangered by numerous disturbances, including natural agents (for example, fires, windstorms, and pathogens) and anthropogenic pressures. Even though forests are highly resilient ecosystems when confronted with long-term changes in environmental conditions, they are vulnerable to sudden changes because the long lifespan of trees limits their ability to rapidly adapt.

Geographic remoteness in some areas and strong cultural identities have also preserved the lifestyle of a traditional rural agrarian past mostly lost in other parts of Europe. These include communal forest management systems in parts of western Ukraine and Transylvania in Romania. Despite the high demand for these cultural and natural assets in the rest of Europe, the region is struggling economically, as evidenced by the high level of unemployment and emigration towards western European countries. This is in stark contrast to locales where there is increasing development pressure, including growing tourism, such as ski areas, and demand for small-scale hydroelectric infrastructure. These in turn create complex interactions in terms of socioeconomic resilience to climate change, with so much of the region dependent on natural resources for rural livelihoods and hoped-for pathways to future sustainable development. Therefore, sustainable economic development and adaptive forest management approaches that increase resilience to climate induced risks must go hand-in-hand.

Forests in the Carpathians, as in the rest of the world, are increasingly valued as Natural Climate Solutions (NCS) and in some regions, such as the western Ukraine, have been a net carbon sink in recent decades due to forest recovery following post-Soviet farmland abandonment (Kuemmerle et al. 2011). Yet alterations of natural disturbance regimes, such as increases in the frequency and severity of bark beetle outbreaks, forest fires, and wind events, may limit or reverse NCS capacity through reduced carbon storage capacity in European forests (Seidl et al. 2014). Thus, forest managers face major challenges as they seek adaptive forest management approaches. Key risks associated with climate change must be identified first in order to guide adaptive management. Ultimately, a full array of adaptive management responses – from stocking management for reduced vulnerability to drought stress, flood control and hydrologic regulation, improved forest road design, to silviculture for plant functional trait diversity – will be particularly relevant to the Carpathian region.

1.1 PREVIOUS REGIONAL AND PAN-EUROPEAN ASSESSMENTS

Several previous European-wide and Carpathian specific assessments, conducted over the last decade, will help guide ongoing climate mitigation and adaptation efforts in the region (see Table 1). These provided the launching point for this assessment and contain a wealth of information on a wide range of forest sector vulnerabilities, risks, and adaptation options.

Table 1. Previous assessments of climate change vulnerability, risks, and adaptation for forests in Europe generally and the Carpathian region specifically.

Publication Date	Assessment Title	Geographic Scope	Citation*
2014	Climate change vulnerability and ecosystem-based adaptation measures in the Carpathian region	Carpathian Region	Saskia et al. (2014).
2014	Future imperfect: climate change and adaptation in the Carpathians.	Carpathian Region	Werners et al. (2014).
2016	Climate change adaptation in the Carpathian Mountain Region	Carpathian Region	Werners et al. (2016).
2017	Outlook on climate change adaptation in the Carpathian Mountains	Carpathian Region	Alberton et al. (2017)
2018	National climate change vulnerability and risk assessments in Europe, 2018	Compilation of national level data for 33 countries	Füssel et al. (2018).
2020	Adaptation to climate change in sustainable forest management in Europe	Pan-European	Lindner et al. (2020).
2021	Vulnerability of European forests to natural disturbances	Pan-European	Forzieri et al. (2021)
2021	European forests for biodiversity, climate change mitigation and adaptation	Pan-European	Science for Environment Policy (2021).

* See References

Concurring with the expert opinion elucidated in our survey responses, previous assessments have focused heavily on disturbance risks to forest resources, biodiversity, and ecosystem services, like carbon sequestration and flood control. They describe a region and a continent where forests are already experiencing climate change impacts and where disturbance regimes, biodiversity, and resource provisioning will continue to change dramatically into the future. And yet a range of adaptive forest management responses are available to help make forest ecosystems more resilient to climate risks. Importantly, several of the previous assessments also make critical recommendations for policy and governance. These provide a roadmap for Carpathian countries to coordinate adaptation planning and monitoring both regionally and at the European level.

1.2 BACKGROUND

The Carpathian Convention Conference of the Parties at its 6th meeting (COP6, 2020[5]) through its decisions[6] encouraged the development of an **assessment of the impacts of climate change on the Carpathian forests and their ecosystems services** by relevant Convention Working Groups and partners and with support of the Convention Secretariat. Subsequently, this activity has been included in the Implementation Framework 2030 accompanying the Long-term Vision towards combating climate change in the Carpathians[7]. The related Workplan for the implementation period 2021-2023 of the Working Group on Climate Change[8] sets out concrete activities and expected results with regard to achieving the strategic objectives and related targets of the Long-term Vision 2030 towards combating climate change in the Carpathians[9].

The 8th meeting of the Carpathian Convention Working Group on Climate Change[10], held on 6 May 2021 in an online format, decided on the very first engagement for developing the assessment of the impacts of climate change on the Carpathian forests to take place at the **Forum Carpaticum 2021**. Within the Forum a ***Special Session and Workshop on Forest ecosystem vulnerabilities to climate change in the Carpathians*** was organized by Dr. William Keeton, University of Vermont and Member of the Science for the Carpathians, and the Secretariat of the Carpathian Convention on 22 June 2021 in an online format. All presentations delivered during the workshop as well as the final Workshop Report can be accessed via the Carpathian Convention website[11].

Following the Special Session and Workshop, a **dedicated informal subgroup** of the Working Group on Climate Change and the Working Group on Sustainable Forest Management was established with experts nominated by the Focal Points of the Carpathian Convention (

ANNEX 1: Nominated experts supporting the assessment), that supports the development of the assessment and shall at the same time strengthen cooperation between these topics under the Carpathian Convention – in line with the COP Decisions and the "Long-term Vision 2030 towards combating climate change in the Carpathians". On **16 November 2021 a first expert group meeting** was conducted online that further discussed key impacts and risks facing forest ecosystems as well as adaptation responses in the Carpathian region. At this meeting the Secretariat

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[5] http://www.carpathianconvention.org/cop6/cop6.html

[6] DECISION COP6/13 Sustainable forest management Article 7 of the Carpathian Convention

Para 5. Appreciates the strengthened cooperation between the WG Forest and the WG Climate Change and WG Biodiversity, facilitating the implementation of Article 14 of the Forest Protocol, welcomes the idea of collecting information from the Parties with the goal of assessing the impacts of climate change on the Carpathian forests and their ecosystem services, including, if possible, climate change effects on large carnivores and their habitats, in that regard recognizes the complexity of the issue and wide range of ecosystem services Carpathian forests provide to the society, and requests the relevant Working Groups and partners to support the development of such assessment, and the Secretariat to facilitate the process

DECISION COP6/18 Climate Change Article 12bis of the Carpathian Convention

Para 8. Specifically encourages the WG Forest and the WG Biodiversity and partners to jointly further develop with the WG Climate Change an assessment of the impacts of climate change on the Carpathian forests and their ecosystems services, including, if possible, climate change effects on large carnivores and their habitats, and requests the Secretariat to facilitate the process.

[7] http://www.carpathianconvention.org/tl_files/carpathiancon/Downloads/03%20Meetings%20and%20Events/COP/2020_COP6_Online/official%20documents/CC%20COP6%20DOC11_Implementation_Framework_2030_WG%20CC_FINAL%20DRAFT.pdf

[8] http://www.carpathianconvention.org/tl_files/carpathiancon/Downloads/03%20Meetings%20and%20Events/Working%20Groups/Adaptation%20to%20Climate%20Change/8%20WG%20CLIMATE%20CHANGE/Workplan2021-2023_WG%20CC_DRAFT_27042021_incl.comments_received.docx

[9] http://www.carpathianconvention.org/tl_files/carpathiancon/Downloads/03%20Meetings%20and%20Events/COP/2020_COP6_Online/official%20documents/CC%20COP6%20DOC10_Long_Term_Vision_2030_FINAL%20DRAFT.pdf

[10] http://www.carpathianconvention.org/2021/05/06/eight-meeting-of-the-working-group-on-climate-change-06-05-2021-online-meeting/

[11] http://www.carpathianconvention.org/2021/06/22/forum-carpaticum-2021-special-session-and-workshop-on-forest-ecosystem-vulnerabilities-to-climate-change-in-the-carpathians-22-06-2021-online-meeting/

presented a draft structure for the assessment (**Error! Reference source not found.**) that was later populated with in-depth information received through a **survey** sent to focal experts (ANNEX 2: Survey). Nominated experts provided valuable input and background information, forming the basis for the scope and topics covered by this assessment.

1.3 APPROACH AND SCOPE

Figure 2 illustrates a variety of climate change impacts and risks of concern, relative to forest ecosystems and resources, identified by participants in the Forum Carpaticum´s Workshop. The word cloud depicted in the figure was generated by the *Mentimeter application* based on the question "*What information would you most like to see with an assessment of climate change impacts on the Carpathian forests and their ecosystem services that would be most beneficial for your country/work?*": Although clearly a non-scientific approach, the word cloud was useful in helping to visualize the full diversity of topics of greatest concern to the workshop participants, with each topic weighted by the number of times it was mentioned as a rough indication of priority. We condensed these into an abbreviated list of topics by collating sub-themes around broader themes, such as ecosystem services, biodiversity, or disturbances.

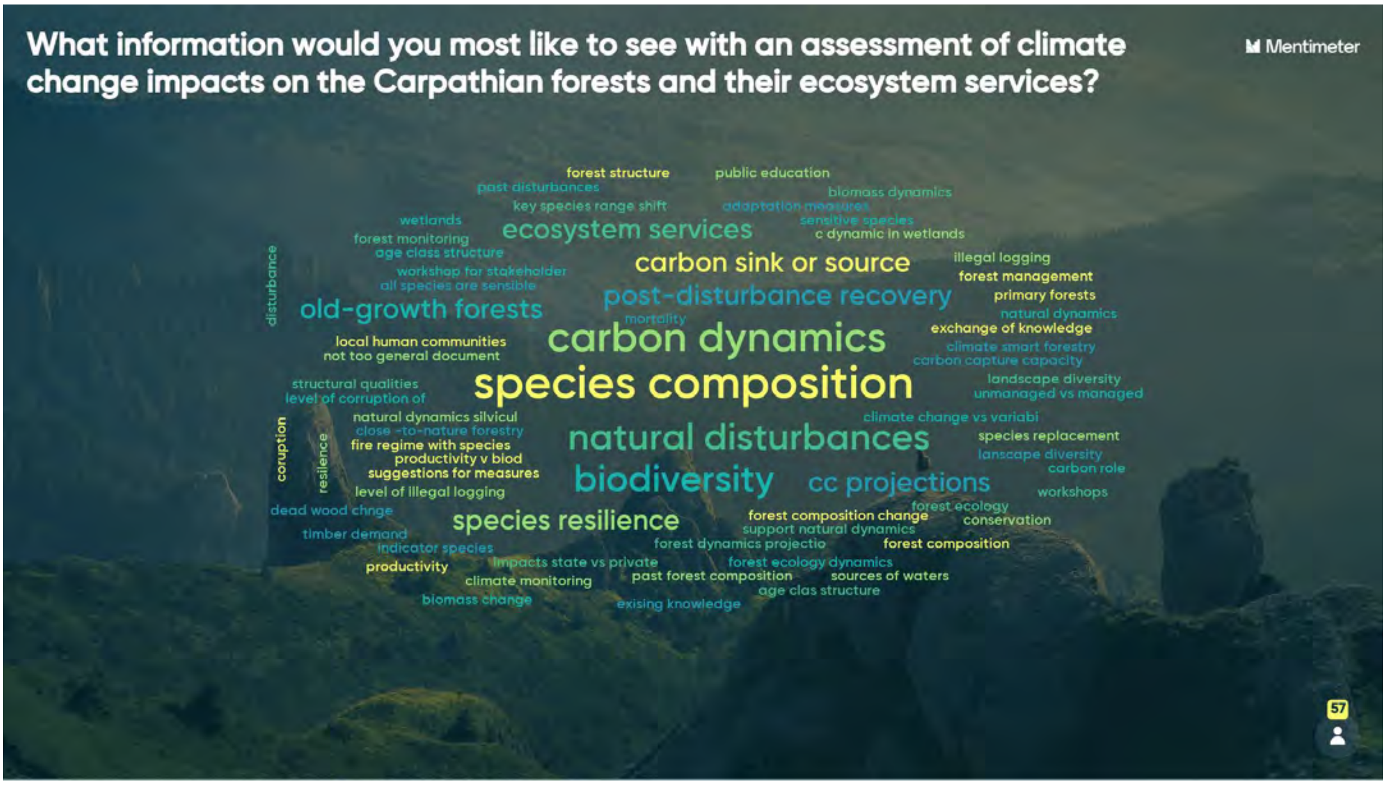

Figure 2. Mentimeter generated word cloud of climate change impacts and risks of greatest concern to participants in a workshop conducted at the Forum Carpaticum 2021.

The subsequent exchange and discussion highlighted several areas of concern were then condensed to list of sub-topics, priority risks, and proposed adaptation responses presented. There were further discussed and elaborated at the expert workshop on held on 16 November 2021 (online), resulting in the final list and matrix presented in Table 2. Key topics, impacts, and responses addressed by the survey.Table 2 (see below):

The Secretariat together with Dr. William S. Keeton developed and administered a survey (see ANNEX 2: Survey) sent to the focal experts (listed in

ANNEX 1: Nominated experts supporting the assessment). The intent was to gather more detailed qualitative data on priority topics of concern that should be address by the assessment, including priority risks and adaptation responses. The survey contained a series of questions following the structure of Table 3. Ranked preliminary findings identified through the meta-analysis of survey responses.**Error! Reference source not found.**, including a matrix for each of the seven key sub-topics identified at prior Working Group meetings. The nominated experts were asked to fill in the matrixes and answer a variety of related questions, also consulting with national colleagues to gather further input.

Survey responses were received by the Secretariat in the first half of 2022, paving the way for the analysis and synthesis conducted for this report. Findings were supported by a review of previous European-scale and regional-scale scientific assessments, interviews with leading research groups with on-going projects in the Carpathians, and a literature review using a key word search in Web of Science. The latter focused exclusively on peer-reviewed papers published in English language scientific journals.

Table 2. Key topics, impacts, and responses addressed by the survey.

Topic	Impacts / Risks (sample)	Response prospects
Forest growth and productivity	• Effects of temperature increase, variations in precipitation • CO2 fertilization effects: short term vs long term; interactions with stressors • Effects of altered disturbance regimes • Effects of drought • Increased physiological stress in trees leading to reduced growth and vigor	• Adaptive silviculture • Expanded use of exotic species (pros and cons) • Stocking management, including thinning to reduce stand densities
Biomass and Carbon Stocks	• Carbon stored in terrestrial ecosystems is vulnerable to fluxes back into the atmosphere. Key mechanisms include an increase in fire frequency and other disturbances due to climate change and the sensitivity of ecosystem respiration to rising temperatures. • Changing/reduced carbon uptake and carbon dynamics (sequestration, storage, and fluxes)	• Improved forest management/carbon forestry • Afforestation/reforestation • Avoided land-use conversion • Core area protection/rewilding • Managing land use, fire, and other disturbances and non-climatic stressors
Tree mortality	• Interaction between mortality and disturbance risks[12] • Drought impacts on mortality	• Adaptative management of fire, pests, and pathogens (variable approaches and opinions) • Restoration of site-endemic species • Restoration of landscape heterogeneity
Changes in species range, habitat shifts and abundance	• Extinction risk for species with intrinsically low dispersal rate and species in isolated habitats such as mountain tops • Impacts on keystone and flagship species and the composition of forest communities • Habitat shifts through interaction of climatic factors and anthropogenic pressures	• Reduction of habitat modification and fragmentation, pollution, over-exploitation, and invasive species • Protected area expansion, assisted dispersal and migration, ex situ conservation
Invasion by non-native species	• Disruptions of species interactions and altered climatic conditions	• Forest management practices that reduce susceptibility to invasive

[12] Attributed in some cases to direct climate effects (higher risk of extreme events and forest fires) and indirect effects due to insect outbreaks, drought, and disease processes, etc. Dead trees further increase the risk of forest fires.

Topic	Impacts / Risks (sample)	Response prospects
	increases the vulnerability of ecosystems to invasion by non-native (alien) species. • In the extreme, this can result in biome shifts, with consequent changes in the spectrum of ecosystem services provided	species, largely based on reducing other stresses (except from climate) including expanded invasive species monitoring and control efforts
Forest ecosystem services	• Alteration of critical services, such as timber and non-timber resource production, carbon sequestration and storage, hydrologic regulation, habitat provisioning • Further ecosystem services potentially impacted include provisioning services (bioenergy, water), regulating services such as climate regulation, pollination, pest and disease control, and flood control, supporting services such as primary production (timber) and cultural services, including recreation and aesthetic and spiritual benefits	• Adaptive forest management to build resilience within at-risk ecosystems by identifying the full set of drivers of change and most important areas and resources for protection and restoration • Foster inclusion of climate change considerations into the management of protected areas (incl. Natura2000) and core area restoration • Broad stakeholder and community engagement to build consensus approached to adaptation • Socio-economic inclusive approaches that may also have community and cultural benefits (Ecosystem-based Adaptation)
Forest – water interactions, including hydrologic regulation and riparian dynamics	• Altered hydrology regimes due to climate change will have impacts on forests and the watershed services they provide and affect water quality, aquatic habitats and species and soil resources • Large-scale disturbances, such as fire, bark beetle outbreaks, mistletoe and defoliating insects, will reduce water uptake by trees, reduce infiltration by the soils, causing an increase in runoff, increases and potentially severe erosion and chemical loading • Warmer temperature may accelerate the rate of nutrient cycling in some systems, promoting increased forest growth and elevated nitrogen levels in streams	• Better integrate water-related ecosystem services supply into climate-smart forest management objectives • Broader adoption of riparian buffer standards • Improved forest road planning, design, and regulation

The survey responses have been coded to indicate the number of times particular risks, impacts, and adaptation responses were mentioned (see example in Table 3). This was performed individually for each topic and then as a cross-cutting synthesis (or meta-analysis) across all the topics. The triangulation method allowed to identify the top priorities (i.e., greatest concerns) shared among the respondents. When synthesized this way, survey responses were unequivocal with respect to the issues of central concern to national experts throughout the Carpathian region. The significance of these issues was subsequently validated by literature review: the priority risks identified in survey results aligned closely with the topics of most active investigation within recently published and on-going forest science research.

Table 3. Ranked preliminary findings identified through the meta-analysis of survey responses.

SYNTHESIS OF RISKS AND IMPACTS	**Primary Risks Identified**	**Convergence/Divergence of views regarding impacts**
Top ranked	Disturbances	Reduced carbon storage, growth increment, and climate regulation. Accelerated shifts in species distributions. Accelerated spread of invasive species
Second ranked	Drought	Forest decline, dieback, and reduced productivity. Shifts in species distributions, exacerbation of insect and fire risks, and diminished ecosystem services
Third ranked and other	Flooding, invasive species, land use pressure	Interactions across a range of ecosystem services and habitat provisioning, including carbon sequestration, hydrologic regulation, and wood production as well as biodiversity
ADAPTATION SYNTHESIS	**Theme**	**Convergence/Divergence of Views Regarding Impacts**
Top ranked	Forest restoration	High agreement on need for restoration and climate-adapted regeneration practices
Second ranked	Sustainable management, including broader use of close to nature silviculture and continuous cover forestry	High agreement on need for broader use of sustainable forest management practices including ecological silviculture
Third ranked and other	Landscape heterogeneity to increase resilience to disturbance and drought	High agreement on need to address altered disturbance regimes, promote future-adapted forest composition, increase landscape heterogeneity and complexity, and reduce spread of invasive species

2. EUROPEAN FOREST POLICY

The new EU forest strategy for 2030[13] (EC 2021) is one of the flagship initiatives of the *European Green Deal*[14] and builds on the *EU biodiversity strategy for 2030*[15]. It recognises the central and multifunctional role of forests, and the contribution of foresters and the entire forest-based value chain for achieving a sustainable and climate neutral economy by 2050 and preserving lively and prosperous rural areas. The EU forestry strategy sets a vision and proposes concrete actions to improve the quantity and quality of EU forests and strengthen their protection, restoration and resilience. It aims to adapt Europe's forests to the new conditions, weather extremes and high uncertainty brought about by climate change. This is seen as a precondition for forests to continue delivering their socio-economic functions. Provisions of the strategy cover aspects of protecting, restoring and enlarging the EU's forests to combat climate change, reverse biodiversity loss and ensure resilient and multifunctional forest ecosystems. This includes, inter alia, promoting a sustainable forest bioeconomy, protecting EU's last remaining primary and old-growth forests, and ensuring forest restoration and reinforced sustainable forest management for climate adaptation and forest resilience.

In March 2023 the European Commission adopted two sets of guidelines to support the implementation of the Forest Strategy within the broader framework of *the EU Biodiversity Strategy for 2030*, while supporting the general EU commitments under the *Kunming Montreal Global Biodiversity Framework*[16] (UN Convention on Biological Diversity). These guidelines shall support efforts to strengthen the protection, restoration and resilience of EU forests to help them adapt to a changing climate and improve their quantity and quality. The **guidelines on Biodiversity-Friendly Afforestation, Reforestation and Tree Planting**[17] provide a set of practical recommendations to support authorities, forest and landowners, and managers and civil society to better implement biodiversity-friendly afforestation, reforestation and tree-planting projects including at the local level. Through both active planting and natural regeneration, these guidelines constitute one of the key milestones to implement the 3 billion additional trees pledge of the EU by 2030. They address afforestation initiatives in agricultural land; reforestation actions in forest land, including restoration actions; and tree planting in urban and peri-urban environments, as well as agricultural land (agroforestry). The **guidelines for Defining, Mapping, Monitoring and Strictly Protecting EU Primary and Old-Growth Forests**[18] provide practical guidance to national policy- and decision-makers that will allow them to effectively identify and protect remaining primary and old-growth forest in the EU. The guidelines set out criteria for identifying primary and old-growth forest areas based on a list of indicators or principles. A timeline is suggested for their mapping and strict protection.

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[13] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0572
[14] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[15] https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en
[16] https://www.cbd.int/article/cop15-final-text-kunming-montreal-gbf-221222
[17] https://environment.ec.europa.eu/publications/guidelines-biodiversity-friendly-afforestation-reforestation-and-tree-planting_en
[18] https://environment.ec.europa.eu/publications/guidelines-defining-mapping-monitoring-and-strictly-protecting-eu-primary-and-old-growth-forests_en

3. CLIMATE CHANGE RISKS AND IMPACTS ON CARPATHIAN FOREST ECOSYSTEMS AND THEIR SERVICES

3.1 INTRO

Changing climatic conditions have been evident over the past 50 years and are highly likely to continue over the coming decades in the Carpathian region (Werners et. Al. 2014). Mean annual temperatures have increased by 1° to 1.5°C, exhibiting distinct seasonal and sub-regional trends, such as greater warming in summer and western portions of the region (Hlásny et al., 2017). Seasonal precipitation has become more variable year to year, exhibiting an overall increase in winter and autumn rainfall and a decline in summer precipitation (Ceballos et al., 2018). Rainfall patterns have also changed spatially throughout the Carpathian region, increasing in most places while decreasing in western and south-eastern sub-regions (Spinoni et al. 2014).

According to a synthesis by Werners et al. (2014), regional climate models project a warmer future with more erratic precipitation, likely leading to more frequent and more intense heat waves and, idiosyncratically, both droughts and floods. Mean annual temperature will increase to 3.0 - 4.5°C over pre-industrial levels by the year 2100 (see Werners et al. 2014, page 5). The intensity of predicted warming varies depending on the particular climate scenario. These comprise different pathways of societal response and greenhouse gas (GHG) emissions reduction (IPCC 2018). Models predict that total annual precipitation over this time period will increase by 300–400 mm in northern portions of the region, while southern portions will experience a 100–150 mm decrease (see Werners et al. 2016, page 1). However, there is likely to be pronounced seasonal variation, with a 20% decrease in summer rainfall and a wintertime increase of 5-20% regionally (Werners et al. 2016). These observed and predicted climatic trends, together with the on-going trend of increased frequency of extreme weather events causing droughts and floods, are the ultimate drivers of the specific risks and impacts described in the findings below.

3.2 KEY RISKS AND IMPACTS

Through the synthesis of survey responses (see chapter 1.3), we identified several key climate change related risks and impacts posing significant threats to forest ecosystems, natural resources, and human communities. These risks represent potential vulnerabilities within the forest sector that necessitate adaptive planning and management (see chapter 5). The key risks and impacts, organized by major theme are presented in the following section together with supporting information from the scientific literature.

The risks and impacts articulated by focal experts (survey respondents) closely mirror those identified by peer-reviewed scientific literature. These are also the subject of on-going investigations at research institutions throughout both the Carpathian region and Europe generally. Climate change poses direct risks to forest ecosystems through shifts in the competitive environment and induced physiological stress in constituent organisms. These are compounded by indirect risks caused by alteration of disturbance dynamics (e.g., windstorms, insect outbreaks, and forest fires), particularly high intensity events that remove forest canopies (Keeton et al. 2007).

ALTERED DISTURBANCE REGIMES

The most frequently mentioned risk to all key topics (forest growth, biomass, tree mortality, etc.) was the effects of climate change on natural disturbances, particularly pest outbreaks, insect infestations and windstorms. This risk is related to the alteration of disturbance regimes (both human and natural). The scientific literature also provides strong support for the concern regarding disturbance risks expressed by survey respondents, creating a consistent picture that disturbance events are becoming more frequent and severe in the Carpathians and that climate change is a contributing factor. Survey responses made clear the concern that increased disturbance risks will accelerate overall rates of forest change, exacerbating other threats such as the spread of invasive species, species range shifts, and loss of important habitats for biodiversity. An additional risk is that disturbance impacts will create feedback loops that diminish the provisioning of critical ecosystem services, including timber and non-timber resource production, carbon storage, and hydrologic regulation.

One major threat identified for the Carpathians, specifically, in this assessment relates to possibly increased pest outbreaks and mistletoe infestation due to warmer temperatures and altered precipitation patterns. The mechanistic link is that soil moisture deficits produce physiological stress that increases the susceptibility of trees to insect infestations. Warmer temperatures also affect the reproductive cycles of bark beetles and other insect disturbance agents, potentially increasing the number of generations born within a single year (called "voltinism") and leading to higher overall reproductive rates. For this reason, especially bark beetle outbreaks in Carpathians spruce forests have been linked to warmer temperatures and drought stress creating climate niches that increase both vulnerability of host trees and optimal pest reproductive success.

Another major threat identified concerns the increased frequency and intensity of windstorms resulting in greater tree mortality and associated changes in the production of critical ecosystem services, including habitat, hydrologic regulation, carbon storage, and timber resources (Seidl et al. 2014, Grodzki et al. 2018). The structure, composition, and age class distribution of Carpathian forests are likely to shift in response to an increased prevalence of severe windstorms. Wind disturbances can also interact with other disturbances by increasing the availability of dead and dying host trees for insects and pathogens and enhanced fuel loading as a major fire risk.

There is an interaction with the land-use history of Carpathian countries, which has made forests more vulnerable to climate exacerbated disturbances. This concern was clearly expressed by focal experts. Many studies have also projected that climate change will increase the vulnerability of Carpathian forests to multiple disturbances, including forest fire, drought, windstorms, and pests and diseases. For forest managers, this will pose significant challenges both in terms of damage to timber resources and the need to manage for resilient landscapes (Hlásny et al. 2019). Similarly, warmer temperatures combined with sufficient rainfall and soil moisture (e.g., during years with unusually high precipitation) create conditions that favor growth and dispersal of fungal tree diseases, such as *Armillaria* and *Phytophthora* root rots. These climate related stresses will exacerbate the phenomenon of forest dieback, which is already severe in some areas such as western Ukraine (Baradat et al. 2019). Compounded disturbance events may have cascading impacts on forest ecosystems, such as increased erosion, landslides, and soil compaction (Hlásny et al., 2017).

It is also important to note that disturbances play a critical structuring role in Carpathian forest ecosystems. When operating within a more natural range of variability [i.e., one less altered by climate change and forest management history], disturbances not only create the diversity of seral (i.e. successional) habitats and stand structure elements that many species depend on but can also maintain an optimal mix of carbon environments and processes, including both patches with high levels of carbon uptake (sequestration) and patches with high levels of biomass (storage) (Mikolas et al. 2021, 2023). The formation and persistence of species diversity and critical, yet under-represented, habitats like "natural" and virgin forests and old forest elements, such as large legacy trees persisting within younger stands, is dependent on natural disturbance and successional processes. Many of these stand structure conditions yield resilience to climatic changes, such for instance by buffering microclimates beneath complex forest canopies and maintaining high genetic diversity (i.e., evolutionary potential). Thus, restoring the forest conditions needed to support a desired level of disturbance activity may, in fact, comprise one of many adaptation approaches (Aszalos et al. 2022). However, while these functions were stressed in some of the survey responses, many others focused rather on the threats, illustrating differing viewpoints around this issue. The latter view also finds support in the literature, for example with respect to reduced forest carbon storage as disturbance frequencies increase (Seidl et al. 2014). The temporal dynamics of the carbon balance following very large disturbances can be highly complex, as shown after a major wind event that affected more than 12,000 ha of mature forest in the Tatra Mountains in 2004 (Fleischer et al. 2020). Immediately after the event, forests shifted to carbon sources, only later becoming carbon sinks with the growth of successional vegetation. Areas infested with bark beetles after the wind event remained carbon sources for longer periods (Fleischer et al. 2020). On the other hand, landscapes that are diversified to enhance resilience may accommodate a range of disturbances closer to historic ranges of variability and a more optimal mix of carbon sequestration and storage and seral habitats for biodiversity (Mikolas et al. 2021, Aszalos et al. 2022).

The identified risks closely match the leading topic within current forest science research in Europe. Both national experts and scientific literature suggest a variety of adaptation responses, including forest management to increase compositional heterogeneity across landscapes, restoration of mixed-species and beech forest where these were historically endemic, and management for forest structures that are less susceptible to disturbances (see chapter 4.2.) Recent assessments also stress the importance of not just protecting forests from disturbances, but rather restoring diverse landscapes that are more resilient, both through natural recovery processes and adaptive silvicultural practices (Lindner et al. 2020).

DROUGHT AND WILDFIRES

The second most frequently mentioned risk was drought, a topic clearly of great concern given recent climate trends and severe drought events that suggest drought and associated disturbance risks are increasing within the Carpathian region as they are for Europe as a whole (Science for Environment Policy 2021). This is perceived by national experts to pose grave consequences for forest growth and productivity, regional tree mortality rates, biodiversity, future shifts in species composition and the climate regulating functions of Carpathian forests. The connection to forest-derived water resources and other ecosystem services, such as carbon storage, is also clear. Drought stress is a major concern for forests in the Carpathians, particularly in the southern and eastern parts of the range where soil moisture availability is more limited (Hlásny et al., 2017). In the wake of several recent drought events, the Carpathian forest sector has become acutely aware of the risks posed by increasingly frequent and severe drought events. At the same time there is clear evidence that drought risks will be more pronounced in some sub-regions and locales than others, such as particular sub-basins in the Polish Tatra Mountains (Bokwa et al. 2021). There is great concern that droughts will interact with other stresses, such as wind, fire, insects and pathogens, to reduce tree growth rates, increase mortality, alter tree regeneration dynamics, and exacerbate forest decline, not just in spruce forests but other types as well, including beech (Petritan et al., 2015, Thom et al. 2023). The persistent and sometimes lagged (or multi-year) influence of droughts on disturbance risks is also likely to have major structuring effects on temperate forests into the future (Senf and Seidl 2021b).

With greater interannual variability in seasonal precipitation, dry seasons will lengthen, and droughts will become more frequent. When combined with warmer temperatures and heat waves, forest fire risks are also highly likely to increase. These climatic changes will directly influence key drivers of fire ignition and spread, including ambient relative humidity and fuel moisture content, thereby exacerbating forest fire risks. Fire frequencies have already been shown to be increasing in portions of the eastern and southern Carpathians (Kelley et al. 2019) and relative to Europe overall, the Carpathian Mountains have been assessed to have particularly high vulnerability to climate change driven forest fires (Forzieri et al. 2020). Greater fire activity is likely, in turn, to increase rates of vegetation transition between plant community types, as fires disturb forest canopies and alter the regeneration environment. The resulting shifts in forest composition and structure may have pros and cons, on the one hand helping to diversify landscapes and increasing carbon uptake rates in successional stands, but on the other increasing declines in desirable forest types, shifting landscape to young seral stages, reducing net carbon storage, and exacerbating spread of invasive species (Costa et al. 2020).

ALTERED HYDROLOGIC REGIMES, FLOOD RISKS, INVASIVE SPECIES, LAND-USE PRESSURES, AND THE NEED FOR RESTORATION

No single theme emerged with a clear tertiary ranking. Rather, responses varied with respect to a variety of additional risks and impacts identified by national experts. These included flood risks and their connection to forest cover and management; spread of invasive insect pests, tree pathogens, and noxious plants; and concerns over increased land-use pressures on forest ecosystems. Concern over floods risks may seem idiosyncratic given an overall trend of increasing drought frequency, but there was acute awareness of vulnerability to extreme precipitation events and the likelihood that the Carpathians, like much of Europe, will experience more of these in the future.

The assessment identified altered hydrologic regimes to be a major vulnerability within the region and one that interacts with both disturbance risks and human impairment of watershed functioning. Regarding the former, respondents stressed that large-scale disturbances, such as fire, bark beetle outbreaks and defoliating insects, will reduce water uptake by trees and reduce infiltration into soils. And with respect to the latter, poorly designed forest roads, development, and imperious surfaces change the form of the hydrograph, meaning that water after precipitation events is delivered more rapidly and at greater volumes directly to streams, rivers, and other surface waters. Collectively these interacting climate and human impacts increase runoff and the intensity of peak flows, thereby inducing severe erosion, flooding during high precipitation events, and possibly chemical loading.

Respondents had different views on some issues, such as restoration of older forests, the carbon sequestration and storage value of older forests, and whether forest management intensity should be increased or decreased. In some cases, the views expressed in survey responses matched the findings of scientific studies, for instance those relating to flooding and invasive species. In other instances, respondent views sometimes diverged from the developing consensus within the scientific literature, for example on the carbon value of older forests (Keeton et al. 2010, Mikolas et al. 2023). However, the literature review showed the same degree of debate on the topic of optimal forest management intensity, suggesting that the survey respondents are not alone in having reached widely different conclusions. There was general support for forest restoration, afforestation and reforestation, and conversion cutting to restore endemic species composition and to create more heterogeneous landscapes.

DECLINES IN FOREST GROWTH AND PRODUCTIVITY

While not one of the top two most highly mentioned risks, survey responses showed a clear concern for the impacts of climate change on forest growth and productivity, although acknowledging that those risks will be expressed differently throughout the region. Temperate increases and variations in precipitation were the most commonly cited drivers of productivity impacts. Accordingly, respondents stressed that productivity responses will vary by climate sub-region, topographic position, and plant species, developing both through the direct effects of climate on tree physiology, phenology, and reproductive success, as well through indirect effects on the dynamics of natural disturbance regimes (see above). Views differed on the potential for CO2 fertilization – the phenomenon of higher photosynthesis efficiency in plants growing in a CO2 enriched environment – to enhance forest productivity. Respondents were aware that there is conflicting scientific evidence on this topic, depending on the time frame of analysis, interactions with other stressors like moisture availability, and nutrient limitations that can lead to down regulation of productivity responses over time (Penuelas et. al. 2020).

The scientific literature is exploring the forest productivity implications of changes in temperature and precipitation patterns across the Carpathians. Warmer spring temperatures can lead to earlier budburst and production of foliage (i.e., altered phenology), which can influence a variety of ecosystem processes, including availability of sunlit patches for spring ephemerals, nutrient uptake rates, and tree growth associated with the length of growing season (Vitasse et al., 2018, Mihai et al., 2018). With a longer growing season, increased water uptake by trees and other plants may lead to soil moisture deficits if precipitation is also lower (Buras et al. 2018), creating negative feedback on forest productivity (Dobrowolska et al. 2017, Kruhlov et al. 2018). Other effects associated with altered phenology include the timing of insect emergence and bird migration (Buras et al. 2016), which carry risks for biodiversity if other environmental conditions (e.g., populations of natural predators, food availability, etc.) do not shift congruently. And where phenology does not keep up with the rate of warming, tree species may become less competitive and more prone to niche displacement or invasion by non-native species.

ALTERED SPECIES COMPOSITION AND DISTRIBUTION

An important finding of the assessment is the shared concern by all Carpathian countries regarding the future of their natural heritage. While not mentioned as frequently as disturbance or drought risks, the effects of climate change on species and biological diversity were highlighted as a major threat in every focal expert response. Of particular concern is climate related extinction risk for species with intrinsically low dispersal rate and species in isolated habitats, such as mountain tops and highly fragmented landscapes. Many respondents stressed the likely impacts of climate change on keystone and flagship species and the overall composition of forest communities. Habitat shifts through the interaction of climatic factors and anthropogenic pressures were frequently cited as representing a fundamental risk to the viability of at-risk populations of plants, wildlife, and other taxa. There was consensus that these risks require broader, coordinated adaptation responses to minimize the potential for local or broad scale extirpations and to facilitate species range shifts.

The assessment findings are supported by scientific literature, which has predicted that Carpathian tree species will respond individualistically to the direct effects of climate. Risk factors vary by species according to the different physiological mechanisms linking climate to growth and survival, such as hydraulic failure, frost damage, and carbon starvation (Petit-Cailleux et al. 2021). Some are likely to experience increased growth and competitiveness while other plant species will become less competitive or will see their available habitat decline (Kobiv 2018). In particular, non-native species possessing future-adapted traits may become more competitive, in some cases allowing them to become more widely invasive (Mátyás et al., 2019). Further, it remains uncertain whether species ranges will be able to adapt to rates of climatic change, migrating to and colonizing new locations within their environmental tolerance ranges (Thuiller et al. 2005). Also, higher tree mortality is predicted to increase rates of succession and compositional change across European forests (Ruiz-Benito et al. 2017).

As temperature and precipitation patterns change across the Carpathian Mountains the competitive environment will be altered, favoring some tree species over others depending also on the site characteristics and local growing conditions. For example, less drought tolerant tree species distributed at lower elevations may expand their ranges to higher elevations where moisture availability is higher, resulting in elevational shifts in the relative abundance of tree species (Grodzki et al, 2018). In boreal forest types, such as montane spruce-fir, deciduous species are likely to increase in relative abundance. Oak, beech, and maple are all predicted to increase within previously boreal zones in this way. At still higher elevations, the composition of subalpine forests will be increasingly dominated by mesic species such as spruce, fir, and beech. Drought tolerant species, such as oak, pine, and fir, are predicted to increase in relative dominance, particularly on drier sites, as species requiring higher soil moisture, such as beech and spruce, decline. Researchers predict that beech-dominated forests may decline by as much as 50% by the dawn of the 22nd century, whereas oak forests are likely to increase by 40% in the Carpathians (Hlásny et al. 2017, García-Duro 2021). The area occupied by spruce forests is projected to shrink to 60% of its current spatial extent.

FEEDBACK MECHANISMS AND EFFECTS ON ECOSYSTEM SERVICES INCLUDING CARBON STORAGE

Finally, a major theme in survey responses was the potential for climate change to alter the mix of ecosystem services provided by Carpathian forests through a variety of feedback mechanisms. Based on survey responses and supporting literature, the assessment finds that that complex interactions between climate change and forest ecosystem processes, such as productivity, carbon, and water cycles, may create feedback loops that accelerate rates of change both in the climate system and in forest resources. For example, positive feedbacks link climatic conditions and the water cycle to the distribution of forest types, their age class distributions, stand structure characteristics influencing hydrological regulation, and their associated biomass and carbon storage (Ceballos et al., 2018, Kruhlov et al. 2018). There are critical interactions between disturbance types, increasing system vulnerability overall (Thom and Seidl 2016, Seidl et al. 2017). In addition, Carpathian forests have heightened vulnerability to climate risks due to historic forest management and land-use changes which have homogenized forest composition and structure. These have increased susceptibility to disturbance and forest health risks, creating positive feedback loops that are likely to accelerate change (Keeton et al. 2013, Hlásny et al. 2017).

As identified by focal experts and presented in the literature, climate change is expected to lead to major vulnerabilities related to the growth and productivity of forest ecosystems in the Carpathian Mountains. For example, beech forests in the Polish Carpathians are predicted to experience a 40% decrease in productivity by the year 2100 in response to rising temperatures and declining summer rainfall (Czajkowski et al. 2017). Clearly this would have significant economic impacts, feeding back on forest sector revenue and ecosystem services underpinning the sustainable management of these systems.

Focal experts were particularly concerned about greater rates of carbon flux to the atmosphere due to disturbances, drought stress, and reduced forest productivity, reducing the effectiveness of Carpathian forests as a natural climate solution. Increased net carbon fluxes to the atmosphere could potentially exacerbate both regional and global climate change. Carpathian forests store approximately 6% of Europe's total forest carbon stock (Zlatanov et al. 2016). However, the direct and indirect effects of climate change are likely to lead to a significant decline and possibly a reversal in sink capacity (Kruhlov et al 2018). In a 500-year projection of climate change impacts on the Ukrainian Carpathians, Kruhlov et al. (2018) found that, due to the combined effects of compositional changes and disturbances, aboveground carbon storage in forests declined between 6.6% to 20.6% depending on the climate scenario. These results were supported by Pfeifer et al. (2018), who predicted that the Carpathian Mountains will become a carbon source over the current century due to the drivers identified by Kruhlov et al. (2018).

Feedbacks between climate change and water resources posed another great concern to the survey respondents. Hydrologic regimes may be especially sensitive to shifts in seasonal precipitation and evapotranspirative demand, leading to changes in both the quantity and quality of freshwater resources. These effects will be distributed unevenly both spatially and seasonally, with annual precipitation predicted to increase in the northern Carpathian and decrease in the southern portion of the region (Werner et al. 2016). Research suggests that stream flow, soil moisture availability, and clean water production will decline the most during the summer months and in the drier south, while 30-year flood risks will increase slightly to strongly, although predictions are sensitive to uncertainties in climate scenarios and data limitations (Didovets et al. 2019). Feedbacks between climate change and forest productivity (negative reinforcement) and disturbances like forest fires (positive reinforcement) are highly probable, with significant implications for regional economies, livelihoods, and human communities.

An often poorly recognized yet critically important feedback between climate and forests relates to albedo, or reflectivity of the Earth's surface. Vegetation types and land surfaces with lower albedo reflect less of the incoming shortwave (or ultraviolet) radiation, converting more of it to long wave radiation (or heat). Forest ecosystems typically have lower albedo and thus absorb more solar radiation compared to other land cover types, such as grasslands or agriculture (Drever et al. 2021). If oak and pine forests increase in relative abundance in the Carpathians as predicted, this is likely to decrease the region's albedo, since beech and spruce forests typically have higher albedo (Vincze et al. 2019). This would create a positive feedback loop, exacerbating a warming regional climate.

4. ADAPTATION APPROACHES

4.1 INTRO

In this chapter our aim is to elaborate on adaptation approaches for forests and the forest sector, particularly those shared widely throughout the region and prioritized by regional experts. From the key risks and impacts identified, experts were asked to indicate adaptation response options they are aware of and briefly highlight their intended effects for each key topic. The following tables provide a synthesis of responses received for each of the key topics in terms of adaptation response options presented in brief fact sheets and further supported by related literature.

4.2 RESPONSE OPTIONS ALONG IDENTIFIED KEY TOPICS

FOREST GROWTH AND PRODUCTIVITY

ADAPTATIVE SILVICULTURE	
Characteristics	Emphasizes ecological principles and aims to maintain or enhance the natural processes and functions of the forest ecosystem. Considers factors such as biodiversity, soil health, water quality, and habitat connectivity. Considers multiple objectives, such as timber production, wildlife habitat conservation, water balance and carbon sequestration, disturbance processes as well as recreational opportunities. It seeks to find a balance among these objectives based on the specific context and goals of forest management. Shifts or converts species composition, harnessing both natural and artificial regeneration, to mixed forests where these were historically endemic or where they will be future adapted. This may take the form of a variety of silvicultural approaches, including but not limited to close-to-nature forest management - identified in the region conferring resistance or resilience to climate change. Including e.g.: • Continuous cover forestry with uneven aged, diverse forests. • Stocking management, including thinning to reduce stand densities. • Diversified landscape mosaics in terms of patch structure and composition • Gap- and retention-based regeneration harvesting systems. • Use of prescribed burning in forest types and drier sites that once supported low intensity, ground fires. Requires ongoing monitoring of forest conditions and response to management actions. This helps in assessing the effectiveness of different approaches and making informed decisions.
Main Impact/Risk addressed	Spruce mortality and decline in vigor of other forest types, including beech. Drought and increased disturbance risks, such as bark beetles, wind, and forest fires. Increased physiological stress in trees leading to reduced growth and vigor. Landscape-scale continuity of vulnerable host trees for insect pests.
Intended effects	New forest composition will be better adapted to future climatic conditions and resilient or resistant to a variety of stresses.

ADAPTATIVE SILVICULTURE	
	Decrease of drought and disturbance related risks. Managing tree density reduces wildfire risk, as does thinning to remove shrubs and flammable vegetation in between the ground and the crown level (vertical continuity). Species with a higher age mix and species mix tend to be less vulnerable to wildfires compared to mono-age and mono-species stands, since their more complex structure can slow fire spread. Restores capacity for low intensity fires that do not "canopy out" and become high intensity, stand replacing burns. Rehabilitated and sustainable ecosystems; continuation of native tree cover having usually better productivity than invasive species. Increase functional and structural diversity.
Pros and cons (if any)	Key advantages: • Creates greater resilience to abiotic damage in comparison with even-aged stands. • Improves biodiversity through the creation of a vertically and horizontally diverse habitats at stand scales and mosaics of seral habitats at landscape scales. • Leads to more diverse landscape that limit disturbance spread and optimize ecosystem services such as carbon sequestration and storage. Potential disadvantages: • Time constraints and costs in achieving irregular structures through lost production during the transformation period. • Lack of knowledge of the process of transformation. • Limited range of sites where transformations may be possible.

AFFORESTATION AND REFORESTATION	
Characteristics	Afforestation: Converting land that has not been tree-covered for at least 50 years (according to UNFCCC) into forest • Establishment of forests in areas that historically have not been forested, such as barren lands, agricultural fields, or urban areas. It involves planting tree seedlings or direct seeding, and sometimes soil preparation and protection from herbivores and competing vegetation, to initiate the growth of new forests. • Conversion of non-forest land, e.g., through land-use planning, land acquisition, and implementation of suitable silvicultural practices. • Careful consideration is needed for selecting appropriate tree species that are well-suited to the local and future climate and soil conditions and intended objectives. The selection may include native species, non-native species, or a combination of both, depending on the goals, ecological context and applicable legal frameworks. Use of climate forecasts to estimate future site-specific growing conditions is advised. Reforestation: Converting recently non-forested land into forest • Focuses on restoring forest cover in areas that have been deforested or significantly degraded. It involves the replanting or natural regeneration of trees in areas that were previously forested but have experienced forest loss due to clearing, logging, fire, or other disturbances. • Aims to restore ecological integrity and functionality to degraded forest ecosystems. It involves the reintroduction of native tree species and other associated vegetation, promoting natural processes, and recovering biodiversity and ecosystem services. • Often requires site preparation activities such as removing debris, controlling competing vegetation, and improving soil conditions to facilitate successful tree establishment. Careful management practices, including monitoring and maintenance, are implemented to ensure the long-term success of the restored forests. • Often considers appropriate game management and landscape-scale planning to enhance connectivity between fragmented forest patches. This helps to support wildlife movement, genetic exchange, and ecosystem resilience. • Should consider socio-economic factors, such as local community involvement, livelihood improvement, and sustainable forest management practices. It can provide economic opportunities through sustainable timber production, non-timber forest products, and ecotourism.
Main Impact/Risk addressed	Floods and landslides. Droughts, extreme temperatures, water scarcity. Soil degradation. Biodiversity loss. Declines in rural livelihood opportunities.
Intended effects	Landscape diversification to enhance resilience to disturbances, for example by increasing the complexity and diversity of patch mosaics to limit disturbance contagion and spread. Reduce the destruction or degradation of habitats and safeguarding ecosystem services. Reduce fragmentation/increasing ecological connectivity (thus facilitating species migration under climate change conditions).

AFFORESTATION AND REFORESTATION	
	Reduce the risk of landslides, restore riparian and floodplain functionality, protect water bodies from sedimentation, and promote healthy watershed management. Help replenish groundwater, reduce runoff, and improve water availability and quality. Provide valuable resources for local communities, such as timber, non-timber forest products, wood bioenergy, and medicinal plants. Provide a renewable source of timber and other forest products, supporting the forestry industry and contributing to sustainable rural economic development. Local communities' involvement efforts foster a sense of ownership, empowerment, and stewardship. It can strengthen community resilience, promote social cohesion, and enhance cultural values associated with forests. Offer opportunities for all forms of forest-based recreation, including activities like hiking, biking, skiing, wildlife observation, and nature tourism.
Pros and cons (if any)	Potential disadvantage: • High initial investment to establish new stands coupled with the several-decade delay and the need for subsequent pre-commercial thinning until afforested areas generate revenue or provide desired ecological functions. This may represent a major constraint.

BIOMASS AND CARBON STOCKS

CARBON FORESTRY	
Characteristics	Planting or natural regeneration of future-adapted tree species, producing diverse forests and landscape mosaics with high carbon sequestration and storage capacity. Use of carbon forestry practices that yield high biomass/high carbon storage forests over time. These include stand improvement thinning, extended harvest rotations, retention systems for regeneration harvests, close to nature silviculture, and unmanaged inclusions or reserves. support chosen management practices for offsetting carbon emissions. The combination of these practices is intended help mitigate climate change by capturing carbon dioxide (CO_2) from the atmosphere and storing the carbon in forest biomass, both above and belowground, thereby offsetting GHG emissions from other sources.
Main Impact/Risk addressed	Carbon stored in terrestrial ecosystems is vulnerable to greater flux rates (i.e., CO_2 flux to the atmosphere) as the climate changes and is dependent on the specific mix of economic uses of forests, including conversion to non-forest land-uses. Key mechanisms include increases in forest management intensity and disturbance frequency. The latter are sensitive to climate change and physiological stresses in trees that are related to rising temperatures and increased soil moisture deficits. Changing/reduced carbon uptake and carbon dynamics (sequestration, storage, and fluxes).
Intended effects	Use carbon stored in forest biomass as renewable resource, while the growing, sustainably managed, and protected forests act as carbon sinks and storage reservoirs. Maintain and/or enhance the carbon stored belowground in the soil system.

CARBON FORESTRY	
	Enhance the removal of carbon dioxide (CO_2) from the atmosphere (carbon sequestration), thereby helping to mitigate climate change. Store the carbon over the long-term both in-situ in the forest as well as in durable (long-lasting) wood products. Increased wood processing efficiency, re-use, and recycling may also have carbon benefits, depending on the overall portfolio of forest carbon management approaches and their net effect. Generate emissions offsets, which are tradable credits representing the additional reduction or removal of greenhouse gas emissions over a baseline. These offsets can be sold or used to compensate for emissions in other sectors, such as energy production or transportation, effectively neutralizing a portion of their carbon footprint. Bring socio-economic benefits to local communities including job creation in tree planting and forest management, income generation from carbon credit sales, and opportunities for sustainable land use practices.
Pros and cons (if any)	Key advantages: • Increased carbon sink capacity and stocks, substitution effects when wood products replace materials with high carbon footprints, such as plastic, steel, and concrete. • Generate carbon credits, also known as forest carbon offsets, which can be sold in carbon markets or used to offset emissions from other sectors. • Carries co-benefits like provision of complex, late-successional habitats for biodiversity, riparian functionality, and hydrologic regulation. Potential disadvantage: • Some carbon forestry practices, such as extended rotations, carry heightening disturbance risks and therefore must be planned carefully at landscape scales. • There can be tradeoffs with some forms of timber production and is therefore best planned holistically alongside other forest management objectives.

REWILDING / CORE AREA PROTECTION	
Characteristics	Rewilding: • Conservation efforts aimed at restoring and protecting natural ecosystems processes and wilderness areas that will involve fewer active forms of natural resource management. • May include recreation management, invasive species control, use of prescribed fire, and other reserve-based management practices. • Reintroducing species that have become locally extinct or have declined due to human activities. These species are typically keystone species or ecosystem engineers that play critical roles in shaping their habitats. By reintroducing such species, ecosystem services can be restored, and habitats can be revitalized. • Reinstating ecological processes, including predation, herbivory, natural disturbance dynamics, and ecological succession, which can have cascading effects throughout the ecosystem. Core area protection: • Designating and safeguarding specific areas within a larger landscape or ecosystem for the conservation of biodiversity and ecological processes (often involves the establishment of protected areas, such as national parks, nature reserves, wildlife sanctuaries, or other forms of protected land).

<table>
<tr><th colspan="2">REWILDING / CORE AREA PROTECTION</th></tr>
<tr><td></td><td>Formation of contiguous areas of natural forest linked by forests and landscapes managed for ecological connectivity.</td></tr>
<tr><td>Main Impact/Risk addressed</td><td>May result in reduced net carbon uptake over centuries but compensates with high levels of carbon storage and continued high rates of carbon sequestration over the near to mid-term as forests recover and develop towards a late-successional condition.</td></tr>
<tr><td>Intended effects</td><td>By revitalising natural processes, rewilding as a Nature-based Solution (NbS) restores the overall health and functionality of entire ecosystems and provides carbon benefits through high levels of carbon storage. Core reserves complement more intensive forest management employed elsewhere on the landscape, thereby providing “risk spreading”.</td></tr>
<tr><td>Pros and cons (if any)</td><td>Key advantages:
Ecosystem Restoration: Rewilding can restore ecological processes and functions that have been disrupted due to human activities. This includes natural predator-prey dynamics, seed dispersal, pollination, vegetation succession, and nutrient cycling. Restoring these processes can have cascading positive effects on the entire ecosystem.
Core area protection is one of the most effective ways to conserve biodiversity and protect sensitive ecosystems. By establishing protected areas, critical habitats can be preserved, allowing for the conservation of endangered species, rare plants, unique ecosystems and their ecosystem services.
Carbon sequestration: Rewilded areas often have increased vegetation cover and a greater variety of plant species, which can enhance carbon sequestration. This helps mitigate climate change by reducing atmospheric carbon dioxide levels and storing carbon in soils and vegetation.
Ecotourism and Economic Benefits: Rewilded areas can attract tourists and nature enthusiasts, creating economic opportunities for local communities. Ecotourism related to rewilding projects can generate revenue, job opportunities, and support local businesses, contributing to sustainable development.
Scientific and Educational Value: Core areas offer opportunities for scientific research and education. They provide undisturbed ecosystems for studying natural processes, ecological interactions, and species behavior. These areas also serve as outdoor classrooms and living laboratories, contributing to ecological knowledge and environmental education.
Potential disadvantages:
Human-Wildlife Conflicts: Introducing or reintroducing large predators or other wildlife species can lead to conflicts with human activities such as agriculture, livestock farming, and infrastructure development. Predation on livestock and crop damage may create challenges and tensions between local communities and rewilding initiatives. On the other hand, there are many examples of community-based partnerships formed to overcome these challenges, leading to successful reintroduction programs.
Change in the type and distribution of flora and fauna: Introducing new species or increasing the cover of historical endemic vegetation can shift the landscape from current or cultural norms, sometimes requiring an adjustment in cultural aesthetics, uses, and acceptance.
Uncertainty and Long Timeframes: Rewilding is a complex process that requires careful planning and implementation. It can take many years or even decades for ecosystems to fully recover and for rewilding efforts to demonstrate their intended benefits. There is inherent uncertainty in predicting outcomes and the success of rewilding initiatives particularly in the face of climate change and altered successional dynamics.</td></tr>
</table>

REWILDING / CORE AREA PROTECTION	
	• Restricted Land Use: The establishment of core areas often involves restricting or prohibiting certain land uses and activities. This can create conflicts with local communities, landowners, and resource-dependent industries such as agriculture, logging, or mining. Balancing conservation goals with socioeconomic needs and ensuring equitable solutions is a challenge.

TREE MORTALITY

INCREASE RESILIENCE TO DISTURBANCE	
Characteristics	Approaches to enhance resilience include: • Enhancing and maintaining species, structural and genetic diversity by favoring existing genotypes that are better adapted to future conditions, incorporating genetic diversity from a greater range of population sources and including pest- or drought-resistant varieties where appropriate. • More intensive thinning practices and care of forest stand edges. • Promoting redundancy of ecological representation within core protected areas. Also "functional redundancy" which means having multiple species or ecological components that perform similar functions, providing compensatory capacity if one species declines or is adversely affected by climate change. This functional diversity ensures that multiple ecological processes and services are maintained, even if some species or functional groups are lost or impacted. • Establishing ecological corridors and maintaining landscape connectivity to facilitate the species' range shifts, dispersal and genetic interchange among populations, and continuation of ecological processes. Connected landscapes allow for the dispersal of species, enabling recolonization and gene flow following disturbances. Corridors can also help species adapt to shifting environmental conditions caused by climate change.
Main Impact/Risk addressed	Increasing soil moisture deficits and prolonged drought due to reduced precipitation and higher temperatures likely in some areas.
Intended effects	Enhanced diversity in forests exhibits a higher variability in resistance to pests, drought and access heat. Reducing stand densities, for instance in intensively managed coniferous forests, will lower competition and thus the probability of drought-related tree mortality. Enhanced complexity and diversity of patch mosaics (e.g., different types and ages of vegetative communities) across the landscape helps limit contagion and spread of insects and plant diseases.
Pros and cons (if any)	N/A depending on approaches to increase resilience

CHANGES IN SPECIES RANGE, HABITAT SHIFTS AND ABUNDANCE

ASSISTED DISPERSAL AND MIGRATION	
Characteristics	Moving species or genotypes to new locations that should better match their climatic suitability in the future: • Assisted population migration (also assisted genetic migration or assisted gene flow) – moving seed sources or populations to new locations within the historical species range; or • Assisted range expansion – moving seed sources or populations from their current range to suitable areas just beyond the historical species range (adjacent areas), facilitating or mimicking natural dispersal; or • Assisted species migration (also species rescue, managed relocation, or assisted long-distance migration) – moving seed sources or populations to a location far outside the historical species range, beyond locations they would naturally spread.
Main Impact/Risk addressed	Extinction risk for species with intrinsically low dispersal rate, and species in isolated habitats such as mountain tops. Impacts on keystone and flagship species and the composition of forest communities. Habitat shifts through interaction of climatic factors and anthropogenic pressures.
Intended effects	Assisted population migration and assisted range expansion may help maintain forest productivity, particularly when suitable seed sources or populations are moved to locations within, or just beyond, the historical range where growing conditions are likely favorable under future climatic conditions. Assisted migration can help maintain crucial ecosystem functions like wildlife habitat, carbon sequestration, and watershed services under ecosystem restoration conditions. Control of herbivory on tree seedlings is a critical component of this approach. Assisted migration can help populations and species move across ecological barriers in fragmented landscapes, such as roads, agriculture, cities, and other human infrastructure.
Pros and cons (if any)	Key advantages: • Ecosystem Restoration: Assisted dispersal and migration can be used as a tool for ecological restoration, especially in areas where species have been extirpated or ecosystems have been degraded. It can aid in the reestablishment of natural ecological communities and the recovery and preservation of ecosystem processes such as such as pollination, seed dispersal, and nutrient cycling. • Conservation of Species: Assisted dispersal and migration can help conserve species that are at risk of extinction due to the loss of suitable habitats or changing climate conditions. By facilitating the movement of species to more suitable environments, it increases their chances of survival and reduces the risk of local extinctions. • Increased Biodiversity: Assisting the dispersal and migration of species can enhance biodiversity in certain regions. By introducing new species or expanding the range of existing species, it can increase species richness and promote more diverse ecosystems. This can contribute to ecosystem resilience and adaptive capacity. Potential disadvantages: • Species introductions may unknowingly introduce pests or diseases into new areas, particularly with longer transfer distances.

ASSISTED DISPERSAL AND MIGRATION	
	• Long-distance transfers based on projected climate conditions raise the likelihood that current habitat may not be suitable, which could result in poor growth or planting failure. • Site factors other than climate, such as soil type, moisture regime, herbivory, competition, endemic pests and pathogens, and photoperiod may preclude successful establishment. • Newly introduced species may become invasive. • Can be resource-intensive and logistically challenging. It requires careful planning, monitoring, and long-term management to ensure the success of introduced populations. Limited resources and competing conservation priorities may make assisted migration impractical or less feasible in certain cases. • Uncertainty in predicting future species' ranges and community compositions with climate disruption. The paleo-ecological record shows that current species assemblages break apart and new assemblages form when the climate changes.

INVASION BY NON-NATIVE SPECIES

MANAGEMENT PRACTICES TO MAINTAIN OR IMPROVE THE ABILITY OF FORESTS TO RESIST PESTS AND PATHOGENS	
Characteristics	Forest management practices that manipulate the density, structure, or species composition of a forest may reduce susceptibility to some pests and pathogens, inter alia: • Thinning to reduce the density of a pest's host species in order to discourage infestation, based on the knowledge that species are especially susceptible to pests and pathogens at particular stocking levels. • Adjusting rotation length to decrease the period of time that a stand is vulnerable to insect pests and pathogens, based on the knowledge that species are especially susceptible to pests and pathogens at particular ages. • Creating a diverse mix of forest or community types, age classes, and stand structures to reduce the availability of host species for pests and pathogens. • Managing canopy conditions depending on types of invasive species, e.g., maintaining closed-canopy conditions to reduce the ability of light-loving invasive species to enter the understory or keeping canopy more open to reduce spreading of species (e.g., Pinus strobus) or pathogens that prefer conditions of shade, less wind, and higher humidity. • Using biological control methods to manage pest populations in heavily infested areas. • Restricting harvest and transportation of logs near stands already heavily infested with known pests or pathogens. • Using impact models and monitoring data to anticipate the arrival of pests and pathogens and prioritize management actions.
Main Impact/Risk addressed	Invasion by non-native (alien) species may result in biome shifts, with consequent changes in the spectrum of forest ecosystem services provided.
Intended effects	Improved non-native species management with dedicated measures for prevention, early detection, control management, including rapid response and rehabilitation and restoration.
Pros and cons (if any)	N/A depending on management practices.

CLOSE-TO-NATURE SILVICULTURE / ECOSYSTEM-BASED MANAGEMENT	
Characteristics	Close-to-nature silviculture is a forest management approach treating forests as an ecological system performing multiple functions. This approach provided an array of ecosystem services with the aim of promoting forest health and biodiversity while also producing timber and other forest products. The approach is based on the principle that forests are complex ecosystems that function best when natural processes from the point of view of mass and energy fluxes are continuous and automatic. Practices used are designed to create forest landscapes that contain all the diversity and irregularity of natural forests, for example with regard to the size and shape of stands and the presence of trees of different sizes. Forest management interventions are designed to mimic natural disturbances such as windthrow, insect outbreaks, and fire. This can include measures such as selective thinning, gap creation, and retention of deadwood and snags towards creating a more diverse forest structure. Involving local communities in forest management can help ensure that forest management practices are adapted to local needs and priorities, while also promoting sustainable use of forest resources. This can include measures such as community-based forest management agreements, forest user groups, and forest certification schemes.
Main Impact/Risk addressed	Alteration of critical services, such as carbon sequestration and storage, hydrologic regulation, habitat provisioning. Further ecosystem services potentially impacted include provisioning services (bioenergy, water); regulating services such as climate regulation, flood control, and pollination, pest and disease control; supporting services such as primary production (e.g., timber); and cultural services, including recreation and aesthetic and spiritual benefits.
Intended effects	Improved forest health and biodiversity conservation: By maintaining a diverse forest structure and reducing the risk of large-scale disturbances such as wildfires, close-to-nature silviculture can help improve forest health, promote biodiversity, and enhance resilience to climate change. Sustainable timber production: By using selective harvesting and other sustainable management practices, close-to-nature silviculture can provide a steady supply of timber while also maintaining forest health and biodiversity. Carbon sequestration: By maintaining healthy forests, close-to-nature silviculture can help sequester carbon and mitigate the effects of climate change. Improved aesthetics and recreational value: By creating a more natural forest structure, close-to-nature silviculture can improve the aesthetics of the forest and provide opportunities for recreational activities and sustainable tourism.
Pros and cons (if any)	Key advantages: • By imitating natural disturbance patterns, such as individual tree mortality or gap dynamics, it allows for the regeneration and development of diverse age classes and species composition. This promotes forest adaptability and improves long-term ecosystem stability. • Through selection harvesting individual or small groups of trees, it can provide a continuous supply of high-quality timber while minimizing the negative impacts on forest ecosystems. • By maintaining a diverse range of tree species and age classes, forests under this management approach can sequester and store more carbon after conversion to site-endemic species compositions and development of high

CLOSE-TO-NATURE SILVICULTURE / ECOSYSTEM-BASED MANAGEMENT	
	biomass conditions. This contributes to climate change mitigation by reducing greenhouse gas emissions and enhancing carbon sinks. • There is an opportunity to further expand the portfolio of close-to-nature silvicultural practices, for instance through greater emphasis on large dead tree retention and downed wood enhancement, irregularly structured and shaped gap creation, development of patch mosaics, and incorporation of tip-up mounds into managed stands. • Close-to-nature silviculture can be used as a "conversion" or restoration method to transition plantations or monocultures to site-endemic species compositions, including species mixtures that are more adapted to future climatic conditions. Potential disadvantages: • Complexity and knowledge requirements: Forest managers need to have a good understanding of the natural dynamics of the forest, including tree species interactions, regeneration strategies, and long-term planning. • Reduced timber production: Overall timber yield may be lower compared to intensive plantation forestry or clear-cutting practices. longer rotation periods between harvests compared to traditional management systems may pose financial challenges for forest owners or managers who rely on timber income. • Management costs associated with this approach can be higher compared to more conventional management systems. The need for continuous monitoring, selective harvesting, and maintenance of desired forest structures can increase the overall management expenses. • Limited applicability: May not be suitable for all forest types or conditions. It is best suited for certain forest ecosystems with specific ecological characteristics. In some cases, the natural dynamics of the forest may not support continuous cover management, or the economic and social context may not favor this approach. • Closer-to-nature forestry practices which promote the retention of deadwood in forests might, depending on the local conditions, require further precautions to prevent forest fires or undesired insect infestations.

FOREST – WATER INTERACTIONS, INCLUDING HYDROLOGIC REGULATION AND RIPARIAN DYNAMICS

INTEGRATING FOREST-WATER INTERACTIONS INTO ADAPTIVE FOREST MANAGEMENT	
Characteristics	Adaptive forest management options to manage hydrological impacts of climate change include: • Thinning. • Selective logging of invasive species or broadleaf species with highwater consumption. • Leave a certain proportion of dead wood in forests, arranged in a slanting or perpendicular pattern relative to slope orientation. • Removal of infected trees, and pest control by introducing predators and biocontrol agents. • Increasing water retention facilities (e.g., terraces and ponds) to guarantee water supply and restore aquatic and floodplain habitats. • Watershed-level planning to incorporate considerations of the hydrological processes and their interaction with the forest ecosystem. This approach will help identify critical areas that need protection and prioritize management actions accordingly.

<table>
<tr><th colspan="2">INTEGRATING FOREST-WATER INTERACTIONS INTO ADAPTIVE FOREST MANAGEMENT</th></tr>
<tr><td></td><td>Maintaining drainage of forest roads, use a net of trenches for water retention via polders and keep undamaged soil and humus layer as a protection against erosion. Installing a greater frequency of water bars (shallow ditches placed diagonally across forest roads), larger culverts, and enhanced stream crossing structures.
Reducing forest road densities and improving the design, layout, and engineering of the permanent forest road system. This approach may conflict with certain styles of Close-to-Nature forestry that rely on dense road or skid trail networks. Therefore, assessment of tradeoffs and multicriteria optimization of road network design is important.
Maintaining riparian zones to act as buffers between the water body and forest. They help reduce erosion and sedimentation, maintain water quality, and provide habitat for aquatic species.
Promoting agroforestry practices, including the integration of trees into agricultural landscapes. Benefits include improved soil health, increased water infiltration, and reduced erosion. Promoting agroforestry practices in areas adjacent to forests can help reduce pressure on forests for agricultural land and promote sustainable land use practices.
Implementing silvopastoral systems that integrate tree cover into pasture lands. Silvopasture helps reduce soil erosion, improve soil fertility, and provide shade and shelter for livestock. These systems can also help increase water infiltration and recharge groundwater.</td></tr>
<tr><td>Main Impact/Risk addressed</td><td> Altered hydrology regimes due to climate change will have impacts on forests and the watershed services they provide and will affect water quality, aquatic habitats, and species and soil resources. Large-scale disturbances, such as wildfire, bark beetle outbreaks and defoliating insects, will reduce water uptake by trees, reduce infiltration by the soils. This will cause an increase in runoff and potentially severe erosion and chemical loading. Warmer temperature may accelerate the rate of nutrient cycling in some systems, promoting increased forest growth and elevated nitrogen levels in streams. </td></tr>
<tr><td>Intended effects</td><td> Integrating forest-water interactions into adaptive forest management can help protect and improve water quality by minimizing soil erosion, reducing sedimentation in water bodies, and filtering pollutants. Adaptive management practices such as riparian buffer zones, reforestation of degraded areas, improved forest road engineering and maintenance, and sustainable logging techniques can help maintain or restore water quality, stream habitats and increase flood resilience. Increased water availability and flow regulation: Preserving or restoring riparian vegetation for example can help stabilize streambanks, reduce water loss through evapotranspiration, and regulate water flow during periods of high rainfall or drought. Watershed resilience: Restoring and promoting heathy, well-functioning watersheds is important to maintain overall resilience in the face altered disturbance regimes and vegetation shifts. </td></tr>
<tr><td>Pros and cons (if any)</td><td> Key advantages: Enhanced ecosystem services including wood production and improved water availability, reduced erosion, enhanced water purification, and increased flood regulation, benefiting both natural ecosystems and human communities.
Supports the principles of integrated water resources management and promotes water security. Potential disadvantages: </td></tr>
</table>

INTEGRATING FOREST-WATER INTERACTIONS INTO ADAPTIVE FOREST MANAGEMENT	
	• Requires a comprehensive understanding of forest ecology, hydrology, and water resource management. It can be a complex undertaking, requiring expertise and coordination among different stakeholders, including forest managers, water authorities, and scientists. Adequate knowledge, data, and monitoring systems are essential for effective integration. • Balancing multiple objectives within the forest-water nexus can present challenges and trade-offs. For example, maximizing timber production may conflict with maintaining water quality or protecting sensitive aquatic ecosystems. Integrating these objectives requires careful consideration and decision-making processes to ensure that all aspects are adequately addressed. Related planning and implementation challenges may arise due to limited resources, competing land uses, governance issues, and conflicting stakeholder interests. • Forest and water resource dynamics are often slow to respond to management interventions, and the benefits may take time to materialize fully.

5. RELEVANT INITIATIVES AND ACTORS

PAN-EUROPEAN FOREST RISK KNOWLEDGE MECHANISM

Building on the Bratislava Ministerial Resolution "Adapting pan-European forests to climate change" (2021)[19], FOREST EUROPE is working towards the pan-European forest risk knowledge mechanism (FoRISK) to support adaptation of forests to changing climatic and site conditions and enhance forest resilience at a pan-European level. The vision of the FoRISK is to provide relevant evidence-based forest risk and adaptation-related information to political decision-makers based on trustful cooperation with scientists, practitioners, and society.

The FoRISK Pilot, running from September 2022 to February 2024, tests policy tools for various disturbance factors like wildfires, biotic threats, and storms. The Pilot involves national focal points from Carpathian Convention signatories dealing with forestry issues to evaluate the feasibility, funding options, adjustments, and improvements related to the FoRISK concept. The Pilot has three successive but interacting pilot phases, each with a specific thematic focus on a forest damage agent and a comparable approach (Pilot phase 1: Wildfires (9/2022-3/2023); Pilot phase 2: Pests & diseases (3/2022 – 8/2023); Pilot phase 3: Storms (9/2023 – 2/2024)).

EUROPEAN WIDE FOREST DISTURBANCE MAPPING AND PROJECTION MODELING

The Ecosystem Dynamics and Forest Management group[20] at the Technical University of Munich, Germany, led by Dr. Rupert Seidl, is conducting on-going research on climate change effects on forests across Europe. This includes the use of remotely sensed data to map and track changing disturbance regimes and the interactions among disturbance agents. Related studies using simulation models project disturbances and their consequences for specific landscapes and the European continent under alternate climate scenarios. This group has published numerous papers[21] on disturbance dynamics, climate impacts on biodiversity, effects on ecosystem services, and forest resilience that are directly relevant to the Carpathian region. This body of research now comprises an indispensable resource for understanding and predicting the consequences of climate change for European forests as well as opportunities for adaptive forest management.

EUROPEAN PRIMARY AND OLD-GROWTH FOREST DATABASES

The current EU Biodiversity Strategy sets an ambitious goal of conserving all remaining primary and old-growth forests by the year 2030. Achieving this goal relies on the availability of accurate old and natural forest inventory (i.e., spatial) data for the entire EU, which presently includes all Carpathian countries except Ukraine and Serbia (both have EU candidate status). Several completed and on-going assessments have addressed this need. In these initiatives, the term "primary forest" is based on the FAO definition (FAO 2018), whereas old-growth is defined differently by the European Commission (2015), as described in the new EU guidelines adopted by the European Commission in 2023[22]. The datasets produced by these assessments will be vital for informing conservation planning, structurally complex forest restoration, adaptive management, and regional forest carbon management strategies, as primary and old-growth forests in the Carpathians typically have exceptionally high carbon stocking (Keeton et al. 2010, Burrascano et al. 2013).

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[19] See https://foresteurope.org/wp-content/uploads/2021/02/Bratislava-Ministerial-Resolution-.pdf
[20] See https://edfm.wzw.tum.de/en/
[21] See https://edfm.wzw.tum.de/en/publications.html
[22] See https://environment.ec.europa.eu/publications/guidelines-defining-mapping-monitoring-and-strictly-protecting-eu-primary-and-old-growth-forests_en

Two assessments of particular relevance are those by Sabatini et al. (2018, 2020) and Barredo et al. (2021). The former assembled a comprehensive data base spanning all previously documented and mapped primary forest sites across 32 countries. A predictive model was then developed from this dataset to estimate the likely occurrence and distribution of additional, unmapped primary forests. The pan-European database was later expanded to incorporate 51 unique data sets from 35 countries, importantly including Russia (Sabatini et al. 2021). This increased the estimated area of primary forest from 1.4 to 41.2 million ha, a massive expansion due largely to the inclusion of Russia and Norway. The state of known, ground validated primary and old-growth forest occurrences was further summarized and updated in Barredo et al. (2021).

The Carpathian Convention has been establishing an Inventory of Virgin Forests of the Carpathians[23], based on officially reported data by the Parties, which shall strengthen the protection of one of the last remaining virgin forests in Europe. This has been undertaken in cooperation with the European Environment Agency (EEA), the European Topic Centre on Urban, Land, and Soil Systems (ETC-ULS). The current inventory will be welcomed by the Carpathian Convention COP7 in October 2023. In addition, it is proposed extending this Inventory to other degrees of naturalness, particularly quasi-virgin forests in the Carpathians and in this respect, specific criteria and indicators for the selection of quasi-virgin forests in the Carpathians are finalized, equally with the intention to be adopted at COP7. These data come from national inventories and often produce different estimates as compared to other sources (see, for example, Mikolas et al. 2019). All of the aforementioned datasets include the most up-to-date spatial data for primary and old-growth forests in the Carpathians, although downscaling, accuracy assessment, and correction of inventory gaps are on-going.

SUPERB - UPSCALING FOREST RESTORATION / EUROPEAN FOREST INSTITUTE

The European Forest Institute (EFI), an international organization with offices in 41 countries, has taken a lead role in producing sustainable forest management guidance that is directly relevant to several of the key risks and adaptation responses identified in this assessment. Working closely with research organizations, forestland owners, and industry, EFI produces information that is practical and timely in terms of addressing hot button forest management concerns. Of particular relevance to climate risks and adaptation is EFI's Resilience Programme, which has produced a wide variety of reports offering guidance on climate data for European forestry, old-growth forest conservation, adaptative management in response to bark beetle outbreaks, disturbance trends and vulnerabilities, and state-of-the-art thinking on "closer" to nature silviculture. Reports and information are made publicly available on the EFI website[24].

EFI's Resilience Programme has also launched, in partnership with Wageningen Environmental Research, a large-scale project called *SUPERB - Systemic solutions for upscaling of urgent ecosystem restoration for forest-related biodiversity and ecosystem services*. Funded by a €20 million grant from the EU Horizon 2020 Research and Innovation Programme, combined with "in-kind contributions of €90 million from its associated partners[25]", SUPERB will synthesize state-of-the art knowledge and examples (both successful and unsuccessful) of forest ecosystem restoration and adaptation relevant to a variety of contexts across Europe. At the core of SUPERB is a demonstration network consisting of 12 sites in 12 countries, one of which is located in the Făgăraș Range of the Carpathian Mountains in Romania. The Romanian demonstration site is testing restoration forestry practices for phased-conversion of spruce monocultures to mixed-species, structurally complex stands in buffer areas around core zones protecting old-growth forests. A complete description is available online.[26]

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[23] For link to the Inventory of Virgin Forests of the Carpathians, see: https://portal.discomap.eea.europa.eu/arcgis/home/webmap/viewer.html?webmap=66813f21202d4724a604a77a82a98ab0

[24] For links to relevant EFI publications, see: https://efi.int/resilience

[25] EFI website, accessed 30 Aug, 2023

[26] For more information about the SUPERB demonstration site in the Făgăraș Mountains, see https://forest-restoration.eu/demo-area-fagaras-mountains/

PROTECTION OF VIRGIN FORESTS IN UKRAINE AND SLOVAKIA

In 2017 and in accordance with the Carpathian Convention, the Ukrainian government set an example for the region by establishing new legal protections for forest natural monuments. The law effectively called for the protection of all remaining virgin or natural forests. According to WWF - Ukraine[27], 37 forest natural monuments had been created by 2019, totalling 4750.8 ha of protected virgin and natural forests in the Trans-Carpathian and Ivano-Frankivsk oblasts (provinces). Since then, the area of newly protected natural, quasi-virgin, and virgin forest has expanded even further to more than 25,000 hectares.

The Slovak Republic followed suit not long afterwards. In November of 2021 the Slovak government approved establishment of a network of protected natural and virgin forest areas comprising 6,500 ha distributed across 76 sites.[28] The new reserve network, called Old Growth Forests of Slovakia, came in response to recently completed mapping (Mikolas et al. 2019) showing that "*approximately 10,180 ha of old growth forests remained in Slovakia, of which one third was unprotected or insufficiently protected*"[29].

The protections in Ukraine and Slovakia both followed the establishment of a UNESCO World Heritage transnational network in 2007 entitled Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe. This network now encompasses 94 separate forested tracts in 18 countries, including 70 tracts in nations signatory to the Carpathian Convention[30]. These protected forests are places where natural processes will predominate and source populations will be maintained, providing the core reserve component a holistic and multi-pronged forest adaptation approach. Furthermore, the protections recognize the necessity of safeguarding rare and unique natural communities and biodiversity hotspots to ensure their future persistence.

CLIMATE SMART FOREST MANAGEMENT FOR CENTRAL AND EASTERN EUROPE

A promising seven year-project (2020 – 2027), called Climate-Smart Forest Management for Central and Eastern Europe (CLIMAFORCEELIFE), is developing, demonstrating, and promoting climate-smart management techniques for Carpathian forests and beyond[31]. Starting with demonstration sites in 3 countries (Bulgaria, Hungary, and Slovakia), the aim of this €5.6 million project is to encourage the transition to future-adaptive forestry across the Central and Eastern European region. Based on extensive stakeholder involvement, the project will transfer experience and information to the forest sector through guidance documents and a variety of science communication media. A strength of the project is its grounding in "real-world" adaptative (or climate-smart) forestry operations, meaning the demonstration sites are located on managed forests where techniques are applied and tested actively. This will allow information to be developed that is readily transferrable and relevant to diverse stakeholders. Techniques such as close-to-nature silviculture, retention forestry, control of herbivore browsing, large woody debris enhancement, and gap-based harvesting are adapted to local conditions, anticipating future climate-driven shifts in forest composition and productivity as well as disturbance risks.

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[27] See https://wwf.panda.org/wwf_news/?715711/old-growth-protected-in-ua

[28] See https://wwfcee.org/our-offices/slovakia/old-growth-forests-in-slovakia-will-be-protected-in-newly-established-nature-reserve-thanks-to-ngos-prales-and-wwf-slovakia

[29] See https://wwfcee.org/, accessed 31 August 2023

[30] See https://whc.unesco.org/en/list/1133/

[31] See https://clima4ceelife.eu/general-information/


Figure 3. Workshop for forestry practitioners on close-to-nature silviculture and climate-smart forest management, held in the Börzsöny Mountains of Hungary, June 2023[32]. © W.S. Keeton.

The CLIMAFORCEELIFE project was launched at an opening conference held in Bratislava, Slovakia in October of 2021, organized as part of the EU Strategy for the Danube Region 10th Annual Forum. The event brought together over 130 forest experts, scientists, and stakeholders from across the greater region, resulting in a large number of presentations and resource about climate change and forest adaptation in the Carpathian region that are now available online[33]. CLIMAFORCEELIFE recently partnered (see Figure 3) with a project funded by the Trust for Mutual Understanding (W.S. Keeton and R. Aszalos P.I.s) called *Bridging the Divide between European and North American Perspectives on Ecological Silviculture*. The latter initiative has conducted several scientific exchange events in Romania, Hungary, Slovakia, Czechia, and the United States of America. These events facilitated the sharing of experiences and information around climate adaptive forest management from the Carpathian and U.S. perspectives.

DISTURBANCE MONITORING AND RESPONSE CAPABILITY

Disturbance risk monitoring and prediction will be critical elements of adaptative forest management in the Carpathians. This point was clearly stressed by the regional experts surveyed in this assessment and is at the forefront of on-going scientific research.

There are promising technological advances that will greatly aid this endeavour. These include several remote sensing platforms used to track and monitor disturbance events and disturbance risks, often in real time depending on the platform. For example, the Global Ecosystem Dynamics Investigation (GEDI) provides high resolution, three-

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[32] The event was organized by the Centre for Ecological Research (Hungary), WWF Hungary, and the University of Vermont (USA) with funding from CLIMAFORCEELIFE and the Trust for Mutual Understanding.
[33] See https://clima4ceelife.eu/opening-conference/

dimensional laser ranging of the Earth's forests, enabling assessment of canopy structure and fuel profile that can be used to map fire risks[34]. The satellite mounted MODIS (or Moderate Resolution Imaging Spectroradiometer) detects day and nighttime thermal anomalies on the Earth's surface[35]. This allows users to monitor fire occurrences day to day for any region of the world. As another example, the EU has invested in the Structured Approaches for Forest Fire Emergencies in Resilient Societies (SAFERS). It combines remotely sensed data from the Copernicus and the Global Earth Observation System of Systems (GEOSS) platforms with crowd sourced data to create "*an open and integrated platform featuring a forest fire decision support system*"[36]. The wild**F**ire c**L**imate impacts and **A**daptation **M**odel (FLAM), hosted by IIASA, operates with a daily time step at various spatial resolutions and uses mechanistic fire modeling algorithms to parameterize the impacts of climate, fuel availability, and human activities on wildfire probabilities, frequencies, and burned areas. FLAM uses daily climate data for temperature, precipitation, wind, and relative humidity. It´s modular structure allows for the inclusion of additional fire-related variables such as distance to roads, cropland, lakes, slope, and elevation. The model is therefore adaptable to unique regional characteristics such as traditional practices of agricultural burning, forest clearing, or peatland draining. Eventually this will allow for the production of integrated regional hot-spot maps for wildland fire risk. One case study implemented with FLAM focussed on current wildland fire patterns and challenges in Europe (Fernandez-Anez, N. et al. 2021).

Other technologies are available to assist forest managers in predicting disturbance risks into the future under different climate and forest management scenarios. Examples include a variety of sophisticated models that simulate disturbances and their interactions with forest dynamics for millions of trees or thousands of pixels across entire landscapes (see, for example, Seidl et al. 2012, Kruhlov et al. 2018). Combining these technologies will give institutions, scientists, and forestry practitioners advanced capabilities, allowing them to better anticipate, plan, and respond to disturbances. Perhaps even more importantly, disturbance prediction capabilities will help forest managers strategically plan the type and spatial configuration of forest restoration and adaptive silvicultural interventions used to reduce or limit disturbance risks, such as efforts to increase forest landscape heterogeneity.

As important as disturbance risk prediction is enhancing the capacity to manage and respond to emerging threats, such as the growing forest fire risk in some parts of the Carpathian region. Carpathian counties are expanding these capabilities through a variety of funding mechanisms and cooperative programs. These include the European Union's initiatives to assist Member States in forest fire prevention (rather than suppression) and cooperative programs between the United States Forest Service and variety of a ministries and stakeholders in Ukraine to improve forest fire management capacity through training and acquisition of fire-fighting resources.

CARPATCLIM – CLIMATE OF THE CARPATHIAN REGION

CARPATCLIM (2010-2013) had brought together 10 research institutes from Austria, Croatia, Czechia, Hungary, Poland, Romania, Serbia, and Ukraine with funding from the European Commission to *"improve the basis of climate data in the Carpathian Region for applied regional climatological studies such as a Climate Atlas and/or drought monitoring, to investigate the fine temporal and spatial structure of the climate in the Carpathian Mountains and the Carpathian basin with unified methods"*[37] . Assessing the 1961 to 2010 timeframe, its three work modules produced a comprehensive understanding and homogenization of climate data for the Larger Carpathian Region, publishing these as online Atlases, gridded climatologies, publicly available datasets, and drought monitoring. As such, the resources CARPATCLIM made available online remain a vital resource for climate impact assessment, forecasting, and planning. The project remains a model for region-wide monitoring based on data sharing and standardization.

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[34] See https://gedi.umd.edu/
[35] See https://modis.gsfc.nasa.gov/data/dataprod/mod14.php
[36] See https://rea.ec.europa.eu/news/eu-funded-projects-helping-fight-forest-fires-2022-08-09_en
[37] See http://www.carpatclim-eu.org/pages/about/

6. CONCLUSIONS / RECOMMENDATIONS

The Carpathian Mountains are a region of significant ecological and cultural importance, which is under threat from climate change and anthropogenic disturbances. The impacts of climate change on forests in the Carpathian Mountains are expected to lead to changes in forest composition, structure, and function, as well as potential feedbacks to the climate system. To address these impacts, a range of adaptation and mitigation strategies have been proposed, which aim to reduce the vulnerability of forest ecosystems to climate change and reduce greenhouse gas emissions from forest management activities. The implementation of these strategies will require cooperation and coordination among stakeholders, including forest managers, policymakers, and local communities.

The vulnerability of Carpathian forests to climate change poses significant challenges to the ecological and socio-economic functions, as well as to the livelihoods of forest-dependent communities. However, through adaptive forest management practices, cross-boundary collaboration, stakeholder engagement, and the integration of local knowledge, Carpathian forests can become more resilient and better equipped to cope with the impacts of climate change. Addressing research gaps and improving long-term monitoring and data availability can also help inform evidence-based adaptation strategies, while ensuring that policies and frameworks explicitly consider climate change impacts in long-term planning and regional coordination.

The following highlights opportunities and pathways in this regard as well as further research needs for evidence-based decision-making.

6.1 OPPORTUNITIES AND PATHWAYS

Given the unique ecological and socioeconomic characteristics of the Carpathians, there are several key pathways to further consider for climate-resilient forest management practices. Fostering collaboration and transboundary cooperation among the Carpathian countries will be vital for effective climate change adaptation in forestry, especially through sharing knowledge and experiences with various approaches and developing pathways for addressing common challenges.

Considering the history of deforestation in the Carpathians, one key pathway is to focus on **forest restoration and reforestation** efforts. This involves restoring degraded forest areas, establishing new close-to-nature forests, promoting natural regeneration of forests, converting planted monocultures to the site-endemic and/or future-adapted species compositions, and protecting and reintroducing rare native tree species in their natural ecosystem, following single or a combination of adaptation response options outlined in chapter 5.

Protecting and conserving natural forests in the Carpathians is crucial for climate change adaptation. Establishing and effectively managing protected areas, national parks, and nature reserves helps preserve intact forest ecosystems, maintain biodiversity, and provide refuges for species. These protected areas also contribute to carbon sequestration and storage.

Enhancing forest landscape connectivity will be vital for allowing species to migrate and adapt to changing climate conditions. This can be achieved through the creation of ecological corridors, which connect fragmented forest patches, enabling species movement and facilitating gene flow. Conserving and restoring riparian zones can also enhance connectivity and provide climate refugia for species.

Managing for diverse landscape composition and structure will help make forest ecosystems more resilient to disturbances, particularly bark beetles and other insect pests as well as fungal pathogens. Increasing the heterogeneity of forest patches both within stands and across landscapes limits contagion and dampens the ability of insects to disperse and colonize new host trees.

Adopting **ecosystem-based adaptation** involves recognizing and harnessing the benefits provided by intact ecosystems and promoting sustainable livelihoods in an inclusive approach. This includes conserving and restoring wetlands, protecting carbon-rich forest ecosystems, coordinated invasive species control, and integrating nature-based solutions such as green infrastructure and natural water retention measures as blue infrastructure.

Incorporating **traditional and local knowledge** can provide valuable insights into forest dynamics, species behavior, and ecosystem responses to climate change. **Community involvement** also promotes local ownership, improves livelihoods, and fosters sustainable forest practices.

Forest Fire Management, Prevention, and Restoration: As climate change increases the risk of high intensity forest fires in the Carpathians, implementing effective forest fire management and prevention measures is critical. This pathway involves developing national and regional early warning systems, improving fire suppression capabilities, and promoting community-based fire management approaches. Ensuring adequate resources and training for forest fire management is essential to mitigate the impacts of wildfires on forests and communities. In forest types where low intensity fires were historically an important part of the natural disturbance regime, silvicultural techniques like fuels treatment and prescribed burning will be useful to restore stand structures that will once again support beneficial ground fires, while limiting the spread of crown fires.

Promoting **sustainable wood utilization and developing value chains for forest products** can enhance the economic viability of forests while supporting climate change adaptation. This pathway involves encouraging responsible harvesting practices, supporting local processing industries, and promoting the use of sustainably sourced wood products.

Sustainable Forest Practices and Certification: Adopting sustainable forestry practices, such as selective logging and reduced impact logging techniques, help minimize ecosystem disturbance and maintain forest health. Certification for sustainable forest management may improve market access and support livelihoods. Experience has been mixed as to whether certified wood products are able to generate price premiums.

Education and Capacity Building: Building the capacity of forest managers, policymakers, local communities, and relevant stakeholders is a key pathway for climate change adaptation. This includes providing training, education, and awareness campaigns to enhance understanding of climate change impacts, adaptation strategies, and the importance of sustainable forest management.

Harmonized monitoring of climate forecasts, disturbance risks, and biodiversity threats will help the region coordinate a variety of adaptation measures, both conservation oriented and responsive to new threats as they arise.

6.2 KNOWLEDGE GAPS AND RESEARCH NEEDS

A major research need with the region is improved regional-scale forest monitoring. Forest monitoring currently is primarily the purview of ministries and research institutions within individual Carpathian countries. Consequently, the region lacks a coordinated monitoring network, important for forecasting and responding to vulnerabilities, such as forest fire risks, as they develop. One such initiative was the CARPATCLIM project, a joint initiative to develop standardized climatological databases for the Carpathian region. Concluded in 2010 (see above), the initiative provided a model that could be extended to other areas of importance within the forest sector, such as disturbance risks, biodiversity, and forest health. Critical questions remain to be resolved, such as the priorities for regional monitoring, their relative value, and their scope. Clear benefits to the region – for climate forecasting, planning, conservation, and adaptation – would need to be established.

If monitoring were further coordinated to enable standardization of monitoring parameters and data at the regional level, it would facilitate both joint adaptation efforts, such as multilateral plans for assisted species migration, and enable comparison of research results across the Carpathian ecoregion (Grodzki et al., 2018). Regional forest monitoring could be expanded to include additional layer and indicators for forest ecosystem dynamics under climate change, including shifts in forest disturbances, structure, species distribution patterns, and ecosystem functioning. Furthermore, forest ecosystems can exhibit ecological thresholds, beyond which they may experience rapid and irreversible changes in structure and function. However, our understanding of these thresholds and the conditions that trigger them is limited and should be further investigated and monitored.

Another area for additional knowledge generation concerns the importance of genetic diversity in forest ecosystems for adaptation. This involves studying the genetic characteristics of tree species, assessing the adaptive potential of different genetic lineages, and investigating how genetic diversity influences ecosystem resilience and productivity.

There is also a need for more comprehensive research on how different tree species and forest ecosystems respond to changing climatic and soil conditions. This includes understanding the physiological and phenological responses of trees, as well as the interactions between species and their environment. While some research has been conducted on the adaptive capacity of forests, there are still knowledge gaps in understanding the mechanisms by which forests can adjust their composition, structure, and functioning to changing conditions, as well as the limits to their adaptive capacity.

Further research would also be needed for assessing the effectiveness of various adaptive silviculture practices in Carpathian forests. This includes evaluating the effects of different adaptation approaches (such as outlined in chapter 5) on forest resilience, productivity, biodiversity and socio-economic factors. Long-term monitoring of adaptive practices will also be important to continuously (re-)evaluate their success. Research is further needed to investigate the interactions and synergies among different adaptation options. Understanding how different approaches can complement or conflict with each other is crucial for optimizing adaptation strategies and avoiding unintended consequences.

Another critical knowledge gap relates to understanding the socio-economic dimensions of adaptation in forestry. This includes assessing the economic viability and costs associated with different adaptation approaches, understanding the social acceptability and equity implications of adaptation interventions, and considering the impacts of adaptation on local communities and livelihoods. On the latter, more research and case studies are needed to foster the integration of traditional ecological knowledge into adaptation strategies, recognizing the importance of local communities' perspectives, practices, and governance systems in sustainable forest management.

Closing these knowledge gaps will improve our understanding of climate dynamics and adaptation in forestry and enable the development of effective and context-specific strategies to enhance the resilience of forest ecosystems to climate change. Collaboration between researchers, practitioners, landowners, and stakeholders is crucial to address these gaps and ensure that adaptation efforts are science-based, practical, and inclusive.

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8. ANNEXES

8.1 ANNEX 1: NOMINATED EXPERTS SUPPORTING THE ASSESSMENT

Expert Group for the development of the assessment of climate risks and adaptation options for Carpathian forest ecosystems and their services

Below experts were nominated by the Carpathian Convention Parties based on the CC NOTIFICATION 2021 - 7 – Requesting nomination of experts to be involved in the climate change assessment / special session at the Forum Carpaticum 2022 /Working Group Climate Change + Working Group Forest.

Country	Name of nominated expert and organization
Czech Republic	Mr. Miroslav Svoboda, Ph.D., Czech University of Life Sciences Prague
	Ms. Eliška Rolfova, Ministry of the Environment of the Czech Republic
	Mr. Radek Pokorný, Mendel University in Brno
Hungary	Ms. Borbala Galos, University of Sopron.
	Ms. Imelda Somodi, Centre for Ecological Research,
Poland	Mr. Bożydar Neroj, Bureau for Forest Management and Geodesy
	Mr. Wojciech Grodzki, Forest Research Institute
	Ms. Małgorzata Czyżewska, Directorate General of the State Forest of Poland.
Romania:	Mr. Laurentiu Radu, Ministry of Environment, Waters and Forest,
	Ms. Liliana Virtopeanu, Ministry of Environment, Waters and Forest of Romania.
	Mr. Borz Stelian Alexandru, Transilvania University of Brasov, Department of Forest Engineering
	Mr. Păcurar Victor Dan, Transilvania University of Brasov
	Mr. Sorin Cheval, National Meteorological Administration of Romania
	Mr. Popa Ionel, Forest Research and Management Institute, Romania
Slovakia:	Mr. Libor Ulrych, State Nature Conservancy of Slovak Republic
Serbia:	Ms. Ilija Dordevic, Institute of forestry, Department for spatial planning, GIS and forest policy, Assistant director for international cooperation
Ukraine:	Ms. Liubov Poliakova, Head of International Cooperation, Science and Public Relation Division, State Forest Resources Agency
	Mr. Volodymyr Korzhov, Deputy Head of Ukrainian Scientific Institute of Mountain Forestry.
Coordinators:	Mr. William Keeton, University of Vermont and Member of the Science for the Carpathians
	Ms. Sabine McCallum, Senior Strategic Advisor and Climate Change Expert – UNEP-SCC
	Ms. Klaudia Kuras, Carpathian Convention Coordination Expert, UNEP-SCC

8.2 ANNEX 2: SURVEY

INTRODUCTION

The Carpathian Convention Conference of the Parties at its 6th meeting (COP6, 2020) through its decisions[38] encouraged the development of an **assessment of the impacts of climate change on the Carpathian forests and their ecosystems services** by relevant Convention Working Groups and partners and with support of the Convention Secretariat. Subsequently, this activity has been included in the Implementation Framework 2030 accompanying the Long-term Vision towards combating climate change in the Carpathians.

This survey aims to gather information for developing the **assessment of climate change risks and impacts on Carpathian Forest ecosystems and their services** along a draft table of contents (see Annex) that has been presented and agreed at the 1rst Expert Workshop on 16 November 2021 (online).

There are **4 sections** of the survey:

A: CONTACT and CONTRIBUTORS
B: KNOWLEDGE BASE on CLIMATE CHANGE RISKS and IMPACTS on CARPATHIAN FOREST ECOSYSTEMS and their services
C: PRACTICAL EXAMPLES / CASE STUDIES
D: REFERENCES

The Secretariat of the Carpathian Convention together with Dr. William Keeton, University of Vermont and Member of the Science for the Carpathians, highly appreciates your willingness to contribute to assessment by sharing your insights and expertise through this survey. We would also encourage you to consult with national colleagues for further contributions.

Please return the filled in survey until **28.01.2022**. Many thanks in advance for your valuable inputs!

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[38] DECISION COP6/13 Sustainable forest management Article 7 of the Carpathian Convention

Para 5. Appreciates the strengthened cooperation between the WG Forest and the WG Climate Change and WG Biodiversity, facilitating the implementation of Article 14 of the Forest Protocol, welcomes the idea of collecting information from the Parties with the goal of assessing the impacts of climate change on the Carpathian forests and their ecosystem services, including, if possible, climate change effects on large carnivores and their habitats, in that regard recognizes the complexity of the issue and wide range of ecosystem services Carpathian forests provide to the society, and requests the relevant Working Groups and partners to support the development of such assessment, and the Secretariat to facilitate the process;

DECISION COP6/18 Climate Change Article 12bis of the Carpathian Convention
Para 8. Specifically encourages the WG Forest and the WG Biodiversity and partners to jointly further develop with the WG Climate Change an assessment of the impacts of climate change on the Carpathian forests and their ecosystems services, including, if possible, climate change effects on large carnivores and their habitats, and requests the Secretariat to facilitate the process.

SECTION A. CONTACT AND CONTRIBUTORS

* 1. Contact details

Name:
Click or tap here to enter text.

Institution you represent:
Click or tap here to enter text.

Type of institution:
Choose an item.
If you chose Other, please specify below:
Click or tap here to enter text.

Gender:
Choose an item.

Email Address:
Click or tap here to enter text.

* 2. country

This survey will ask you a series of questions about a particular country where you operate. We appreciate that you may work in multiple locations, so please indicate one below that you will discuss here.

Please use the dropdown list below to select the country:
Choose an item.

* 3. CONTRIBUTORS

You may want to list colleagues that contributed to filling in this survey and shall be acknowledged:
Name:
Click or tap here to enter text.
Institution
Click or tap here to enter text.

SECTION B. KNOWLEDGE BASE ON CLIMATE CHANGE RISKS AND IMPACTS ON CARPATHIAN FOREST ECOSYSTEMS AND THEIR SERVICES

* 1. Key risks and impacts

For distinguishing between risk and impacts, we are using the concepts of how the IPCC assesses and communicates to decision-makers:

The 'core' definition of **risk** is "**the potential for adverse consequences**":

- The word "potential" makes clear that uncertainty, or more broadly, incomplete knowledge (as defined in IPCC), is a key element of the concept of risk.
- In IPCC use, risk refers only to negative ("adverse") consequences[39].

The term **impact** is used to describe the consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability.

- Impacts may be referred to as consequences or outcomes occurring within a specific time period.
- Impacts can be adverse or beneficial.[40]

From your experience, please indicate the main risks and potential impacts along the identified key topics:

FOREST GROWTH AND PRODUCTIVITY

Key risk	Potential impacts (consequences, outcomes)

BIOMASS AND CARBON STOCKS

Key risk	Potential impacts (consequences, outcomes)

[39] https://www.ipcc.ch/site/assets/uploads/2021/02/Risk-guidance-FINAL_15Feb2021.pdf
[40] https://apps.ipcc.ch/glossary/

Key risk	Potential impacts (consequences, outcomes)

TREE MORTALITY

Key risk	Potential impacts (consequences, outcomes)

CHANGES IN SPECIES RANGE, HABITAT SHIFTS AND ABUNDANCE

Key risk	Potential impacts (consequences, outcomes)

INVASION BY NON-NATIVE SPECIES

Key risk	Potential impacts (consequences, outcomes)

FOREST ECOSYSTEM SERVICES

Key risk	Potential impacts (consequences, outcomes)

FOREST – WATER INTERACTIONS, INCLUDING HYDROLOGIC REGULATION AND RIPARIAN DYNAMICS

Key risk	Potential impacts (consequences, outcomes)

* 2. Adaptation responses

From the key risks and impacts identified under B.1, please indicate adaptation response options that you aware of and briefly highlight their intended effects for each key topic. Please note that there is an additional possibility to share adaptation response options that are cross-cutting in tackling more than one of the key topics.

FOREST GROWTH AND PRODUCTIVITY

Please indicate adaptation response options addressing the key risks and impacts mentioned above:

Name / Key word	Main Impact/Risk addressed	Brief description	Intended effect	Pros and cons (if any)

BIOMASS AND CARBON STOCKS

Please indicate adaptation response options addressing the key risks and impacts mentioned above:

Name / Key word	Main Impact/Risk addressed	Brief description	Intended effect	Pros and cons (if any)

TREE MORTALITY

Please indicate adaptation response options addressing the key risks and impacts mentioned above:

Name / Key word	Main Impact/Risk addressed	Brief description	Intended effect	Pros and cons (if any)

CHANGES IN SPECIES RANGE, HABITAT SHIFTS AND ABUNDANCE

Please indicate adaptation response options addressing the key risks and impacts mentioned above:

Name / Key word	Main Impact/Risk addressed	Brief description	Intended effect	Pros and cons (if any)

INVASION BY NON-NATIVE SPECIES

Please indicate adaptation response options addressing the key risks and impacts mentioned above:

Name / Key word	Main Impact/Risk addressed	Brief description	Intended effect	Pros and cons (if any)

Name / Key word	Main Impact/Risk addressed	Brief description	Intended effect	Pros and cons (if any)

FOREST ECOSYSTEM SERVICES

Please indicate adaptation response options addressing the key risks and impacts mentioned above:

Name / Key word	Main Impact/Risk addressed	Brief description	Intended effect	Pros and cons (if any)

FOREST – WATER INTERACTIONS, INCLUDING HYDROLOGIC REGULATION AND RIPARIAN DYNAMICS

Name / Key word	Main Impact/Risk addressed	Brief description	Intended effect	Pros and cons (if any)

CROSS-CUTTING

Name / Key word	Impacts / Risks addressed	Brief description	Intended effect	Pros and cons (if any)

Name / Key word	Impacts / Risks addressed	Brief description	Intended effect	Pros and cons (if any)

ADDITIONAL FOCUSED QUESTIONS DERIVED FROM THE EXPERT DISCUSSION

Please provide your thoughts on the following topics regarding **specific adaptation response options** raised at our first Expert Workshop on 16 November 2021. In case you already covered one or more of these additional questions, please refer to the respective section above.

Planting and management of exotic species.
Should use of exotic, non-European species comprise an element of adaptative management? Where, when, and how?

Click or tap here to enter text.

Role of landscape level planning, including a diversity of forest zonation and management strategies.
What is your view on the role of protected areas vs. active adaptive management?

Click or tap here to enter text.

Expanded use of "close-to-nature" silviculture (e.g., selection harvesting, continuous cover forestry, retention forestry, etc.).
How is the forest sector in your country considering broadening its portfolio of forest management practices to adapt to climate change, including altered disturbance regimes?

Click or tap here to enter text.

Forest road density, design, and location.
How should forest road systems be managed to reduce vulnerabilities to flooding?

Click or tap here to enter text.

Long-term adaptive forest management objectives.
Should we manage for the historic, current, or future potential vegetation? How is the forest sector in your country approaching these challenging questions?

Click or tap here to enter text.

Public policy, perception, and science.
What are the greatest challenges you face relating to formulating adaptation responses, given the interplay between public perception and public policy that may or may not always be consistent with the science?

Click or tap here to enter text.

Forest harvest rotations.
Is the forest sector in your country considering reducing or increasing forest harvest rotations? Why or why not?

Click or tap here to enter text.

Adaptation to altered natural disturbance regimes.
How is the forest sector in your country adapting to increasing risks of bark beetles, wind, fire, and drought?

Click or tap here to enter text.

Mix of old vs. younger forest stands.
How is the forest sector in your country adjusting the mix of forest ages as adaption to disturbance risk, for the purpose of carbon management, or to conserve biodiversity in the face of climate change?

Click or tap here to enter text.

* 3. Further opportunities and pathways

If you are aware of any further unused potentials and opportunities for effective adaptation responses / pathways (e.g., in other countries/mountain regions), please briefly describe:

Click or tap here to enter text.

Please specifically outline possible approaches and pathways you know focusing on inclusive ecosystem restoration using Nature based Solutions (NbS) and Ecosystem based Adaptation (EbA):

Click or tap here to enter text.

* 4. **Key initiatives**

Please share ongoing relevant initiatives / larger scale projects in your country / the Carpathian region / elsewhere:

IN YOUR COUNTRY

Name of the initiative /project	Duration of implementation	Brief description	Weblink (if available)	Contact for further information

IN THE CARPATHIAN REGION

Name of the initiative /project	Duration of implementation	Brief description	Weblink (if available)	Contact for further information

ELSEWHERE

Name of the initiative /project	Duration of implementation	Brief description	Weblink (if available)	Contact for further information

Name of the initiative /project	Duration of implementation	Brief description	Weblink (if available)	Contact for further information

* 5. Limitation and barriers to overcome

From your experience, please highlight the most common limitations and barriers to overcome for developing and implementing effective adaptation responses. These could potentially link to policy frameworks, shortcomings with financing for implementation, cross-border cooperation, etc.

Click or tap here to enter text.

* 6. Knowledge gaps and research needs

In your opinion, where do we still have major knowledge gaps and thus research needs toward better informed decision-making for forest ecosystem climate change adaptation?

Please indicate in which areas you see knowledge gaps and research needs and briefly explain why:

Knowledge gap	Research need	Brief explanation

SECTION C. PRACTICAL EXAMPLES / CASE STUDIES

Within this section we aim to collect practical examples that could be showcased as promising approaches with upscaling potential to other countries/regions.

As a general orientation for considering practical examples to share, please reflect the following aspects[41]:

KEY DIMENSIONS TO QUALIFY FOR A MOUNTAIN ADAPTATION SOLUTION

- ☑ Relevant

  The solution addresses one or more current or anticipated mountain-specific climate change risks and provides a promising approach to becoming effective[1] in tackling the issue at stake. In this regard, the solution is based on scientific evidence and/or traditional knowledge and practices.

- ☑ Practical and feasible

  The solution can be implemented on relevant timescales to address the risks in question, is realistic in terms of resources available (human and financial) and tailored to the actors and their capacities needed for implementation and is sustainable in the longer term (both human capacities and financial resources can realistically be maintained).

- ☑ Direct benefits and co-benefits

  The solution promotes ecological, economic and/or social benefits. It shows synergy with and offers co-benefits to climate change mitigation and other sustainable mountain development topics, such as eradication of poverty, averting unemployment, provision of humanitarian aid in case of conflict or disasters, universal health coverage and education, achieving gender equality and empowering women and girls.

- ☑ Flexible and robust

  The solution is designed in a way that allows for adjustments and incremental implementation and reiteration depending on the level and degree of climate change, i.e. allows for adaptive management and responds to multiple interests and purposes. Thus, the solution is robust in terms of maintaining its effectiveness under a range of different climatic and socio-economic development scenarios. In doing so, the solution should ideally have built-in mechanisms to enable its monitoring and evaluation of time.

- ☑ Replicable and/or scalable

  The solution including its enabling factors has the potential for adjustment, replication or upscaling in other geographic, social or sectorial contexts (even though as such customized and tailored to specific local circumstances).

- ☑ Legitimate and coherent

  The solution is politically, culturally, and socially accepted. The solution is not in conflict with other adaptation or sustainable development efforts and coherent with existing or planned policies on local, regional and national level (please note that this does not translate into a requirement that the solution is already integrated in a local, regional or national policy!)

[41] These key dimensions are being used under the Adaptation at Altitude programme for gathering and selecting mountain adaptation solutions in South Caucasus and East Africa.

Please share **one or more** promising adaptation approaches from your country that are already in the process of being implemented describing them along the following simple structure. For sharing more than one case study please simply copy the text box below:

Name of the practical example / case study:
Click or tap here to enter text.

Description:

- The issue

Short description of the issue to be tackled, which specific related risk/s and impacts are or were being addressed and what the *evidence base /need* for developing this adaptation response in this particular area is. [responding to the dimension of *Relevance*]

- Click or tap here to enter text.

- The solution
- Detailed description of the solution in response to the issue at stake: Short background why the approach has been chosen for addressing the specific mountain-related risk/s and how it has been designed for effective implementation in the geographical location. If applicable, reference shall be made to necessary enabling factors that contribute to the solution´s success such as social inclusion, women empowerment, taking account of the broader socio-economic context, securing political commitment and financing. The description shall also include the time planned for implementing the solution in this area, built-in mechanisms for evaluation and feedback-loops, room for adjustment if needed and the timescale for which the solution is planned to last.
  [responding to the dimensions of Practical and efficient; Flexible and robust]
-
- Click or tap here to enter text.

- Coverage and Impact
- Brief summary of the main effects adverse which are already evident through implementing the solution, including reference to all areas where the approach provides impacts at the moment of writing the text. A portrait of a beneficiary or a project "owner" will give a more personal aspect to the text. The text can be supported by further elements **such as graphs and photographs to better explain the impact of the solution.**
  [responding to the dimensions of Direct benefits and co-benefits; Legitimate and coherent]
-
- Click or tap here to enter text.

- Applicability
- Short description about the potential to upscale, replicate or transfer this solution in a different context or continent. In particular, the context specificity but also characteristics of the location are relevant factors for the transferability and scalability of a solution.
  These factors include, inter alia, the social and cultural context in which the solution is implemented (e.g. the solution responds to gender-differentiated vulnerabilities, is socially accepted and generally compatible with mountain livelihoods systems), characteristics of beneficiaries of the solutions (e.g. in terms of risk aversion, capacity building towards increasing climate resilience), possibly technology characteristics (e.g. costs, familiarity, perceived usefulness, profitability, co-benefits and/or 'no regrets' potential), the policy environment and other transfer mechanisms such as incentives. Referring to the specific location the solution is being implemented, similar climatic and geophysical factors may also be a precondition for a solution to achieve a similar outcome in a different geographical region.
  [responding to the dimension of Replicable and/or scalable]
-

Click or tap here to enter text.

SECTION D. REFERENCES AND ADDITIONAL INFORMATION

* 1. References and further information

Please use this section to share further references and additional information that you see relevant for the assessment (from your country / from the Carpathian region / from elsewhere).

FROM YOUR COUNTRY

Click or tap here to enter text.

FROM THE CARPATHIAN REGION

Click or tap here to enter text.

FROM ELSEWHERE

Click or tap here to enter text.

* 2. Final comments

Please add any other comments or thoughts you would like to share here regarding climate change vulnerabilities and adaptation in forest ecosystems in your country or for your institution.

Click or tap here to enter text.