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Reporting on forest damages and disturbances in the UNECE region

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FOREWORD

The frequency and intensity of wildfires, storms and pest outbreaks has been increasing rapidly for several decades, highlighting the vulnerability of the world's forests and the impact of natural and human threats accelerated and intensified by climate changes.

Although disturbance and mortality are inherent to forest ecosystems, and forest disturbance has always been a concern in forest management, monitoring the extent of damage has become a key priority in recent decades.

Forests are vital carbon sinks for climate change mitigation and reservoirs of global biodiversity. This makes reliable information, data and accurate reporting of damage and disturbance even more important for effective policies ensuring the sustainable management of forests.

To ensure that this critical information is available to all, UNECE and FAO have summarized in this publication the main dynamics and significance of forest damage, and their reporting in the UNECE region.

Understanding the scales, patterns, causal factors, and the need for accurate monitoring is vital in addressing current and future challenges for forest management. Global and regional reporting, such as the FAO Forest Resources Assessment (FRA) and the Joint UNECE/FAO/Forest Europe Pan-European Data Collection on Forests and Sustainable Forest Management (JPEDC), takes a central role as the source of information on forest damage and disturbance.

The publication invites readers to reflect on possible harmonized methodologies and reporting schemes. In this regard, it also underlines the collective effort that is essential for the forest sector.

Real-world scenarios, such as the analysis of forest damage and disturbance data, require state-of-the-art techniques beyond the usual statistical evaluation. Innovative technologies highlighted in this publication such as remote sensing, artificial intelligence and machine learning will need to be integral parts of any advances in forest damage assessment.

This publication is an important step towards improving international reporting on forest damage and the result of a collaborative effort of national and international experts, supported by the secretariat. We would like to express our gratitude to the authors and contributors, as well as governments that supported this process.

Reporting on forest damage is not just a technical exercise. It is a critical element of our shared commitment to biodiversity, climate resilience and livelihoods. Supporting comprehensive reporting will lay the foundation for safeguarding forest ecosystems for future generations.

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The study on forest damage/disturbance in the UNECE region is a joint effort of authors, members of the UNECE/FAO Team of Specialists on Monitoring Sustainable Forest Management and the secretariat, and is based on information provided by national focal points in topical surveys, other literature and data.

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ACRONYMS, ABBREVIATIONS AND SYMBOLS

(Infrequently used abbreviations spelled out in the text may not be listed here)

BFAST	Breaks for Additive Seasonal and Trend
C&I	Criteria and Indicators
CCDC	Continuous Change Detection and Classification
CESBIO	Centre d'Etudes Spatiales de la Biosphère (France)
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
DEFID2	Database of European Forest Insect and Disease Disturbances
DFDE/ DFDE2	Database on Forest Disturbances in Europe
ECMWF	European Centre for Medium-Range Weather Forecasts
EFFIS	European Forest Fire Information System
FAO	Food and Agricultural Organization of the United Nations
FIA	Forest Inventory Assessment
FORWIND	Database of Wind Disturbances in European Forests
FRA	Forest Resources Assessments
GEDI	Global Ecosystem Dynamics Investigation
GEE	Google Earth Engine
GHG	Greenhouse Gas
GIS	Geographical Information System
HLS	Harmonized Landsat and Sentinel-2
HPC	High-Performance Computing
ICP Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
IDS	Insect and Disease Survey (USA; Forest Service)
JPEDC	Joint Pan-European Data Collection
JRC	Joint Research Centre (European Commission)
JUST	Jumps Upon Spectrum and Trend
Lidar	Light Detection and Ranging
LTS	Landsat Time Series
LandTrendr	Landsat-based Detection of Trends in Disturbance and Recovery
MODIS	Moderate Resolution Imaging Spectroradiometer
MTBS	Monitoring Trends in Burn Severity (USA)
NAFD(-ATT)	North American Forest Dynamics (-Attribution)
NASA	National Aeronautics and Space Administration (USA)
NBR	Normalized Burn Ratio
NCEI	National Centers for Environmental Information (USA)
NDVI	Normalized Difference Vegetation Index
NFI	National Forest Inventory
NIFC	National Interagency Fire Center (USA)
NLCD	National Land Cover Data (USA)
PRISMA	Precursore IperSpettrale della Missione Applicativa
Radar	Radio Detection and Ranging
SAR	Synthetic Aperture Radar
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
SFM	Sustainable Forest Management
SoEF	State of Europe's Forests (report)
ToS	Team of Specialists (UNECE/FAO)
UNECE	United Nations Economic Commission for Europe
USA	United States of America
USDA	United States Department of Agriculture
VCT	Vegetation Change Tracker
VeRDET	Vegetation Regeneration and Disturbance Estimates through Time

EXECUTIVE SUMMARY

Background

Forest health and vitality are fundamental requirements for forest durability and resilience, and forests' ability to provide multiple essential ecosystem services to society. Temporary or locally limited loss of vitality of individual trees is a normal and non-detrimental phenomenon in forest ecosystems. However, the health of forests becomes critical when large areas deteriorate, or when the deterioration persists beyond the natural recovery time. In the 1980s and 1990s, forest dieback in the United Nations Economic Commission for Europe (UNECE) region caused great concern. The subsequent implementation of air pollution control measures by member States gradually improved forest conditions, restoring the vitality and health of forest ecosystems in the region.

Nevertheless, droughts, fires, storms and insect infestations continued to cause large-scale tree mortality in forest ecosystems. Since the late 2010s, an increased number of reports have concluded that the vitality and health of forests are once again an area of concern. These losses of vitality and health are associated with several consecutive periods of drought, which are known to weaken trees and increase the vulnerability of forests to other damage agents.

The consequences of these losses of vitality and health are striking. Forests are struggling to provide the entire range of their ecosystem services and landscapes are altered by the wide-ranging mortality of forests. Timber markets are in economic distress owing to the massive accumulation of salvage timber, forest owners lose their livelihoods and forest tourist regions lose attractiveness.

While the resilience of forest ecosystems as well as their protective function is weakened, the risk of other natural hazards such as fires, flooding or erosion is increasing, also leading to a decrease in carbon storage. Consequently, forests are no longer an ensured sink for atmospheric carbon dioxide (CO_2) and might become a source of CO_2. Current forest damage might increase further by anticipated climate changes resulting in a loss of vitality and health that may well exceed everything experienced to date.

Strengthening ecosystem resilience and adapting forests to climate change requires action at the local, regional and global level. International reporting of forest data should not only provide the necessary information but also must be adapted over time to the forest conditions, hazards, technology and societal demands. Therefore, the question arises whether the current systems in international reporting can address these challenges. This UNECE study on assessing forest damage and disturbance monitoring in the region addresses this question by critically analysing the present international reporting systems, while revealing gaps and identifying opportunities for improvement.

Distinction of forest damage and disturbance

Forest damage is the reduction of health and vitality of individual trees, stands, and forest habitats and biomes. It can be caused by biotic agents such as insects, fungi, diseases, wildlife or grazing livestock. Damage can also be caused by abiotic phenomena such as wind, drought or snow. Forest damage can also be human induced, ranging from large-scale industrial pollution to local factors such as forest operations. Forest fires occupy a special position since they can occur naturally or as an intentional or accidental result of human activities.

Serious losses of ecosystem vitality and health are often synonymously referred to as damage or disturbance. However, there is a significant difference between the two terms:

a) Disturbance is ostensibly value-neutral;

b) Damage involves the interpretation of disturbance information as it relates to negative impacts on human values.

The distinction between damage and disturbance may be relevant for several reasons:

a) Human values associated with forests will vary over space and time and therefore compromise the comparability of damage and disaster risk reduction (DRR) measures taken in different places and time periods, or focused on different outputs;

b) Some level of disturbance is endemic to all forest ecosystems and may be part of their natural or desired development; and

c) Separating damage and disturbance will often require further information, such as the addition of thresholds and/or computational steps, further complicating statistical reporting.

The use of the respective terms depends to a large extent on the perspective from which ecosystem vitality and health are valued, interpreted and assessed. Here, many forest owners primarily consider the economic loss of their assets. The loss of vitality, including extensive dieback, could also be considered an ecologically beneficial event for the restoration of natural habitats and for the adaptation of forest ecosystems to climate change.

The aim of monitoring and reporting is to provide value-free and unbiased information, since their interpretation differs among the respective users. Assuming that information about forest damage in the UNECE region is expected from this reporting, additional knowledge would be needed to separate damage from overall disturbance. Current reporting in the UNECE region, which is based on the causes of damage/disturbance, does not provide this information. Therefore, a rigorous separation of the two terms, however desirable, does not seem to be immediately applicable with regard to the current national reporting, especially since some languages do not distinguish between the two terms. In the project study, the two terms are used synonymously; however more attention should be paid to this aspect in future development of international forest damage/disturbance reporting.

National data assessment

Forest damage/disturbance can be assessed by terrestrial (in-situ) surveys, remote sensing methods or a combination of both. National forest inventories (NFI) are a basic source of information on forest disturbance. In combination with additional information, the NFI data can allow for reporting on damage/disturbance. In the case of large-scale damaging events, such as storms and forest fires, special surveys are often carried out immediately after the damaging event. In some countries, there are also regular phytosanitary monitoring systems that collect data on biotic damage/disturbance.

The observation units for damage/disturbance assessments can be individual trees or forested areas. The various systems differ in terms of the number and type of damage/disturbance causes that are covered, threshold values above which a given measure is reported and the period in which a damage/disturbance event must have occurred to be included in the current survey. While some systems collect data on current damage/disturbance, others are oriented around accumulated values.

Differences in national systems of nomenclature often reflect the importance attached to individual causes of damage/disturbance. Differences in the statistical survey designs used in the different countries play a minor role, as they are generally based on sampling theory and provide unbiased estimates for individual countries.

Current reporting in the UNECE region

International reporting on forest damage/disturbance in the UNECE region is fragmented, with diverse and incomplete data availability of countries, subregions and causes of damage/disturbance. Basic data on forest damage/disturbance is collected by FAO's Global Forest Resources Assessment (FRA); however, there is no regular reporting dedicated to forest damage/disturbance in the UNECE region.

a) Global Forest Resources Assessment reporting on forest damage/disturbance

The Global FRA, published by FAO and carried out in collaboration with the UNECE, has compiled information on forest conditions at the global level since 1946. Currently, the FRA receives data from up to 100 countries on the forest area damaged by fires and data from up to 60 countries for insect damage, diseases and severe weather events. Since 1990, the assessments have been published in five-year intervals, with the FRA 2020 being the latest release.

According to the FRA 2020 results, the most commonly reported damage/disturbance factor in the UNECE region is fire, followed by insects. Damage/disturbance caused by diseases and extreme weather are reported least often. Insects caused the most widespread damage/disturbance (18 million ha), followed by forest fires (11 million ha). The areas affected by diseases (1.4 million ha) and extreme weather (1 million ha) are considerably smaller. The geographical extent of damage/disturbance, however, does not automatically indicate the severity of the impact.

b) Regional reporting on forest damage/disturbance

For Central Asia and the Caucasus, country reports have been prepared with the assistance of UNECE, providing an overview of the state of forests and forest management for the reference year 2020. These reports, except for those of Azerbaijan and Georgia, include more detailed information on forest damage/disturbance (all abiotic and biotic causes, including fire, insects and diseases) as a percentage of total forest area. In Canada, forest damage/disturbance data are organized federally and most often collected by sub-national jurisdictions. At the national level, data are summarized, harmonized and aggregated for international reporting. In the Russian Federation and the United States of America, aggregated national statistics for forest damage/disturbance are reported through various channels, including the national forest inventories. Canada, the Russian Federation, and the United States report forest damage/disturbance in accordance with the Montreal Process Criteria and Indicators (C&I).

In Europe, national data on damage/disturbance are collected by the Joint UNECE/FAO/Forest Europe Pan-European Data Collection on Forests and Sustainable Forest Management and published every five years in the FAO/UNECE topical databases and are also included in Forest Europe´s "State of Europe's Forests" (SoEF) report. Information about forests condition in Europe is also gathered through the ICP Forests programme.

Reporting challenges

Comparable reporting on forest damage/disturbance is challenged by differences in data-collection systems, availability, definitions, accuracy, timeliness, evaluation and interpretation.

The data analysis shows that forest damage/disturbance is reported inconsistently among member States of the UNECE region, making data comparison and interpretation difficult. The main source of information remains national inventories, primarily developed according to national priorities, which include different data-collection systems and monitoring cycles. Therefore, monitoring and reporting on the time and duration of forest damage/disturbance are not uniform in the UNECE region.

The variety of technical approaches in recording severity and type of damage/disturbance, reference information (e.g., forest type, form of ownership) on forest areas affected by damage/disturbance, as well as information about the condition of adjacent areas, hampers more refined international analysis.

Current information needs

A questionnaire for FRA National Correspondents was developed and shared through the project to assess whether the current reporting of FAO and the UNECE satisfies the information needs on forest damage/disturbance. Most of the respondents found the reported damaging agents, a reporting period starting in 1990 with 5-year intervals and the division into regions to be sufficient. However, owing to the high annual variability, there were demands for more frequent, annual damage/disturbance reporting.

No clear picture emerged about the need to introduce common thresholds, e.g. of certain minimum amounts of damaged areas, damaged timber volumes or financial losses to be reported as damage/disturbance. A threshold based on national needs was preferred. A distinction between areas affected by one or more causes of damage/disturbance was not considered necessary. Respondents indicated that in addition to the report on areas affected by forest damage/disturbance, the volume of damaged wood should also be included.

Interpreting damage/disturbance data

The interpretation of data can be done from different points of view and is therefore a critical process. For example, tree mortality can be a serious loss of capital for forest owners, while for ecologists it may be a desirable process of natural forest development. The interpretation of data can therefore lead to contradictory assessments.

The interpretation of the damage/disturbance data is an inevitable element of policy and decision-making. However, the interpretation process and related need for additional information is complex. Therefore, the question remains whether international reporting should focus on the presentation of the current state and trends of forest resources, or should include also interpretation from multiple perspectives.

Innovative tools

Understanding and showing the spatial distribution of forest damage/disturbance has always been important. For this purpose, remote sensing systems facilitate the integration of spatially explicit information into the reporting process. Furthermore, the increasing diversity of remotely sensed data sources, combined with an ever-expanding data archive, makes it possible to evaluate historical damage/disturbance trends of forested locations over decades.

Nevertheless, integrating remote sensing data into international reporting poses several challenges. Owing to the considerable areas that must be analysed for reporting, particularly when assessing damage/disturbance trends and patterns through time, the substantial computational effort requires cloud computing platforms and workflows instead of isolated solutions. Artificial intelligence (AI) approaches are increasingly available to evaluate complex, multisource data sets. To assess the accuracy of the damage/disturbance maps and incorporate them into the interpretations, reliable accuracy assessments are required. Remote sensing data provide only a limited view of damage/disturbance symptoms that can be recognized over a wide area but cannot necessarily determine the causes of these symptoms. While a dead tree can be identified, a definitive statement about the reasons for its death is seldom possible using only remote sensing data. Here, combinations of additional data sets, technologies and methods of data analyses open new possibilities to provide an overall picture.

Conclusions

Various conclusions for future international reporting can be derived from the project and the prepared study. The increase of country responses to international reporting on forests and better integration of national assessments is urgently needed. For this purpose, relevant international data-collection systems should be refined, ideally in close connection with the adjustments of national systems.

Although current reporting already covers a large part of the information needs, improvements are desirable. Reporting on forest damage/disturbance enhances timely communication of information for instant decision-making. Therefore, a transition to annual reporting should be considered to cover the most recent damage/disturbance events. The latest developments in forest damage/disturbance are also reflected in the high incidence of salvage timber, which has serious implications for timber markets. Therefore, the volume of salvage timber should be included in the programme of international reporting.

Forest areas that are simultaneously affected by multiple disturbance agents are a reporting challenge, especially in relation to double counting. The development and implementation of proper guidance to avoid double counting is strongly recommended.

International reporting obligations often receive only limited resources in terms of personnel and funding. The increasing importance of forest damage/disturbance for society, the environment and the economy call for a re-evaluation of the current reporting. The increased dedication of resources commensurate with the scale of the problem is urgently needed.

1. Introduction

1. Introduction

Forests provide multiple ecosystem services to society which are directly dependent on the vitality and health of forest ecosystems. In the past decades, the frequency and scale of events leading to large-scale damage/disturbance of forests have been increasing in the UNECE region.

Examples include the forest dieback in Europe in the 1980s, the mountain pine beetle calamity in Canada in the late 1990s, drought and bark beetle damages in Central Europe since 2018, and devastating forest fires in the United States and Canada since the past decade. To some extent this tendency can be attributed to the changing climatic conditions, and it is very likely that the frequency and intensity of climate-induced extreme weather events will increase in the future.

Forest health and vitality are important aspects for assessing the state of forests and their sustainable management. This involves reporting on damage/disturbance that are caused by biotic and abiotic factors and are of natural or human-induced origin. Biotic factors include insects and diseases, wildlife and cattle grazing in forests. Abiotic factors include fire, storm, wind, snow, drought and avalanche. Direct human-induced damage//disturbance can be caused e.g., by illegal activities or carelessness, or is the consequence of indirect effects such as damage/disturbance caused by air pollution. Therefore, information on the current state of and trends in forest damage/disturbance at multiple spatial scales will be essential for effective policy and management response to these challenges (Attiwill, 1994; Gardiner *et al.*, 2013; Johnson *et al.*, 2003; Lertzman and Fall, 1998; Perera and Buse, 2004; Wei and Kimmins, 2012).

Despite the pressing need for additional knowledge about forest damage and disturbance, international reporting on forest damage/disturbance faces serious challenges, making an assessment significantly more difficult. Apparent problems are the lack of data as well as fragmented and/or unharmonized national monitoring systems.

Evidence-based decision-making is in constant need of comparing current information demands with the information provided by international reporting. As forest ecosystem services are endangered by the increase of forest damage/disturbance, the reporting and assessment of biotic, abiotic and human induced forest damage/disturbance in the UNECE region calls for urgent adjustments to meet the current information needs.

The objective of this study is to provide a basis for improved reporting by analysing the current international understanding of forest damage/disturbance reporting, as well as current international reporting schemes. Further, the study contains a detailed analysis of national forest damage/disturbance assessments, highlighting the data that could be available for international reporting.

Finally, the study lists a number of conclusions for improving the information on forest damage/disturbance and the transparent, complete, consistent, comparable and reliable reporting in the UNECE region.

Literature

Attiwill, P. M. (1994): The disturbance of forest ecosystems: the ecological basis for conservative management. Forest Ecology and management, 63, 247-300.

Gardiner, B.; Schuck, A.; Schelhaas, M.-J.; Orazio, C.; Blennow, K.; Nicoll, B. (eds.) (2013): Living with Storm Damage to Forests. What Science Can Tell Us 3. European Forest Institute. Joensuu, Finland

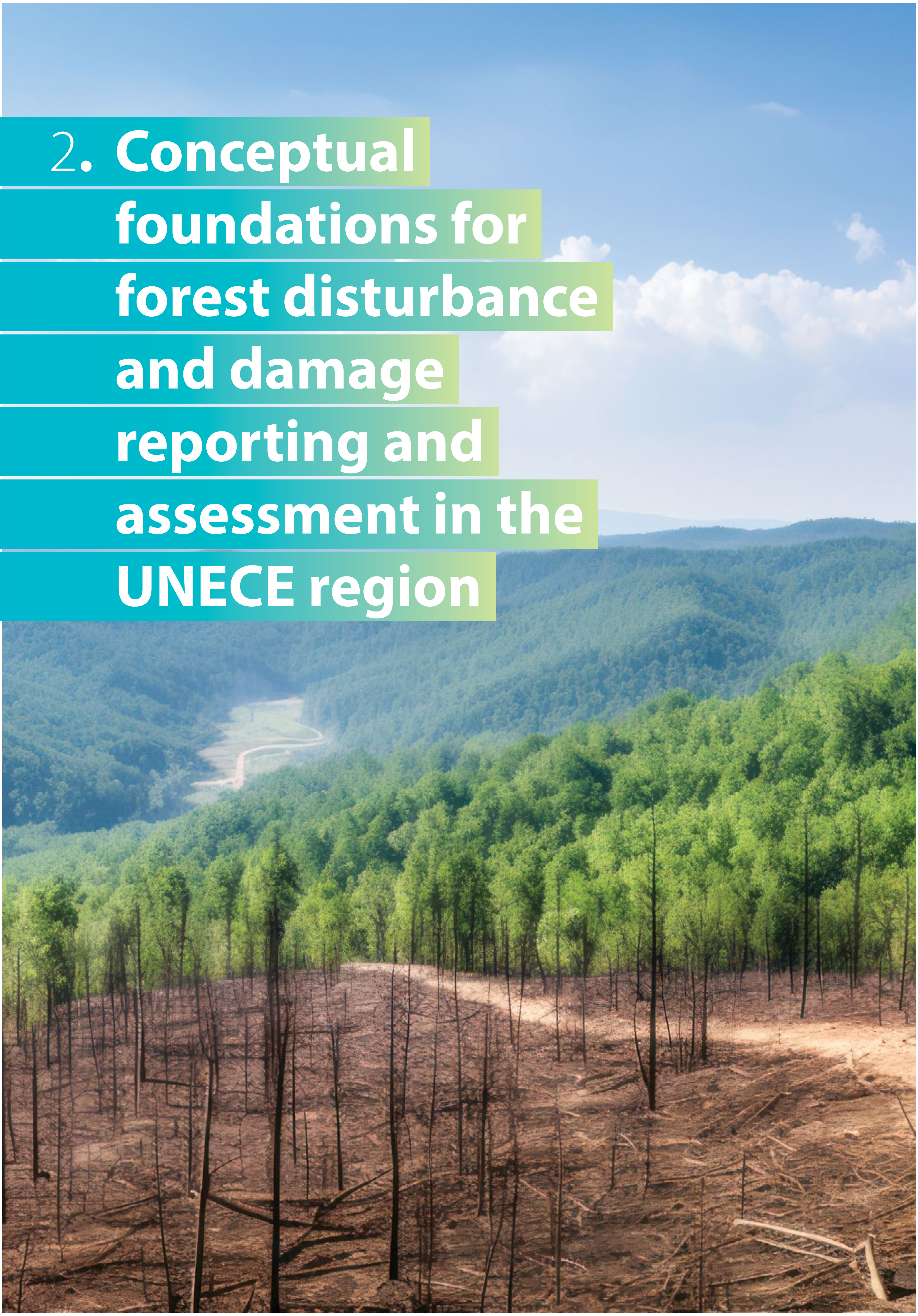
Johnson, E.A., Morin, H., Miyanishi, K., Gagnon, R., and Greene, D.F. (2003): A process approach to understanding disturbance and forest dynamics for sustainable forestry. In P.J. Burton, C. Messier, D.W. Smithand W.L. Adamowicz (Eds). Towards Sustainable Management of the Boreal Forest. NRC-CNRC, NRC Research Press, Ottawa, Canada.

Lertzman, K., and Fall, J. (1998): From forest stands to landscapes: spatial scales and the roles of disturbances. In: D. Peterson and V. T. Thomas (Eds), Ecological Scales-Theory and Applications. ISBN: 10: 0231105037. New York: Columbia University Press.

Perera, A.H., and Buse, L.J. (2004): Emulating natural disturbance in forest management: an overview. In A.H. Perera, L.J. Buse and M.G. Weber (Eds), Emulating Natural Forest Landscape Disturbances: Concepts and Applications. ISBN 0-231-12915-5. New York, Columbia University Press.

Wei, X.; Kimmins, J.P. (2012): Sustainable Forest Management in a Disturbance Context: A Case Study of Canadian Sub-Boreal Forests. In: Sustainable Forest Management - Case Studies. J.J. Diez (ed.) IntechOpen, pp. 119-140. DOI: 10.5772/32391.

2. Conceptual foundations for forest disturbance and damage reporting and assessment in the UNECE region



2. Conceptual foundations for forest disturbance and damage reporting and assessment in the UNECE region

Guy Robertson, Michael Köhl and Stefanie Linser

The following chapter addresses conceptual issues underlying forest damage/disturbance reporting and assessment. These issues are discussed in relation to the overarching goal of gaining better understanding of forest damage/disturbance via more comprehensive and harmonized reporting at national, regional and international levels. The analysis is done in the context of the UNECE region. However, it can be relevant and applicable to other parts of the world.

The UNECE has 56 member States and the region covers more than 47 million square kilometres[1]. The region is home to 17% of the world population and hosts 40% of global forests. Table 2.1 lists the groups of countries applied in this study.

2.1 What is forest damage/disturbance?

Forest damage and disturbance relates to impairments of forest ecosystem functions as well as ecosystem goods and services. Ecosystem functions are perceived as a subset of ecological processes and ecosystem structures. Natural processes are the result of complex interactions between biotic (living organisms) and abiotic (chemical and physical) components of ecosystems through the universal driving forces of matter and energy. Ecosystem function is the capacity of natural processes and components to provide goods and services that satisfy human needs, either directly or indirectly.

TABLE **2.1**

The groups by which the UNECE countries were clustered for the purpose of this study

Group	Countries
North Europe	Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, Sweden
Central-West Europe	Austria, Belgium, France, Germany, Ireland, Liechtenstein, Luxembourg, Netherlands, Switzerland, United Kingdom of Great Britain and Northern Ireland
Central-East Europe	Belarus, Czech Republic, Hungary, Poland, Republic of Moldova, Romania, Slovakia, Ukraine
South-West Europe	Andorra, Italy, Malta, Monaco, Portugal, San Marino, Spain
South-East Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Greece, Israel, Montenegro, North Macedonia, Serbia, Slovenia, Türkiye
North America	Canada, United States of America
Caucasus	Armenia, Azerbaijan, Georgia
Central Asia	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
Russian Federation	Russian Federation

1 https://unece.org/member-states-and-member-states-representatives

In forest reporting activities and related discussions, "disturbance" and "damage" are often used interchangeably. There is, however, an important difference between the two terms: disturbance is ostensibly value neutral, relying on an objective set of information emerging from forest monitoring. Damage involves the interpretation of disturbance information as it relates to negative impacts to human values. For example, under this distinction, tree mortality would be considered as disturbance within ecological process, or as damage due to economic loss of merchantable wood.

From a practical standpoint, there is a fair amount of agreement as to what constitutes damage or disturbance, these being processes or agents that significantly impact forests through loss of vitality, tree mortality, or retarded growth (FAO, 2020a; Gardiner *et al.*, 2013; Forest Europe, 2020).

In practice, the use of the respective terms will depend to a large extent on country conventions, perspectives and goals in reporting. The question of when a disturbance becomes damage also requires the introduction of decision criteria and thresholds. In one third of the languages spoken in the UNECE region, no distinction is made between the negatively connoted term damage and the value neutral connoted term disturbance. However, a number of UNECE country respondents favoured a distinction between damage and disturbance (see Chapter 6).

As a result, and especially when considering harmonization across space and time, the value neutral measures associated with disturbance may be better candidates for harmonized data reporting at regional and global scales.

The distinction between disturbance and damage is nonetheless important for several reasons:

1. Human values associated with forests will vary over space and time and thus compromise the comparability of damage measures taken in different places and time periods, or focused on different outputs;
2. Some level of disturbance is endemic to all forest ecosystems and may be part of the natural or desired development of these systems. This may be true even for catastrophic disturbances such as fire in certain fire-adapted ecosystems (Attiwill, 1994; Gardiner et al., 2013; Lertzmann and Fall, 1998);
3. Damage assessments will often require additional assumptions and computational steps to be applied to disturbance measures, adding further complexity to international harmonization and reporting.

The aim of monitoring and reporting is to provide value-free and unbiased information since their interpretation differs among the respective users. Assuming that forest damage is the expected information resulting from this reporting, additional information would be needed to separate damage from overall disturbance. Reporting in the UNECE region, which is based on the causes of damage/disturbance, does not provide this information. A rigorous separation of the two terms, however desirable, is not appropriate in international reporting. A distinction between the terms does not seem to be immediately applicable in regard to the current national reporting and in this study, the two terms are used synonymously. In the future, more attention should be paid to this aspect in the further developments of international forest damage reporting.

2.2 A note on cause

The agent-centred variables used in the FAO Global FRA and Criteria and Indicator (C&I) frameworks of the Montréal Process and Forest Europe, for example, do not include harvest in their damage/disturbance reporting sections. On the other hand, impact-centred measures (e.g., soil compaction, forest degradation, or remotely sensed changes in forest cover without attribution to a specific disturbance agent) may register impacts from harvesting.

C&I reporting frameworks provide examples of general categories commonly used in reporting damage/disturbance. A common distinction is between biotic agents (e.g., insects, diseases, and animal damage) and abiotic agents (e.g., fire, drought, and storms) of damage/disturbance. This agent-centred approach is used in the Montréal Process C&I framework for sustainable forest management (SFM), where biotic and abiotic damage/disturbance are each given a separate indicator under an overarching forest health criterion (Montréal Process, 2015).

In its Global Forest Resource Assessment, FAO also organizes damage/disturbance measures by agents, reporting area measures for damage/disturbance by fire, insects, diseases, severe weather events, and an "other" category that, if used, is described further in country-specific notes (FAO, 2020b).

Forest Europe's State of Europe's Forests (SoEF) report (Forest Europe, 2020), on the other hand, uses an impact-centred approach. It provides five indicators on deposition and concentration of air pollutants, soil condition, defoliation, forest damage and forest land degradation similarly organized under a forest ecosystem health and vitality criterion (Ferretti *et al.*, 2020). Note that the SoEF indicator on deposition does identify specific pollutants and the forest damage indicator is classified by the primary damaging agent. The information on air pollutants, soil condition and defoliation is collected by the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests).

However, the logical structure of C&I frameworks notwithstanding, general categorizations only go so far, and reporting will be driven largely by practical considerations of reporting history, data availability, public concern, and the nature of specific disturbance processes.

2.3 A note on scale

Spatial and temporal scale is an important issue underlying reporting. Over the preceding decades it became increasingly clear that forests, and all ecosystems, are closely linked at varying spatial and temporal scales. Consistent measures of key disturbance and damage processes across the region will not only allow comparison between regions but also identify major trends.

The UNECE region spans most of the Northern Hemisphere. Aggregate damage/disturbance measures are reported for the entire UNECE region and its constituent subregions and countries. Readers who are more used to national or subnational reporting frameworks should bear in mind that the regional scale considered here will entail different reporting conventions and the loss of detail through averaging over space and time. It will also require practical compromises when combining data from different reporting systems.

Damage/disturbance can occur with varying intensity and timing. Of particular importance are "disasters", which denote a sudden damage/disturbance event. Forest-related disasters vary in terms of type, severity, and extent, but all tend to overwhelm available local resources for management response (Brissett, 2002; FAO, 2020a). Also, while sometimes predictable to a limited degree, they all carry an element of surprise and receive heightened public attention, often far greater than is given to more gradual damage/disturbance processes that may be equally damaging (Auf der Heide, 2009).

As a result, the risks associated with forest disasters and their abrupt impacts may require special mitigation and response strategies over and above those required by more gradual processes. Moreover, disasters are usually concentrated over space and time and may not be adequately reflected in annual spatial aggregates. Given the role climate change can play in generating disasters (e.g., through extreme weather events or influence on fire susceptibility), increases in the frequency and intensity of forest disasters will often be interpreted as an overwhelmingly negative indicator of ecosystem resilience and response to changing climate conditions and the potential for more disasters in the future (Robinne, 2021). Particularly abrupt and destructive disturbance events may require special consideration. However, the current study adopts the reporting conventions such as those used by FAO, the Montreal Process, and the pan-European reporting process, and does not treat disaster as a distinct category.

2.4 Why do we measure forest damage/disturbance?

Assessing forest damage/disturbance provides critical information for understanding and managing the vitality and health as well as the sustainability of forest ecosystems, which have far-reaching impacts on biodiversity, climate, economy, and society as a whole. In this context the following aspects are of particular interest:

- **Conservation and Biodiversity**: Forests are critical ecosystems that support a wide range of plant and animal species. Assessing forest damage helps us to understand the impacts of various disturbances on biodiversity.
- **Carbon Sequestration and Climate Change**: Forests play a crucial role in sequestering carbon dioxide from the atmosphere. When forests are disturbed or damaged, either through natural processes or human activities, carbon stored in trees is released into the atmosphere, contributing to climate change. Assessing damage helps us to understand the carbon balance of forests and their role in mitigating climate change.
- **Ecosystem Services**: Forests provide a range of ecosystem services, including water regulation, soil conservation, and air purification. Assessing damage/disturbance allows us to understand how these services are affected by adverse events and helps us to make informed decisions about land use and resource management.
- **Natural Resource Management**: Forests are valuable resources for timber, non-timber forest products, and other resources. Assessing damage/disturbance helps to guide sustainable management practices, ensuring that these resources are utilized in a way that does not deplete the ecosystem's ability to regenerate.
- **Early Warning and Disaster Preparedness**: Monitoring forest damage/disturbance can provide early warning of potential threats such as disease outbreaks, invasive species, and extreme weather events. This information is crucial for disaster preparedness and response.
- **Economic Considerations**: Forests contribute significantly to local economies and livelihoods of individuals through timber production, tourism, and other services. Assessing damage/disturbance helps quantify economic losses and guide decisions on restoration efforts and recovery strategies.
- **Scientific Research**: Studying forest damage/disturbance allows scientists to gain insights into ecological processes, ecosystem dynamics, and the resilience of forest ecosystems. This knowledge informs our understanding of broader ecological concepts and contributes to the advancement of scientific knowledge.

- **Policy and Planning**: Government agencies, conservation organizations, and other stakeholders use information about forest damage/disturbance to develop policies, strategies, and land-use plans that promote sustainable forest management and conservation.

Values associated with forests have changed with the development of human civilization, and the number and types of these values have increased significantly along with our understanding of the ways in which society and forests interact (Dieterich, 1953; Bastrup-Birk *et al.*, 2016; Bengston, 1994; FAO 2020b; Leopold, 1936; Totman, 1989). Similarly, the number and range of stakeholders interested in forests has increased, many holding contradictory expectations regarding forest outputs and characteristics (Isoaho *et al.*, 2019).

Assessment of forest damage/disturbance is often tied directly to these different values (notably in the case of timber production). Additionally, forest conditions are often described in composite measures with implicit value connotations, such as "sustainability," "health" or "resilience," and damage/disturbance impacts may also be evaluated against these measures. Furthermore, forest damage/disturbance effects, most notably in the case of fire, may extend well beyond forest ecosystems to impact values and outputs not immediately associated with forest conditions and metrics. Elevated concentrations of smoke in human settlements relatively distant from fires is a good example - one with potentially major negative effects to human health (Finlay, 2011; Fowler, 2003; Johnson *et al.*, 2011). Similarly, economic impacts resulting from abrupt changes in supply and demand conditions (e.g., a pulse of salvage timber) will have effects extending to regional and even global markets.

Finally, deviations in forest damage/disturbance regimes may provide advance warning of major systemic ecological changes associated with changing climate conditions, with implications for forest management and other actions to reduce the release of greenhouse gases or otherwise mitigate climate change and its impacts (Birdsey *et al.*, 2019).

In the face of climate change and other anthropogenic stressors, broad-scale changes in forest damage/disturbance regimes have long been anticipated and are now apparent to varying degrees (Schelhaas *et al.*, 2003; Lindner & Rummukainen, 2013). Here, damage/disturbance monitoring serves as an indicator of both larger changes in Earth systems and of expected future forest conditions, including frequency and severity of specific types of damage/disturbance events and processes. Moreover, in many forest types, increased damage/disturbance activity constitutes the likely path for forest ecosystem transition - to different structure and species composition or to permanent loss of forest cover (particularly in drier and hotter regions) (Kleinman *et al.*, 2019; Lindner *et al.*, 2010). These changes can be profound, and they will play out on regional to global scales.

The present study is focused on national reporting of damage/disturbance data and on the potential aggregation and interpretation of these data to allow for regional reporting.

The variety of ways in which forest damage can occur is also reflected in the assessment methods used. The decisive factor here is for which reporting unit information is to be provided. National forest inventories periodically assess damage/disturbance for an entire country. Representative sampling methods are used for this purpose. Regionally occurring damage events such as storm damage require special assessments, which can be representative sample surveys or full tallies. Specific damage/disturbance, such as insect damage or snow breakage, can also be assessed through polling local forest services. Last but not least, information from management plans could also be compiled.

Data sources may include remote sensing methods, in-situ assessments, or a combination of both. The units of observation where data are assessed are either forest plots or individual trees.

A compilation of the methods used to assess damage/disturbance can be found in chapter 3.

2.5 Challenges in damage/disturbance reporting

Reporting forest damage presents a number of challenges because of the complex and dynamic nature of forests, as well as limitations in data collection and cross-border reporting mechanisms. Some of the challenges include:

- **Remote and Inaccessible Locations**: Forests can be located in remote and difficult-to-access areas, making it challenging to collect accurate and timely data about damage/disturbance. Inaccessible areas may not have proper infrastructure for accessibility and thus be underrepresented in assessments.
- **Scale and Scope**: Forests can cover vast areas, and damage can occur at various scales – from individual trees to entire ecosystems. Reporting systems must be able to capture and relay data accurately across these different scales.
- **Variety of Damage Types**: Forest damage can result from a wide range of factors, including natural disasters (such as wildfires, storms, and floods), human activities (infrastructure development, pollution, fire), and disease outbreaks. Each of these damage types requires specific monitoring and reporting methods.
- **Double counting**: Double counting in damage reporting refers to the unintentional duplication of reported instances of damage/disturbance. It occurs when more than one damaging agent is affecting a forest area and the respective impact is reported multiple times. Double

counting can happen for various reasons and across different contexts, such as multiple reporting sources, overlapping data collection, inaccurate data validation, lack of data integration, or incomplete reporting procedures. To prevent double counting, organizations and reporting systems should establish clear protocols for data collection, validation, and integration.

- **Timeliness of Reporting**: Unlike assessments that occur in direct temporal relation to a damage/disturbance, periodic assessments may have a time lag between the occurrence and the recording of damage/disturbance. This is particularly true for international reporting, which establishes a common reference year for which data are collected. This reference year can be up to several years before the actual reporting. Since damage/disturbance can occur spontaneously between the reference time and the publication of the report, there is a risk that the reporting does not reflect the current state.
- **Lack of Harmonized Reporting**: Different countries might have varying methods and criteria for reporting forest damage/disturbance. This lack of harmonized reporting can lead to inconsistent data, and difficulties in comparing and aggregating information. Developing and implementing internationally accepted reporting standards is crucial to overcoming this challenge.
- **Complexity**: Forest ecosystems are dynamic and complex; forest damage/disturbance processes are likewise complex, interacting over time with changing forest stand characteristics and other damage/disturbance processes. The sheer number of damage/disturbance processes, and the variety of life cycles, interactions, and effects they possess, constitutes a major obstacle to comprehensive reporting, particularly on a broad spatial scale.
- **Limited Resources**: Countries may lack the necessary resources, both in terms of technology and personnel, to establish and maintain effective reporting systems.
- **Technological Barriers**: Implementing advanced technologies like remote sensing, satellite imagery, and drones for damage assessment requires appropriate infrastructure and technical expertise, which might not be available everywhere.
- **Data Integration**: Combining data from various sources (satellites, ground surveys, agency reports) and countries into a coherent and useful format can be challenging, as different data might utilize different resolutions, accuracy levels, systems of nomenclature, and compatibility issues.
- **Establishing Reference Values**: One of the main reasons for damage/disturbance monitoring at large spatial scales is broad-scale change detection, which proceeds through comparison with reference values or "baseline" conditions. Many damage/disturbance processes are characterized by high stochastic variation across space and time. Strong deviations in damage/disturbance activity may signal substantial shifts in forest dynamics in the face of a changing climate, but in other cases they may just be a string or cluster of extreme observations in a highly variable system. Moreover, many forest stands, particularly those subject to substantial forest management activities, have been altered significantly from their "natural" state. Even in unmanaged forests, conditions are dynamic and the identification of appropriate and relatively stable baselines for comparison becomes more problematic. Reference values involve an arbitrary component depending on the time frame and/or spatial domain over which they are computed. The Montreal Process, for example, explicitly mentions reference conditions in its two damage/disturbance indicators (Montréal Process, 2015) but provides no details on how these reference conditions are to be constructed.
- **Privacy and Security**: Some forest damage reporting might involve sensitive information related to land ownership, indigenous communities, or protected areas. Balancing the need for transparency with privacy and security concerns is essential.
- **Public Awareness and Participation**: Engaging the public in reporting forest damage can be valuable for early detection, but it also requires efforts to educate people about the signs of damage and the importance of accurate reporting.
- **Causal Attribution**: Another challenge posed by the complex and interacting nature of many forest disturbance processes is that of causal attribution and the distinction between proximate and ultimate causes. A well-known example of this arises when trees weakened through drought (ultimate cause) are subject to insect infestations (intermediate cause), resulting in tree mortality, increased fuel loads and greater susceptibility to fire (proximate cause). There are many such interactions between damage/disturbance agents operating in many forests (Rogers, 1996).

Overcoming these challenges requires collaboration among governments, organizations, researchers, and local administrations. Implementing standardized reporting protocols, investing in technology infrastructure, promoting data-sharing, and increasing public awareness are some strategies that can help improve forest damage reporting accuracy and efficiency.

Literature

Åkerblom, M.; Kaitaniemi, P. 2021. Terrestrial laser scanning: a new standard of forest measuring and modelling? Annals of Botany, 128(6), 653–662. DOI:https://doi.org/10.1093/aob/mcab111

Attiwill, P. M. (1994): The disturbance of forest ecosystems: the ecological basis for conservative management. Forest Ecology and management, 63, 247-300.

Auf der Heide, E. (2009): Disaster response: Principles of preparation and coordination. Available online: https://web.archive.org/web/20071213164736/http://orgmail2.coe-dmha.org/dr/static.htm

Bastrup-Birk, A.; Reker, J.; Zal, N.; Romao, C.; Cugny-Seguin, M.; Malak, D.A.; Aggestam, F.; Barbati, A.; Barredo, J.; Camia, A.; Caudullo, G.; Chirici, G; Ciccarese, L.; Corona, P.; Delbaere, B; Rigo, D.; Durrant, T.; Eggers, J.; Elmauer, T.; Estreguil,E.; Garcia Feced, C.; Jones-Walters, L.; Kauhanen, E.; Konijnendijk, C.; Kraus, D.; Larsson, T-B.; Lindner, M.; Linser, S.; Lombardi, F.; Marchetti, M.; Mavsar, R.; Moffat, A.; Nabuurs, G-J.; Pülzl, H.; Raitio, H.; Rousi, M.; San Miguel Ayanz, J.; Schelhaas, M-J.; Schuck, A.; Shannon, M.; Tomé, M.; Van Brusselen, J.; Zizenis, M. (2016): European forest ecosystems. State and trends. EEA Report No 5/2016, 128 pp., Publications Office of the European Union, Luxembourg.

Bengston, D.N. (1994): Changing forest values and ecosystem management. Society and Natural Resources 7(6):515-533.Bickford, C.A., Mayer, C.F., Ware, K.D., 1963. An Efficient Sampling Design for Forest Inventory: The Northeastern Forest Survey. J For 61, 826-833.

Birdsey, R.A.; Dugan, A.J.; Healey, S.P.; Dante-Wood, K.; Zhang, F.; Mo, G.; Chen, J.M.; Hernandez, A.J.; Raymond, C.L.; McCarter, J. (2019): Assessment of the influence of disturbance, management activities, and environmental factors on carbon stocks of U.S. national forests. Gen. Tech. Rep. RMRS-GTR-402. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 116 pages plus appendices.

Brissett, J. (2002): After disaster: Salvage or savage logging? Opposing views on the value of timber harvests after natural disasters. Federal Reserve Bank of Minneapolis. Available online at: https://www.minneapolisfed.org/article/2002/after-disaster-salvage-or-savage-logging

Dieterich, V., (1953): Forstwirtschaftspolitik. Eine Einführung. Hamburg, Berlin, Paul Parey. 398 S

FAO (2020a): Forest-related disasters: three case studies and lessons for management of extreme events. Forestry Working Paper 17. Food and Agricultural Organization of the United Nations, Rome. 114p.

FAO (2020b): Global Forest Resources Assessment 2020: Main report. Rome. Italy. DOI: 10.4060/ca9825en.

Ferretti, M.; Waldner, P.; Vertraeten, A.; Schmitz, A.; Michel, A.; Zlindra, D.; Marchetto, A., Hansen, K.; Pitar, D.; Gottardini, E.; Calatayud, V.; Haeni, M.; Schaub, M.; Kirchner, T.; Hiederer, R.; Potocic, N.; Timmermann, V.; Ognjenovic, M.; Schuck, A.; Held, A.; Nikinmaa, L., Köhl, M.; Marchetti, M.; Linser, S. (2020): Criterion 2: Maintenance of Forest Ecosystem Health and Vitality. In: State of Europe's Forests 2020 Report. Ministerial Conference on the Protection of Forests in Europe – FOREST EUROPE. Bratislava, Slovakia.

Finlay, S.E.; Moffat, A.; Gazzard, R.; Baker, D.; Murray, V. (2012): Health Impacts of Wildfires. PloS Curr. 2012, Nov 2; 4. DOI: 10.1371/4f959951cce2c

Forest Europe (2020): State of Europe's Forests Report. Ministerial Conference on the Protection of Forests in Europe – FOREST EUROPE. Bratislava, Slovakia. https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf

Fowler, C. (2003): Human Health Impacts of Forest Fires in the Southern United States: A Literature Review. Journal of Ecological Anthropology 2003, Jan 1; 7:39-63.

Gardiner, B.; Schuck, A.; Schelhaas, M.-J.; Orazio, C.; Blennow, K.; Nicoll, B. (eds.) (2013): Living with Storm Damage to Forests. What Science Can Tell Us 3. European Forest Institute. Joensuu, Finland.

Isoaho, K.; Burgas, D.; Janasik, N.; Mönkkönen, M.; Peura; M.; Hukkinen, J.I. (2019): Changing forest stakeholders' perception of ecosystem services with linguistic nudging. Ecosystem Services, Vol. 40, December 2019, 101028. DOI: 10.1016/j.ecoser.2019.101028.

Johnson, E.A., Morin, H., Miyanishi, K., Gagnon, R., and Greene, D.F. (2003): A process approach to understanding disturbance and forest dynamics for sustainable forestry. In P.J. Burton, C. Messier, D.W. Smith and W.L. Adamowicz (Eds). Towards Sustainable Management of the Boreal Forest. NRC-CNRC, NRC Research Press, Ottawa, Canada.

Johnson, F.; Hanighan, I.; Henderson, S.; Morgan, G.; Bowman, D. (2011): Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994–2007. Environmental Health 2011, May 6.

Keyser, A.; Westerling, A.L. (2009): Modeling forest fire severity in California, USA. American Geophysical Union, Fall Meeting 2009. U13B-0065.

Kleinman, J. S.; Goode, J. D. ; Fries, A.C.; Hart, J.L. (2019): Ecological consequences of compound disturbances in forest ecosystems: a systematic review. Ecosphere 10(11):e02962. 10.1002/ecs2.2962

Leopold A (1936) Deer and Dauerwald in Germany. J For 34(4):366–375.

Lertzman, K., and Fall, J. (1998): From forest stands to landscapes: spatial scales and the roles of disturbances. In: D. Peterson and V. T. Thomas (Eds), Ecological Scales-Theory and Applications. ISBN: 10: 0231105037. New York: Columbia University Press.

Lindner, M., Maroschek, M.; Netherer, S.; Kremer, A.; Barbati, A.; Garcia-Gonzalo, J.; Seidl, R.; Delzon, S.; Corona, P.; Kolstro, M.; Lexer, M.J.; Marchetti, M. (2010): Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and management 259: 698-709.

Lindner, M.; Rummukainen, M. (2013): Climate change and storm damage risk in European forests. In: Gardiner, B. *et al.* (eds): Living with Storm Damage to Forests. What Science Can Tell Us 3. European Forest Institute, Joensuu, Finland.

Montréal Process (2015): Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests, Fifth Edition. Available online at: https://www.montrealprocess.org/documents/publications/techreports/MontrealProcessSeptember2015.pdf.

Perera, A.H., and Buse, L.J. (2004): Emulating natural disturbance in forest management: an overview. In A.H. Perera, L.J. Buse and M.G. Weber (Eds), Emulating Natural Forest Landscape Disturbances: Concepts and Applications. ISBN 0-231-12915-5. New York, Columbia University Press.

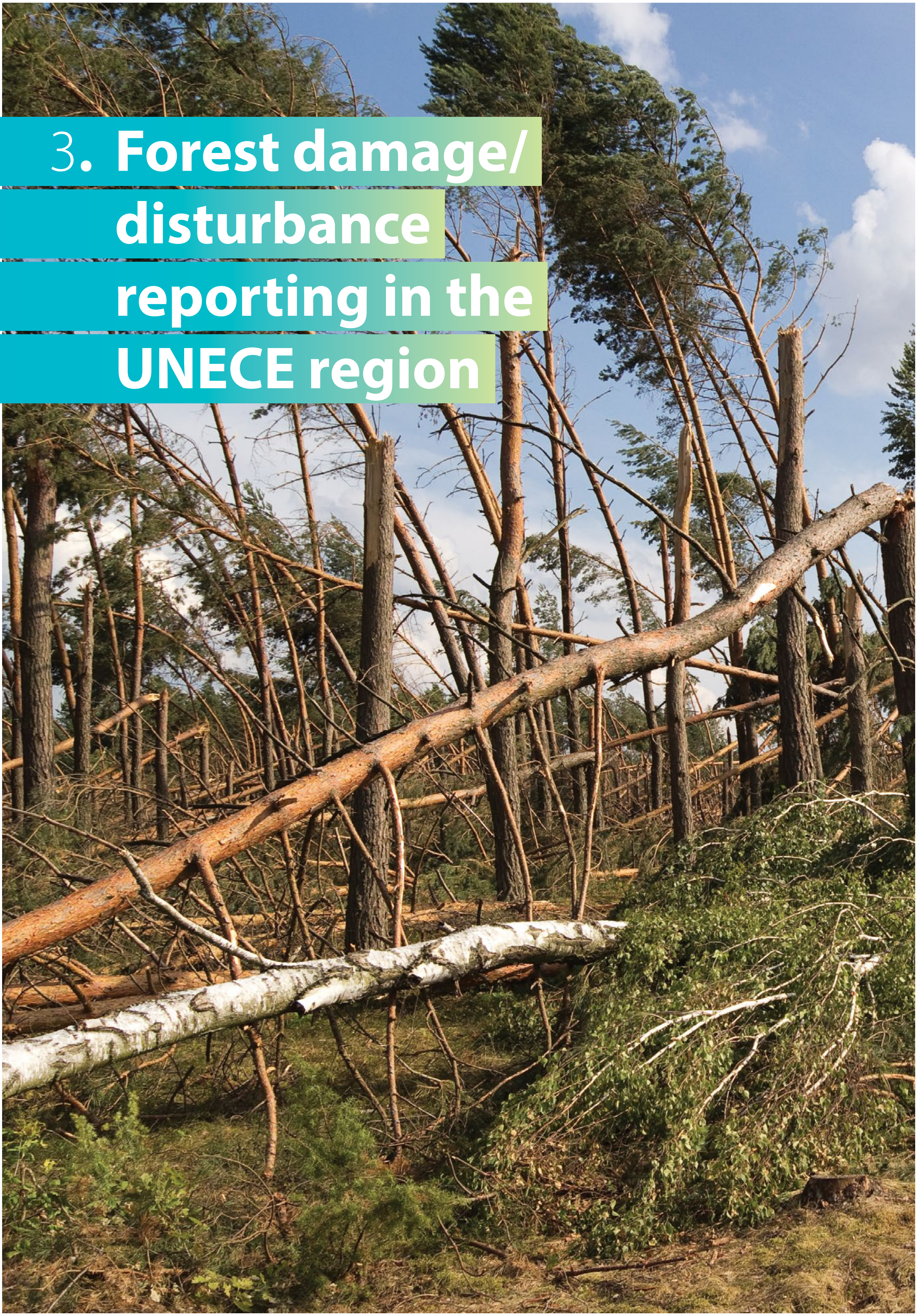
Robinne, F.-N. (2021): Impacts of disasters on forests, in particular forest fires. Background Paper prepared for the United Nations Forum on Forests Secretariat. Available online at: https://www.researchgate.net/publication/350850462_UNFF16_background_paper_Impacts_of_disasters_on_forests_in_particular_forest_fires

Rogers, P. (1996): Disturbance Ecology and Forest Management: a Review of the Literature. General Technical Report INT-GTR-336. United States Department of Agriculture.

Schelhaas, M.-J., Nabuurs, G.-J., & Schuck, A. (2003): Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biology, 9(11), 1620–1633. doi:10.1046/j.1365-2486.2003.00684.x

Totman C (1989) The green archipelago: forestry in preindustrial Japan. University of California Press, Berkeley/London

3. Forest damage/ disturbance reporting in the UNECE region



3. Forest damage/disturbance reporting in the UNECE region

Michael Köhl

3.1 Current state of reporting

Reporting on forest damage in the UNECE region is fragmented. There is no regular reporting activity dedicated to forest damage covering the entire UNECE region.

For Central Asia and the Caucasus, country reports have been prepared with the assistance of UNECE, providing an overview of the national state of forests and forest management. The reports are available for Armenia (UNECE, 2020a), Azerbaijan (UNECE, 2020b), Georgia (UNECE, 2020c), Kazakhstan (UNECE, 2020d), Kyrgyzstan (UNECE, 2020e), Tajikistan (UNECE, 2020f), Turkmenistan (UNECE, 2020g) and Uzbekistan (UNECE, 2020h). All country reports, except Azerbaijan and Georgia, contain data on the area of disturbed forest. Damage/ disturbance (all causes, including fire, insects, diseases) is reported as a percentage of total forest area. In Armenia, 3.7% of the forest area is affected by damage, 1.4% in Kazakhstan, and less than 1% in all other countries.

For North America, links to country reports are available via the Montreal Process web page[2]. For international reporting from that region, FAO Global FRA is the primary reporting mechanism[3].

Forest disturbance and damage data in Canada is federated, most often collected through sub-national jurisdictions and then agglomerated, harmonized and summarized at the national scale for international reporting. National programs within the Canadian Forest Service (Natural Resources Canada) serve to coordinate, compile, standardize and disseminate forest information at the national scale. The main forest information systems include:

- National forest inventory for national scale forest attribute assessment, forest area, biomass, etc.;
- National Forest Information System, the digital infrastructure system for Canadian forest data and information;
- National Forestry Database, which compiles data and surveys the provinces and territories of forest management activities, treatments, disturbance, and wood supply:

Through a pan-Canadian partnership with provinces and territories, the NFI collects, manages, compiles and disseminates forest information for national and international reporting. Because of the federated management of forest data in Canada, data harmonization efforts endeavour to compile, standardize and summarize forest disturbance information. An example is the National Burn Area Composite. This spatial product is generated every year to inform Greenhouse Gas (GHG) accounting and reporting as well as national-level disturbance monitoring.

In Canada, forest disturbance data-sets are generated for different parts of the country by industry, government and academia. Similarly, to the overall data, forest damage data-harmonization efforts endeavour to compile, standardize and summarize forest disturbance information. Examples are:

- The National Burned Area Composite (NBAC), which provides fire polygons from the best-available delineations of burned area for a given year in Canada. This spatial product is generated every year to inform GHG accounting and reporting as well as national-level disturbance monitoring[4] (Hall *et al.*, 2020; Skakun *et al.*, 2022).
- The Pest Strategy Information System (PSIS) is a collaborative web portal consisting of historical forest pest survey data collected by Federal and Provincial pest management agencies[5].
- The Disturbance Data Foundation is currently built up as a warehouse for geospatial data about forest disturbance[6].

In the United States, aggregate national statistics for forest damage/disturbance are reported through various channels. For instance, via the national forest sustainability reporting activity[7] under Montreal Process Criterion 3 "Maintenance of Ecosystem Health and Vitality" (Indicator 3.15: Area and per

2 https://montreal-process.org/Resources/Country_Reports/index.shtml

3 https://www.fao.org/3/ca9983en/ca9983en.pdf

4 https://cwfis.cfs.nrcan.gc.ca/datamart/metadata/nbac

5 https://ca.nfis.org/applications_eng.html

6 https://ca.nfis.org/forestdisturbances/index_eng.html

7 https://www.fs.usda.gov/research/inventory/sustainability

cent of forest affected by biotic processes[8] and Indicator 3.16: Area and per cent of forest affected by abiotic agents[9]).

The main data-generation activities for assessing and reporting forest damage/disturbance in the United States are as follows:

- USDA Forest Service Inventory and Analysis Program (FIA)[10] is the US NFI. Among other things, it surveys forest disturbance by disturbance type and a comprehensive list of causal agents.
- National Interagency Fire Center (NIFC)[11]. Based on current incident reports summarizing fire extent, NIFC reports wildland fire size and total area, which can be aggregated to provide up-to-date annual statistics.
- USDA Forest Service Forest Health Protection Program (FHP)[12]. Among other activities, FHP performs aerial surveys of insect and disease damage that are then summarized in annual reports. FHP uses a purposive sampling approach by flying areas with known issues.

Additional data sources are used for more in-depth analyses, but less intensively used for international reporting. These include the Monitoring Trends in Burn Severity program (MTBS)[13], which provides crucial additional information for understanding forest fires in the USA.

The data generated by these, and related activities feed into national domestic reporting through various summary reports and assessments, such as the Resource Planning Act Assessment (RPA)[14], and the National Report on Sustainable Forests[15].

In the Russian Federation, the monitoring, reporting and assessment of forest damage/disturbance is done in multiple ways via various systems managed by State authorities. The overall phytosanitary and forest pathological conditions of the forest is included in the programme of the State Forest Inventory (SFI), the first cycle of which was completed in 2020[16]. In addition, forest mortality and damage are the subject of several dedicated monitoring systems. The area and growing stock of dead and damaged forests due to various causes (fires, pests and diseases, adverse weather conditions, etc.) are assessed through "State forest pathological monitoring"[17]. Forest fire related risks are assessed by the "Monitoring of fire danger in forests and forest fires"[18], and the "System for remote monitoring of forest fires of the Federal Forestry Agency"[19].

Reporting on forest damage/disturbance in Europe is usually done every five years through the Joint UNECE/FAO/ Forest Europe Pan-European Data Collection on forests and sustainable forest management, which has been carried out since 2003, and published in the Forest Europe's "State of Europe's Forests (SoEF)" report (Forest Europe, 2020). Forest damage is one of the 36 pan-European indicators of sustainable forest management and is reported as the area of forest and other wooded land with damage, classified by primary damaging agent (abiotic, biotic and human induced). The latest SoEF 2020 report includes 45 countries with a total forest area of 227.22 Mio. ha and other wooded land area of 26.92 Mio. ha. The total forest area affected by damage is reported to be 4.4 million ha or 3.3 per cent of the total forest area.

In the SoEF, forest damage/disturbance are reported under the pan-European indicator 2.4 "Forest damage". A distinction is made between biotic, abiotic and human-induced forest damages. Biotic agents include e.g. insects and diseases, wildlife and cattle grazing in woodland. Abiotic agents include e.g. fire, storm, wind, snow, drought, mudflow and avalanche. Direct human induced damage factors include damages occurred during harvesting and forest operations. In the SoEF report, data and analysis on the five causes of damage (1) insects and diseases, (2) wildlife and grazing, (3) forest fires, (4) storm, wind and snow, and (5) forest operation are shown separately.

3.2 Data sources

Forest damage is assessed through various methodologies. National forest inventories are the most common source of data. They provide representative, large-scale data and information periodically depending on the specific inventory intervals. Specific damage events that occur during a few hours (storms, forest fires, ice breakage) or within a single growing season (drought, insect calamities) are often covered by special assessments to obtain a timely overview of the damage situation. Managerial reports, stand inventories, remote sensing -based assessments, or national agency reporting are also frequently used to assess the damage situation.

8 https://www.fs.usda.gov/research/sites/default/files/2022-03/Indicator3.15.pdf

9 https://www.fs.usda.gov/research/sites/default/files/2022-03/Indicator3.16.pdf

10 https://www.fia.fs.usda.gov/

11 https://www.nifc.gov/

12 https://www.fs.usda.gov/foresthealth/protecting-forest/forest-health-monitoring/index.shtml

13 https://www.mtbs.gov/

14 https://www.fs.usda.gov/research/inventory/rpaa

15 https://www.fs.usda.gov/research/inventory/sustainability

16 https://rosleshoz.gov.ru/activity/inventory

17 https://rosleshoz.gov.ru/activity/forest_security_and_protection

18 https://www.consultant.ru/document/cons_doc_LAW_64299/

19 https://ru.wikipedia.org/wiki/ИСДМ-Рослесхоз

3.3 Reporting different causes of damage – the case of the pan-European data collection

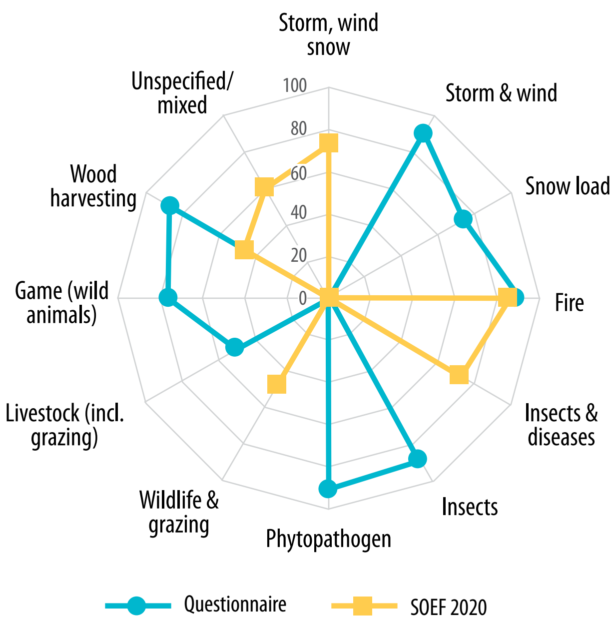
For the Joint Pan-European Data Collection (JPEDC) 2020, data was collected on eight different causes of damage, each of them assessed for the two reference units of forest area and other wooded land (OWL). Data were requested for five points in time and used to derive trends for the period 1990 to 2015.

Not all reporting countries provided data to the JPEDC in the different damage categories. Their number differs both by region and by damage category. Therefore, the regional data do not refer to the total forest area in the regions, but only to the forest areas of these countries that provided data for the corresponding damage category.

The corresponding forest area covered by data varies greatly. For example, forest fire data were provided for 87 per cent of the 2015 forest area in the region, but data on damages by forest operations were provided for only 46 per cent of the forest area. A comparatively good forest area coverage exists in North Europe, except for human induced fire. For South-West Europe only insects and diseases (11%) and fire (89%) are reported. For the other subregions, the data situation is diverse and, in some cases, show considerable differences in the coverage for the individual damage categories, ranging from 15% (forest operations, South-East Europe) to 100 % (fire, Central-East Europe).

FIGURE **3.1**

Data availability in per cent of forest area covered



Source: UNECE ToS 2021, and JPEDC 2020.

In 2021, a survey was conducted for this study to identify the data available on forest damage in the individual countries. The evaluation of data availability in the individual countries shows that not all nationally available data sources are used for pan-European reporting. Figure 3.1 compares the data provision of the current reporting with the nationally available data. Currently, more forest damage data are available in the pan-European countries than are included in the reporting. Efforts to increase response rates are therefore a priority.

3.4 National assessment of forest damages and disturbances

In 2019, the UNECE/FAO Team of Specialists on Monitoring Sustainable Forest Management (ToS on SFM) carried out a survey on national forest damage assessment systems (UNECE TOS, 2019)[20].

Figure 3.2 shows the distinct data-collection systems of the individual responding countries. To derive national estimates of areas affected by forest damage, mainly NFIs and dedicated monitoring of damages are used. Figure 3.3 presents the number of data sources used by individual countries for reporting. Seven out of 26 responding countries indicated that they use only one monitoring system, while the majority of countries use two or more systems.

3.5 Assessment and nomenclature systems in national forest inventories

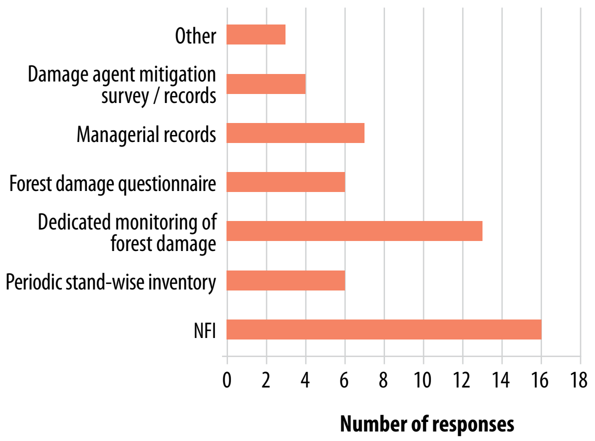
NFIs are the most frequently used data source for international reporting on forest damage (Figure 3.2). The way in which individual NFIs collect data on forest damage has a decisive influence on national reporting. Therefore, the design, assessment and nomenclature systems of the NFIs of Austria (Gabler and Schadauer, 2008; Hauk and Schadauer, 2009), France (IGN, 2021), Germany (BMELV, 2011), Italy (Gasparini, 2016), the Netherlands (Daamen *et al.*, 2017), Poland (Biuro Urządzania Lasu I Geodezji Leśnej, 2020), Sweden (SLU, 2020), Switzerland (Düggelin *et al.*, 2020), and the United States (FIA, 2011, 2019) are compared in the following.

Since all NFIs are based on statistically sound sampling designs, they lead to representative estimates on forest damage for the countries concerned. Beside the fact that sampling errors may differ, differences in sample designs can therefore be neglected for international reporting purposes.

20 The following 26 countries participated in the survey: Albania, Austria, Bulgaria, Canada, Cyprus, Czech Republic, Denmark, Finland, France, Liechtenstein, Georgia, Germany, Iceland, Ireland, Italy, Lithuania, Norway, Poland, Republic of Croatia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, and Switzerland.

FIGURE 3.2

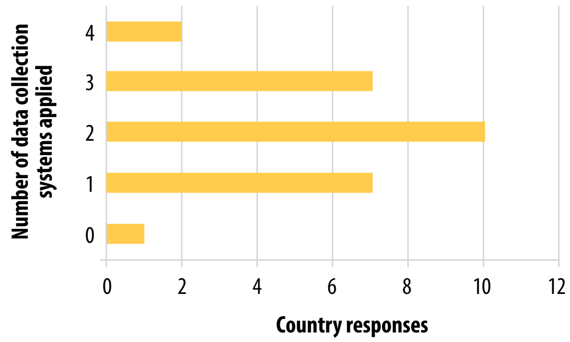
Data-collection systems used by responding countries



Source: UNECE ToS 2019.

FIGURE 3.3

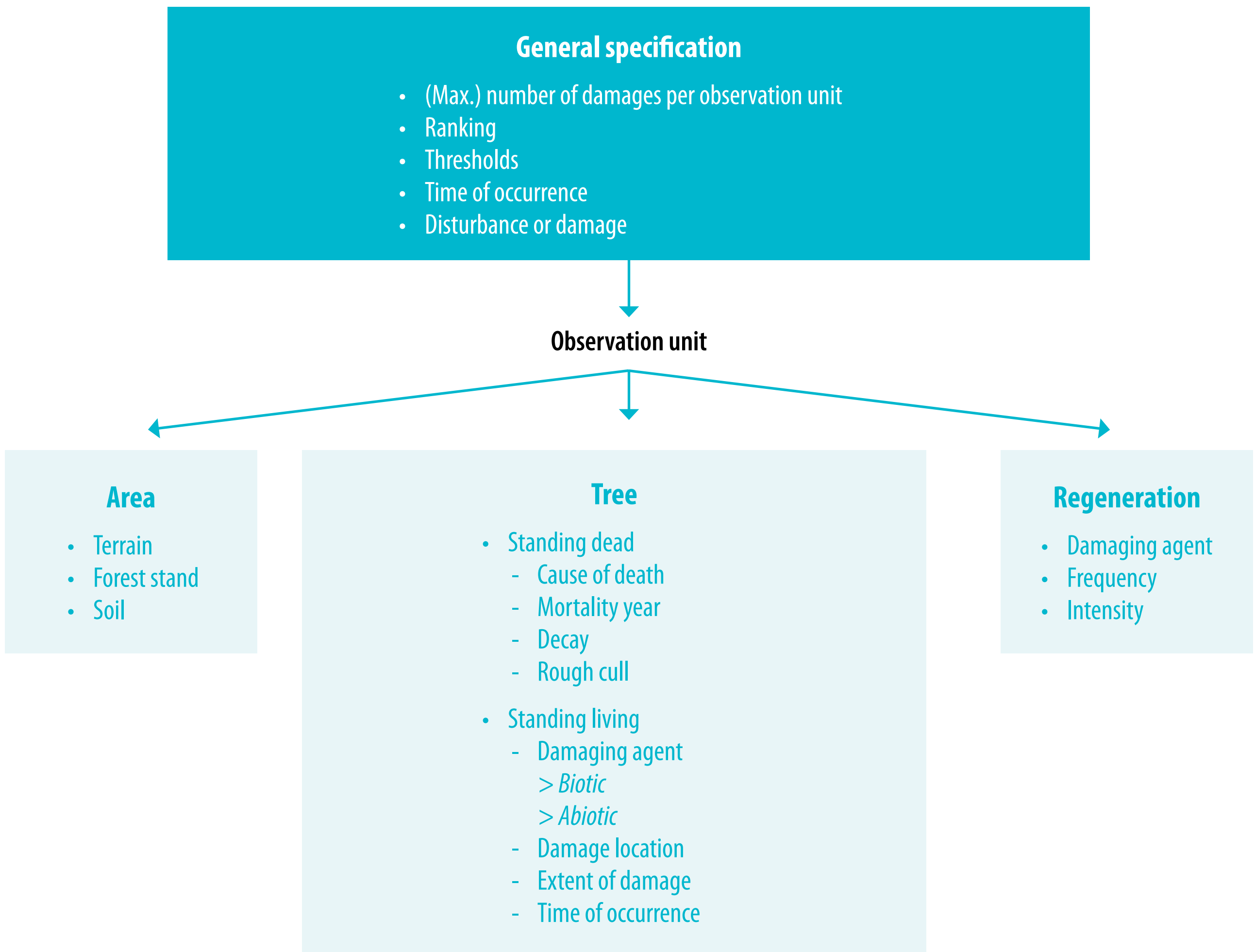
Country responses for number of data-collection systems applied within the country



Source: UNECE ToS 2019.

FIGURE 3.4

Schematic overview for the assessment of forest damage



The nomenclature systems of NFIs usually contain general information on the description and recording of damage, followed by detailed information on the assessment of the three observation units "area", "tree" and "regeneration" (Figure 3.4).

The general information concerns the maximum number of damages assessed on a sample plot, ranking of damages according to severity (e.g., prevent the tree from surviving more than 1-2 years or reduce the growth of the tree in the near term), thresholds (e.g., mortality and/ or damage on more that 25 per cent of all tress in a stand) or time of occurrence (e.g., less than five years before the current assessment). In some NFIs a distinction is made between a phenomenon qualifying as damage or as disturbance (cf. Chapter 2).

3.5.1 Area-related data

Forest inventories generally collect data related to area and individual trees. In area-related assessments of damages, a differentiation between terrain, forest stand and soil is applied in several NFIs, e.g., Austria, Netherlands, Poland, Switzerland and the United States.

Countries not assessing area-related damages expand information assessed on individual trees to areas.

3.5.2 Tree-related data

In the field manuals reviewed, trees were identified as the most commonly utilized observation units for damage detection. In connection with the collection of information of tree characteristics, all consulted field manuals use the term "damage". The term "disturbance" is not used in this context. When recording damage to standing trees, a distinction is made between living and dead trees. For down woody materials, especially coarse woody debris (CWD), no damage assessment is carried out.

In some countries the **location of damage** on a tree is recorded. However, some types of damage are directly related to a specific part of the tree (e.g. defoliation to tree crown) and can be interpreted without additional information about the location.

The **cause of damage** is generally specified as the damaging agent. In the C&I for SFM sets of the Montreal Process and of Forest Europe, a distinction is made between biotic and abiotic damage. This distinction is not made in the consulted national NFI field manuals. Instead, the damaging agents are classified by type without grouping by biotic and abiotic causes.

The **extent of damage** can be formulated in two ways: (1) minimum threshold (area, proportion), which a damage must exceed in order to be recorded, or (2) quantification of the area or proportion (e.g., of foliage, volume, circumference) actually damaged. The extent of damage is not recorded in all countries.

In most surveys damage present at the time of observation is recorded, and it is not common to record the exact **time of occurrence of damage**. This may be mainly due to the fact that the time at which a tree was attacked by a damaging agent, or at which the damaging event occurred, can usually not be reliably determined.

3.5.3 Mortality data

Tree mortality has wide-ranging consequences for biodiversity, ecosystem structure and function, and ecosystem services provided by forests. Where a more detailed analysis of forest condition and damage is desired, further characteristics must be collected, e.g. data on the cause and year of mortality or the state of decay.

3.6 Evaluation of data quality

The 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas (GHG) Inventories[21] provide principles for assessing the quality for GHG reporting. Those IPCC principles for evaluating data quality could also be used for UNECE/FAO reporting on forest damage.

— *Transparency*

From the information provided, it is usually not possible to understand with which methods and for which reference units or (sub-)populations the data was collected. Especially when referring to statistics and reports, it is not clear which methods were used to collect the data or which populations were covered. The following examples should illustrate this:

- In some countries, only data for specific types of forest ownership, for example state forests, are reported. It is questionable whether these data can be transferred to the entire forest area or whether management differences lead to different frequencies and intensities of damages in the individual forest ownership forms.
- If the data source is the reporting of local entities such as forest managers, forest owners or firefighters, it is unclear whether these are spontaneous and therefore non-representative individual reports, surveys with unknown response rates or full tallies.

— *Completeness*

For areas affected by forest fires, over 85% of the forest area of Europe is covered by reporting. For all other causes of damage, the underlying forest area is significantly lower. Therefore, completeness is considered critical.

21 https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_1_Ch1_Introduction.pdf

— ***Consistency***

Some countries indicate that they have adapted their reporting to reflect changes in definitions. Since more than one cause of damage is often observed on affected areas, double counts cannot be ruled out. Data are particularly prone to errors in the case of long-term damage monitoring.

— ***Comparability***

Different reference units, definitions, data sources, thresholds or reporting periods only allow limited comparability between countries. Also, substantial differences in coverage of forest areas for individual regions does not allow a comparison between regions.

— ***Accuracy***

In the reporting forms, data quality is to be indicated as a rough assessment by grouping data into three classes (low, medium, high). Frequently no information on data quality is reported. The information on data quality is highly subjective, as no guidance on the classification is provided. Sampling errors, confidence intervals or other measures of variability that would allow an objective evaluation of the reliability are missing in the reporting process. Therefore, no general, conclusive assessment of the accuracy of the reported data is possible.

Literature

Biuro Urządzania Lasu i Geodezji Leśnej (2020). Wielkoobszarowa inwentaryzacja stanu lasów w polsce Część 1, Wyniki za okres 2015-2019, Sękocin Stary, https://www.bdl.lasy.gov.pl/portal/Media/Default/Publikacje/WISL2015_2019.pdf

BMELV (2011). Aufnahmeanweisung für die dritte Bundeswaldinventur (BWI3) (2011-2012), 2. geänderte Auflage, Mai 2011, Bonn, https://bwi.info/Download/de/Methodik/Aufnahmeanweisung_BWI3.pdf

Daamen, W. P., Clerkx, A. P. P. M. & Schelhaas, M. J., (2017). Veldinstructie Zevende Nederlandse Bosinventarisatie (2017-2021), Wageningen: Wettelijke Onderzoekstaken Natuur & Milieu. 46 p. , (WOt-technical report; no. 101), https://research.wur.nl/en/publications/veldinstructie-zevende-nederlandse-bosinventarisatie-2017-2021-ve

Düggelin, C., Abegg, M., Bischof, S., Brändli, U. B., Cioldi, F., Fischer, C., & Meile, R. (2020). Schweizerisches Landesforstinventar. Anleitung für die Feldaufnahmen der fünften Erhebung 2018–2026. WSL Berichte: Vol. 90. Birmensdorf: Eidg. Forschungsanstalt für Wald, Schnee und Landschaft WSL, https://www.dora.lib4ri.ch/wsl/islandora/object/wsl%3A23637

Forest Europe (2020): State of Europe's Forests Report. Ministerial Conference on the Protection of Forests in Europe – FOREST EUROPE. Bratislava, Slovakia. https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf

FIA Forest Inventory and Analysis (2019). National Core Field Guide Volume I: Field Data Collection Procedures for Phase 2 Plots, Version 9.0, https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2019/core_ver9-0_10_2019_final_rev_2_10_2020.pdf

FIA Forest Inventory and Analysis (2011). National Core Field Guide: Phase 3 Field Guide – Soil Measurements and Sampling, Version 5.1, https://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2012/field_guide_p3_5-1_sec22_10_2011.pdf

Gabler,K., Schadauer,K. (2008). Methods of the Austrian Forest Inventory 2000/02, BFW- Berichte 142, Wien

Gasparini, P., Di Cosmo, L., Floris, A., Notarangelo, G., Rizzo, M., (2016). Guida per i rilievi in campo. INFC2015 – Terzo inventario forestale nazionale.

Hall, R.J., Skakun, R.S., Metsaranta, J.M., Landry, R., Fraser, R.H., Raymond, D., Gartrell, M., Decker, V., Little, J., (2020). Generating annual estimates of forest fire disturbance in Canada: the National Burned Area Composite. International Journal of Wildland Fire 29 (10), 878-891, https://doi.org/10.1071/WF19201

Hauk, E., Schadauer, K. (2009). Instruktion für die Feldarbeit der Österreichischen Waldinventur 2007 – 2009 (Fassung 2009), https://bfw.ac.at/700/pdf/DA_2009_Endfassung_klein.pdf

IGN (2021). Instructions pour les mesures et observations de terrain, Campagne d'inventaire 2021, Service de l'information statistique forestière et environnementale

Skakun, R., Castilla, G., Metsaranta, J., Whitman, E., Rodrigue, S., Little, J., Groenewegen, K., Coyle, M., (2022). Extending the National Burned Area Composite Time Series of Wildfires in Canada. In, Remote Sensing 14(13) 3050; https://doi.org/10.3390/rs14133050.

SLU (2020). Fältinstruktion 2020 – Riksinventeringen av skog, Umea, https://www.slu.se/globalassets/ew/org/centrb/rt/dokument/faltinst/20_ris_fin.pdf

State Forests National Forest Holding, (2021). The National Forest Inventory. Results of cycle III (2015-2019). Sękocin Stary 2021. [URL:] https://www.bdl.lasy.gov.pl/portal/Media/Default/Publikacje/Polands%20NFI%20-%20Results%20of%20cycle%20III.pdf, accessed on 27.04.2023.

UNECE, (2020a). Overview of the state of forests and forest management in Armenia. In: UNECE (Ed.), ECE/TIM/DP/78, Geneva, https://unece.org/DAM/timber/publications/2020/Armenia_DP78_1922453_E_WEB.pdf

UNECE, (2020b). Overview of the state of forests and forest management in Azerbaijan. In: UNECE (Ed.), ECE/TIM/DP/79, Geneva, https://unece.org/DAM/timber/publications/2020/Azerbaijan_DP79_1922468_E_WEB.pdf

UNECE, (2020c). Overview of the state of forests and forest management in Georgia. In: UNECE (Ed.), ECE/TIM/DP/80 , Geneva, https://unece.org/DAM/timber/publications/2020/Georgia_DP80_1922467_E_WEB.pdf

UNECE, (2020d). Overview of the state of forests and forest management in Kazakhstan. In: UNECE (Ed.), ECE/TIM/DP/82,Geneva, https://unece.org/DAM/timber/publications/2020/Kyrgyzstan_DP82_1922472_E_WEB.pdf

UNECE, (2020e). Overview of the state of forests and forest management in Kyrgyzstan. In: UNECE (Ed.), ECE/TIM/DP/82 , Geneva, https://unece.org/DAM/timber/publications/2020/Kyrgyzstan_DP82_1922472_E_WEB.pdf

UNECE, (2020f). Overview of the state of forests and forest management in Tajikistan. In: UNECE (Ed.), ECE/TIM/DP/83, Geneva, https://unece.org/DAM/timber/publications/2020/Tajikistan_DP83_1922475_E_WEB.pdf

UNECE, (2020g). Overview of the state of forests and forest management in Turkmenistan. In: UNECE (Ed.), ECE/TIM/DP/84, Geneva, https://unece.org/DAM/timber/publications/2020/Turkmenistan_DP84_1922477_E_WEB.pdf

UNECE, (2020h). Overview of the state of forests and forest management in Uzbekistan. In: UNECE (Ed.), ECE/TIM/DP/85 , Geneva, https://unece.org/DAM/timber/publications/2020/Uzbekistan_DP85_1922478_E_WEB.pdf

UNECE/FAO, (2021). Survey on reporting and assessment of biotic and abiotic forest damage/disturbance in the UNECE region. internal report, UNECE/FAO Forestry and Timber Section, Geneva

UNECE ToS, (2019). Survey on national forest damage assessment systems, internal report, UNECE/FAO Forestry and Timber Section, Geneva

4. Global reporting on forest damage

4. Global reporting on forest damage

Markus Melin

4.1 Background

FAO's Global Forest Resource Assessment (FRA) has been compiling international information on forest damage since 1946. Since 1990, the assessments have been published at five-year intervals, with the FRA2020 being the latest release. Nowadays, depending on the year, the FRA receives data from up to 100 countries on the forest area damaged by fires and from 40 to 60 countries for insects, diseases and severe weather events.

Over the decades, FAO (in collaboration with UNECE) has taken steps to improve the Global FRA. An important part of the process is the analysis of the current coverage in relation to potential opportunities and shortcomings in national forest damage reporting systems.

Within this study, requests for additional data on forest damages were sent to FRA National Correspondents from 50 UNECE countries to gain further information. The request was sent in early 2022 and asked specifically for data that would offer more information on the forest damage situation than what the country has reported to the latest FRA. The request was made on data that describe the area of forest affected by a given damage agent in different years. The timespan was not restricted. Similarly, the scope of damage agents was not specifically limited.

This chapter first summarizes the current forest damage situation in the UNECE region as well as the overall reporting comprehensiveness based on FRA data from the period 2000 – 2017, and the feedback received from FRA National Correspondents. Subsequently, available FRA data, whenever possible, are compared with the other national data-sets received via FRA National Correspondents to draw attention to the potential shortcomings and opportunities. Throughout the report – unless specified otherwise – the applied unit is always "area (in hectares) of forest affected by", a given damage agent, like applied in the FRA reporting.

4.2 Forest damage reporting in FRA

For the recent FRA 2020 report (FAO, 2020), countries were asked to provide estimates of the forest area affected annually by various disturbances; and of any biotic or abiotic factor affecting the health or productivity of the forests, and which is not directly caused by human activities. The reporting is not done for a species-specific damaging agent (e.g. area affected by Ips typographus), but instead by main biotic and abiotic groups: fire, insects, diseases caused by bacteria, fungi, viruses or phytoplasma, and extreme weather (snow, storms, drought).

While the FRA holds data at the level of individual countries, this chapter focuses on geographical regions. Individual countries are analysed only in the context of providing insights into a specific issue.

4.3 Reporting patterns of damage groups

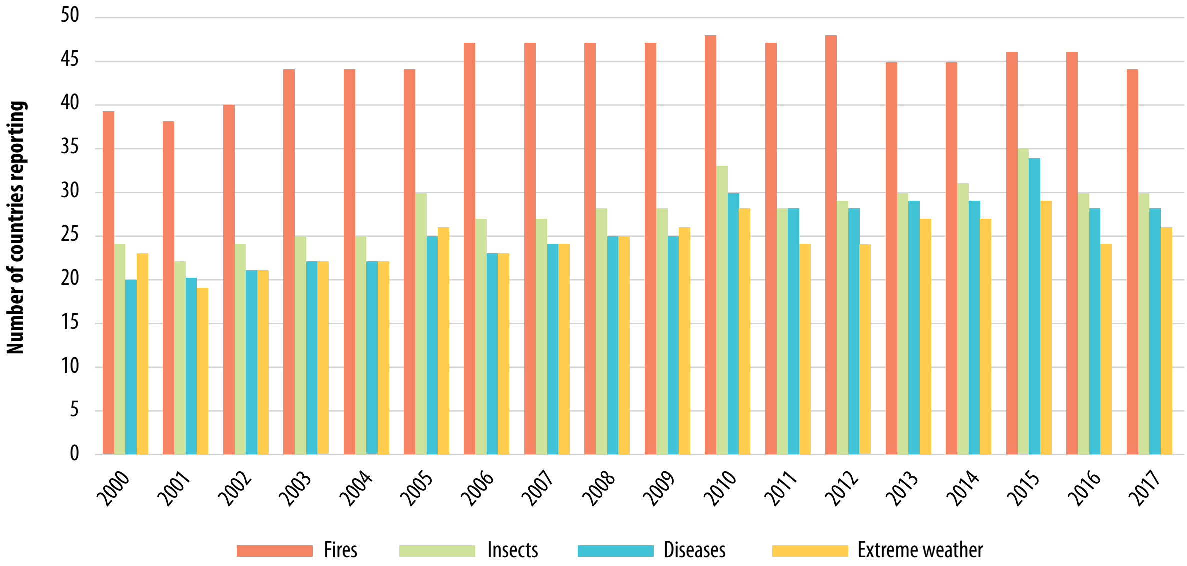
Out of the 56 member States of the UNECE region, between 41–49 countries (depending on the year) have reported damage data to the FRA from at least one of the main damage groups during the reporting period 2000 – 2017. Yet, the number of countries reporting data on every damage group is considerably lower, between 18 and 29 countries depending on the reporting year. Figure 4.1 illustrates the number of countries reporting data in different years by the damage groups.

The most reported common damage group is fire, followed by insects. Diseases and extreme weather events are reported least often. The FRA data on forest fires is prefilled by the secretariat based on international reporting dedicated to fires, (Global Wildfire Information System (GWIS) of the European Commission) which could explain the high response rates for damages by fire. When compared to the early years of the reporting period (2000–2003), the reporting in the recent years is more complete in almost every damage group. Insect data during the last five years were reported by 30–35 countries as opposed to less than 25 countries in the early 2000s. Similarly, fires are reported by 45 countries compared to less than 40 countries in the early 2000s, disease data reporting has increased from about 20 countries to 25 – 30 countries. The only damage group where reporting has not increased so clearly is extreme weather, though one might observe a slight positive trend.

When compared to the entire forest area of the UNECE countries (using 2010 as the reference year), the reporting covers approximately 99% of the UNECE forest area for fires, 96% for insects, 75% for diseases and 75% for extreme weather. Yet it should be noted that a comparison of the area is heavily affected by the reporting activities of Canada, the Russian Federation and the United States of America, since they cover the vast majority of forest area in the UNECE region.

FIGURE **4.1**

Fluctuations in the number of UNECE countries that report damage data to FRA from the main damage groups



Data source: FAO 2020.

4.4 Summary of the damage situation in the UNECE region based on FRA 2020

When assessing, which of the damage agent groups has been responsible for most damage, the results are always affected by the reporting completeness in different years. When averaged over the reporting period 2000–2017 for the entire UNECE area, insects were the major cause (56% of the reported damage), followed by fires (20%), extreme weather event (14%) and diseases (10%).

The role of different damage agent groups changes by different geographic regions. Fires are causing the most damage in Caucasus and South-West Europe. Extreme weather (snow and storms) generates most damage in North Europe. Diseases were reported as the most common damage group in Central-West Europe, while insects induced most of the reported damages in North America, Central Asia, South-East Europe and Central-East Europe (Figure 4.2).

There are significant differences among proportions of damage categories among countries and regions. It is not always certain if these differences reflect the real situation or if they resulted from the different damage or the incomplete reporting resulted from the insignificance of the damage or the lack of information about it. Thus, the results are heavily affected by which categories and damage thresholds were actually included, and how they were reported by countries.

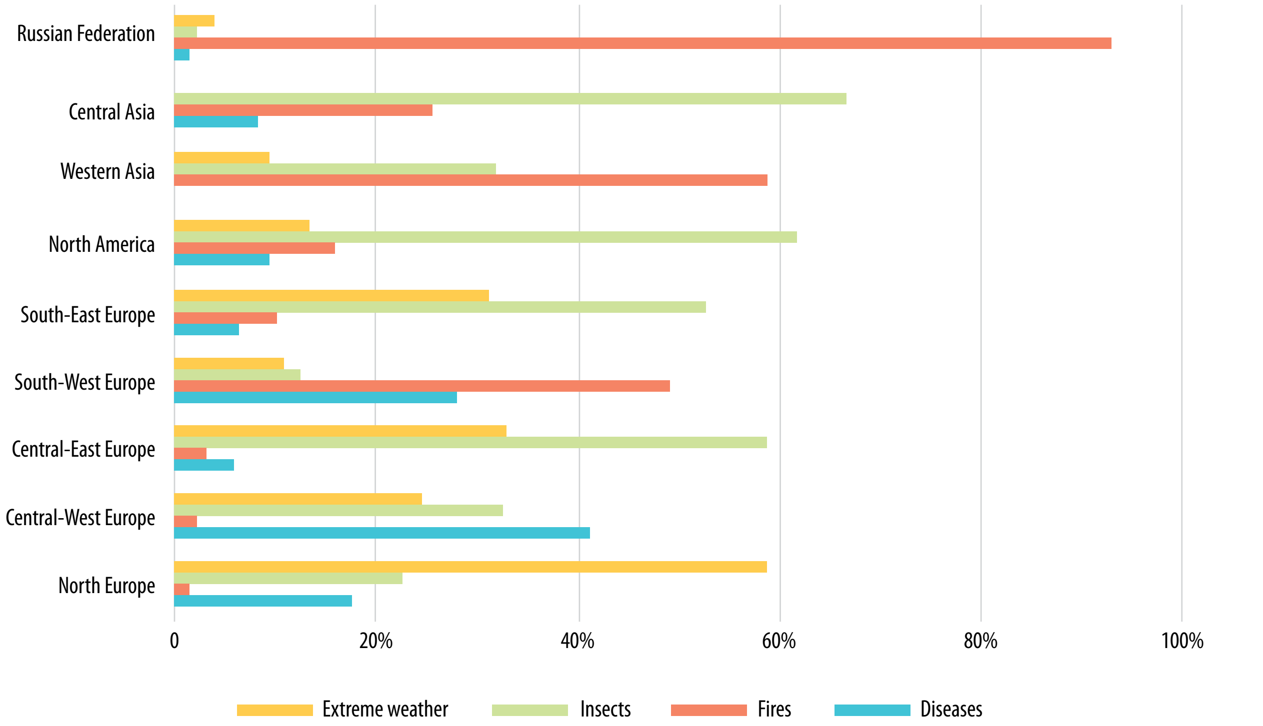
Regarding the period of 2000-2017, despite the differences in national reporting, patterns in the damaged area by different damage groups are identifiable. Insects have always remained the damage agent affecting the largest areas in the UNECE region. The area of forests affected by fires has increased slowly over the reporting period while the area damaged by extreme weather events decreased (Figure 4.3). Yet, the information on forest area affected by damaging agent does not necessarily reflects the full impact of agents on forests. For example, forest fire or a thunderstorm – despite affecting similar area – will have a totally different impact on the forests or the society than defoliation caused by a moth. It is also worth noting that the recent data reported for FRA2020 comes from 2017. Therefore, the data used in this report do not reflect the droughts and the cascading large-scale bark beetle calamities of Central and Eastern Europe since 2018 or the large Canadian and Mediterranean wildfires of 2020 and 2022.

Data presented for the whole UNECE region is also influenced by data from countries with large forest areas such as Canada, the Russian Federation and the United States, which together cover about 86% of the forest area of the UNECE region. Therefore, the aggregation tends to mask out any subregional variety in the intensity and trends of forest damage. Indeed, a more detailed look on the variation caused by reporting activity reveals artefacts not related to the actual damages, but to the specificities of the current reporting.

Figure 4.4 shows temporal trends of area of forest affected by the different damage groups in North Europe based on FRA data. The data show clear inter-annual variation, but one may also see systematic, abrupt increases in the level of damage caused by extreme weather events, insects and diseases occurring at five-year interval: 2005, 2010, 2013, 2015. The

FIGURE **4.2**

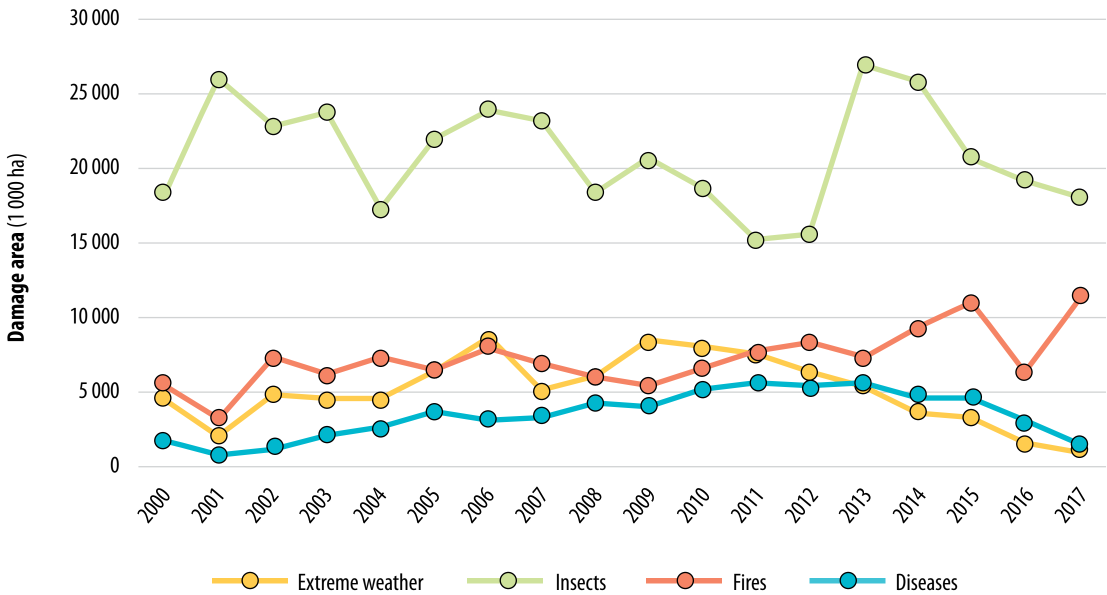
The share of damages by damage groups of all the reported forest damage from the reporting period 2000-2017 in different subregions of the UNECE



Data source: FAO 2020.

FIGURE **4.3**

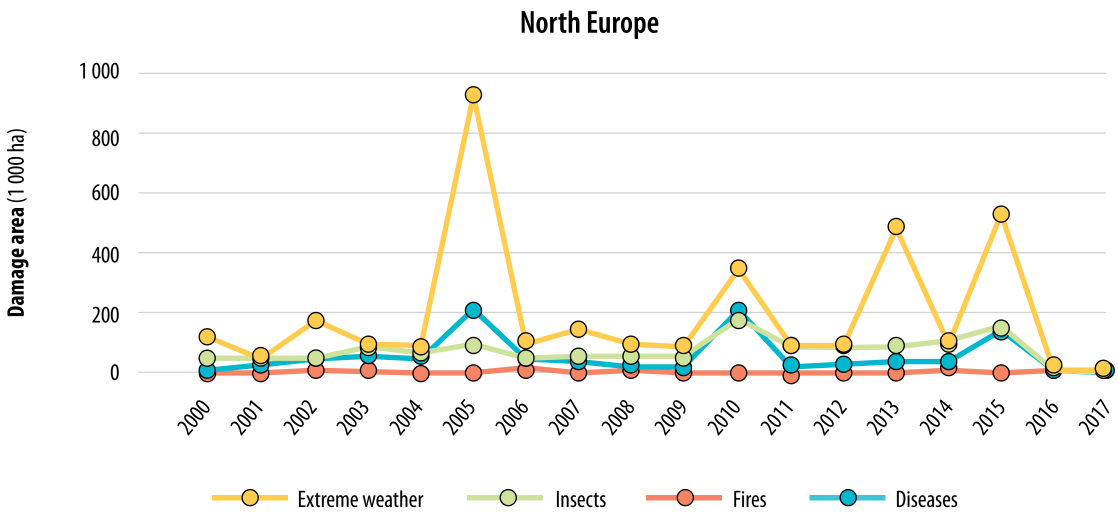
Total area of forests affected by the different damage groups in the UNECE area based on FRA data



Data source: FAO 2020.

FIGURE **4.4**

The total area of forest affected by each damage group in North Europe based on FRA data



Data source: FAO 2020.

pattern is an artefact created by Finland´s and Sweden´s data reporting: both countries only report data to the FRA for every fifth year in accordance with the cycles of their NFIs (Sweden reported data on extreme weather events also in 2013, but not on insects or diseases). Given the countries´ large share of forest area in the subregion, the years when they report the data then appear as abrupt increases in the damage areas of every damage group in North Europe apart from fires (the fires data come from a different source than NFI - national fire monitoring).

Different temporal resolution of submitted data can become a severe issue for interpretation or drawing conclusions and need to be interpreted and addressed properly.

4.5 Comparing FRA damage data with the national data-sets

4.5.1 Differences caused by country-wise application of damage threshold

The differences in the magnitude of areas affected by damage between annually assessed data and those provided for international reporting for the years 2010 and 2015 is based on different thresholds of what has been classified as "damage" when compiling the data.

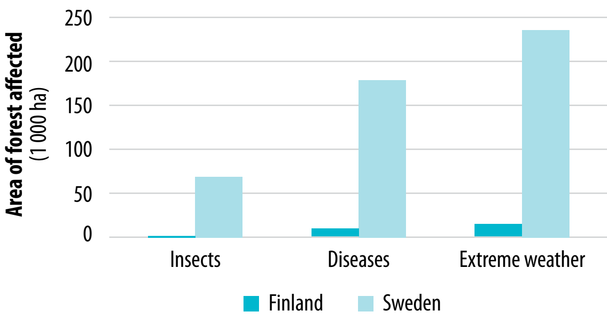
In comparing regions or countries, the focus should also be on differences in the applied definitions of forest damage/ disturbance as well as the diverging utilization of baseline conditions. The use of individual thresholds can cause large differences in the estimation of damaged areas even for apparently similar countries, such as neighbouring countries in a similar forest ecotone. Figure 4.5 shows the FRA numbers for areas of forest damaged by Insects, Diseases and Extreme weather for Finland and Sweden in 2010.

The differences in the forest areas affected by different damage agent groups are not a result of differences in disturbance dynamics but arise from differences in thresholds of damage applied by countries in FRA reporting.

In this case, Finland provides estimates about the "area of forest significantly affected by" a damage agent to the FRA: the damage was severe enough to affect the quality or growth of the forests. For example: defoliation by the pine sawfly Neodiprion sertifer is always assessed in the Finnish NFI and classified into different categories based on the severity – and Finland has not submitted data to the FRA of the classes where the species had caused only mild defoliation not affecting the

FIGURE **4.5**

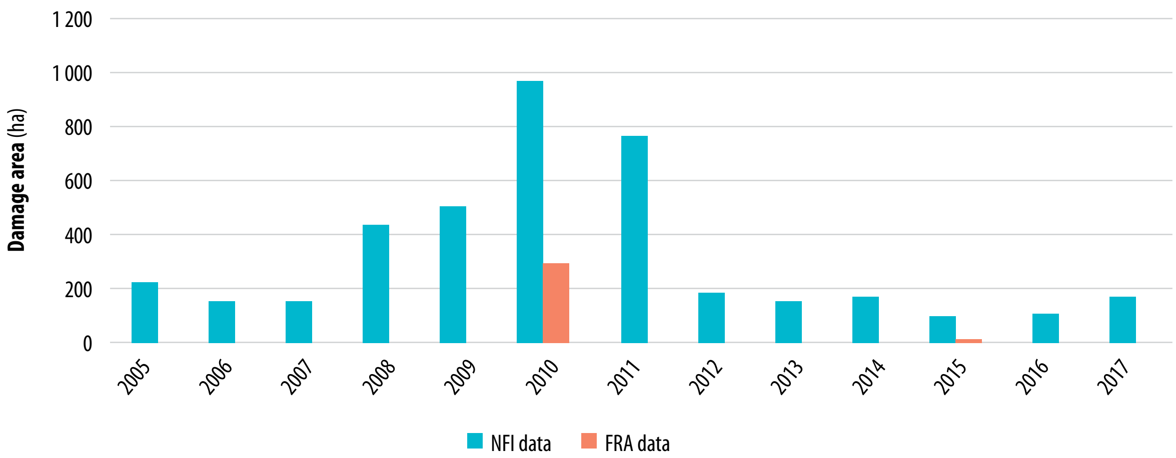
Area of forests affected by insects, diseases and extreme weather in Finland and Sweden in 2010



Data source: FAO 2020.

FIGURE **4.6**

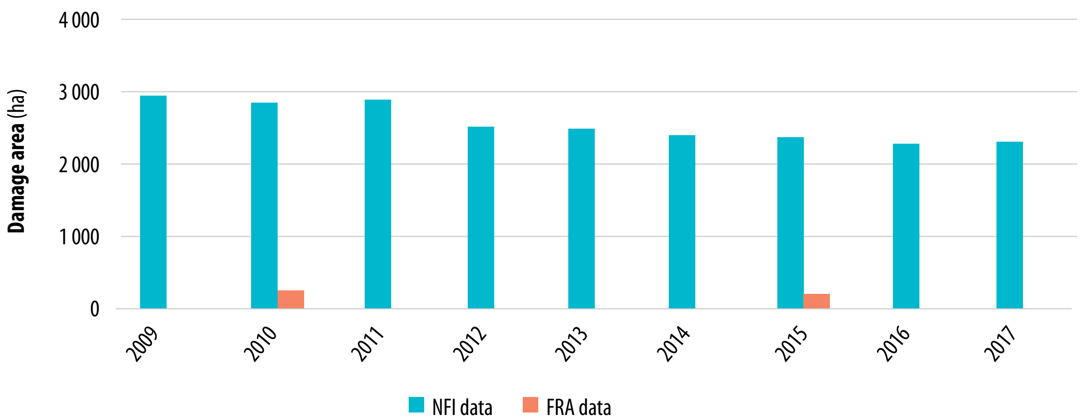
Forest damage by insects during the FRA reporting period 2000–2017 for Finland



Data source: FAO 2020 (for FRA data), Finnish NFI (Korhonen *et al.* 2021 (for the national data, Finnish NFI data not available publicly.

FIGURE **4.7**

Forest area damaged by diseases during the FRA reporting period 2000–2017 for Poland



Data source: FAO 2020 (for FRA data), Polish NFI (Talarczyk 2014) for the national data, Polish NFI data not available publicly.

growth or quality of the forests. Sweden, on the other hand, provided data to this study showing the "area of forest affected by", which includes milder damages as well. Information on the Finnish NFI is available from Korhonen *et al.* (2021), and Fridman *et al.* (2014) and SLU (2023a, 2023b) for the Swedish NFI.

In line with the conceptual foundations in chapter 2, the threshold of what kind of disturbance is classified as forest damage and how this varies between different countries is a clear source of bias for any international reporting and assessment of forest damage.

The possible impact of the choice of thresholds on the reported data can be illustrated with examples of the reporting by Finland and Poland. The data that Finland and Poland report to FRA are based on their NFIs (apart from forest fires). The reporting to FRA is made at the end of an NFI cycle every fifth year. However, additional information on annual estimates of forest area damaged by different agents are also collected (Figure 4.6 and Figure 4.7).

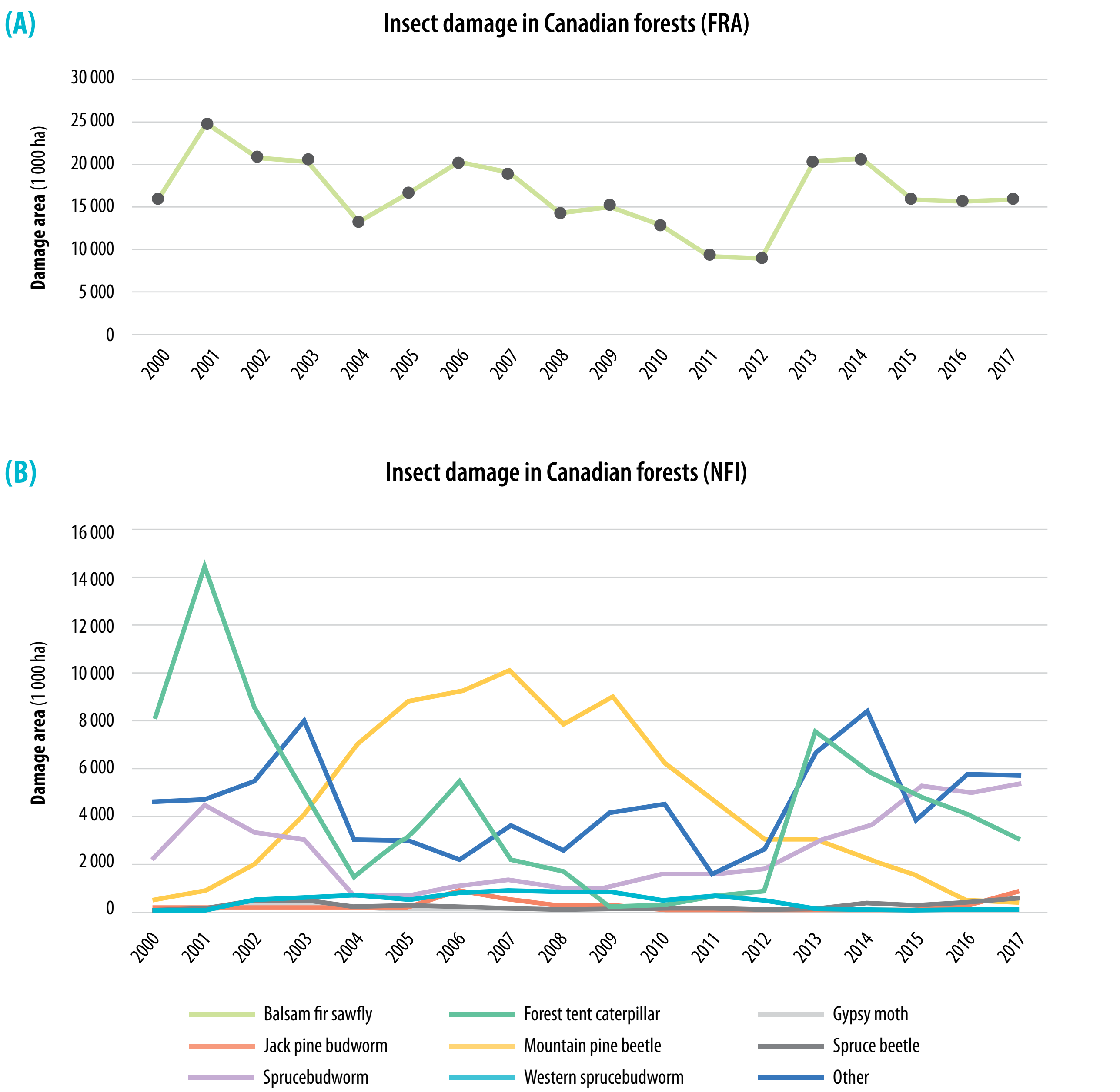
For both countries the data presented in Figure 4.6 and Figure 4.7 are based on the same sources, however what is reported highly depends on the chosen reporting frequency and thresholds. These examples indicate the importance of the background knowledge on the details of the submitted data for their interpretation and the concluding process. More specific guidance for international reporting is needed to support countries in selecting and preparing national information for this purpose.

4.5.2 Differences in level of detail; group- or species-level reporting

In a global assessment such as the FRA, it is difficult to include detailed, species-specific lists of every available damage agent for every country. However, the classification of the damage agents in the current groups may also be problematic if a group (such as insects) includes heterogenous species with very different damage patterns (e.g. bark beetles versus

FIGURE **4.8**

Forest damage in Canadian forest caused by the group insects (A) and separated by the insect species (B)



Data source: Results from the Canadian NFI (CFS 2023a, CFS 2023b).

defoliators); the summarized results can mask the relevant patterns within the damage group in question.

After all, a magnitude of change in insect damage may be driven by a number of damages caused by a single pest induced event, while the damage area of dozens of other insects would have different characteristics. An example of this issue can be illustrated with the use of data reported by Canada. The FRA data for Canada on insects stems from publicly available NFI data, which also has species-level information, which gives more insights about the trends in insect damage across Canadian forests (Figure 4.8). The data in the graphs is FRA data for Canada, image A presents summaries of the species-specific data of image B.

By comparing figures A and B, the main patterns in insect damage (A) are primarily driven by three species (the Mountain pine beetle, the Forest tent caterpillar and the Spruce budworm), as presented in B. These kinds of hidden details about the patterns can become major issues when it comes to the interpretation of the results. Indeed, by focusing on insects as a single group, the widespread Forest tent caterpillar damage of 2001 cannot be easily identified. The same applies to the over 10-fold increase in Mountain pine beetle damages from 2000 to 2007 or the slow and steady increase in Spruce budworm damage throughout the reporting period. However, possible post-adjustments should always consider the added value vs. the added reporting burden by more detailed coverage.

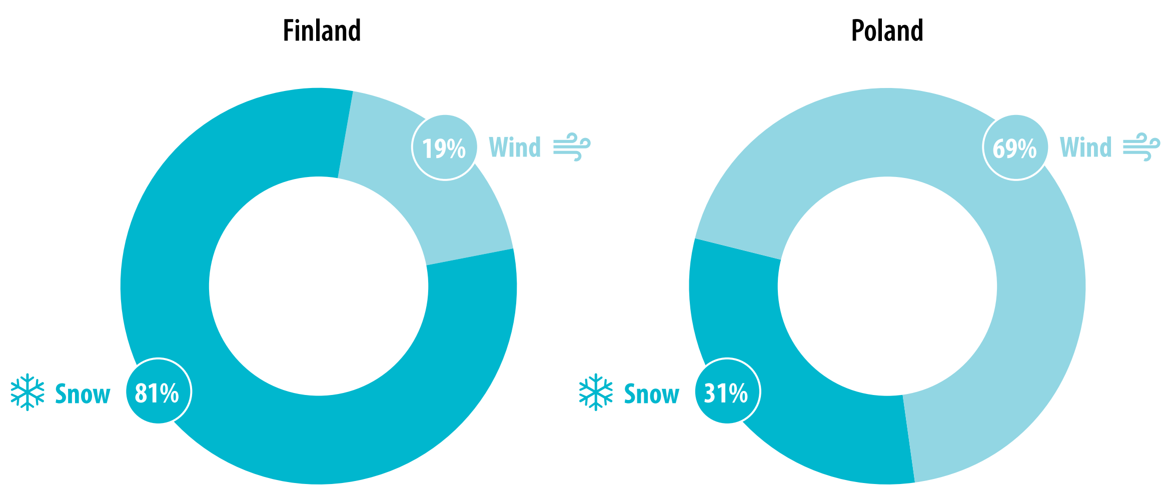
Insect and diseases damage groups are similar in that they both cover various species, some of which can be driving the entire trend and pattern of the damage category. Therefore, the "level of detail in reporting" is decisive in this case. The same situation can also occur in the case of damage caused by extreme weather events.

The grouping of different causes of damage into one category is crucial for international reporting, especially for the FRA due to its global extent. To analyse how extreme weather has caused forest damages on a global scale, the findings are limited without indication on whether the trends are driven e.g. by snow, wind or droughts. For North Europe, the extreme weather was the dominant damage agent in the FRA reporting period 2000-2017, accounting for nearly 60 % of all reported forest damages, and to a large extent is driven by snow. The 30-35 % share of extreme weather events out of all the damages reported to FRA for South-East Europe is more heat- and drought related. Figure 4.9 illustrates such a difference between Poland and Finland based on their NFI data.

The types of differences illustrated in 3 4.9 are not shown in FRA, as both abiotic damage agents (wind, snow, drought etc.) are grouped in the extreme weather category. Similarly, analysing differences between regions when it comes to extreme weather is hampered without knowing more about the type of weather events reported.

FIGURE **4.9**

The share of snow and wind damages out of the total area damaged by snow and wind in the Polish and Finnish NFIs from 2009 to 2020



Data source: National NFI data of Finland (Korhonen *et al.* 2021) and Poland (Statistics Poland 2022, Talarczyk 2014). Data not available publicly.

4.5.3 Varying national data-sets on forest damage

In addition to differences resulting from reporting activities, the use of a different damage threshold (Figure 4.5) or the use of group-level data (Figure 4.8), there are cases where a country has alternative, independent sources of information to assess forest damage. These data-sets assessed for different purposes may provide different figures for the area affected due to a different survey method, sampling schemes, or area coverage.

An illustrative example are the two different assessment programmes that are used in the United States to monitor forest damage. The FRA data for the United States come from the United States Department of Agriculture's (USDA) Forest Inventory and Analysis (FIA) program (Bechtold & Patterson 2005, USDA 2023a). The FIA is based on systematic field plots, providing scientifically sound data on an annual basis, and provides data not only on forest health, but also on forest resources, growing stock and volume, or forest structure.

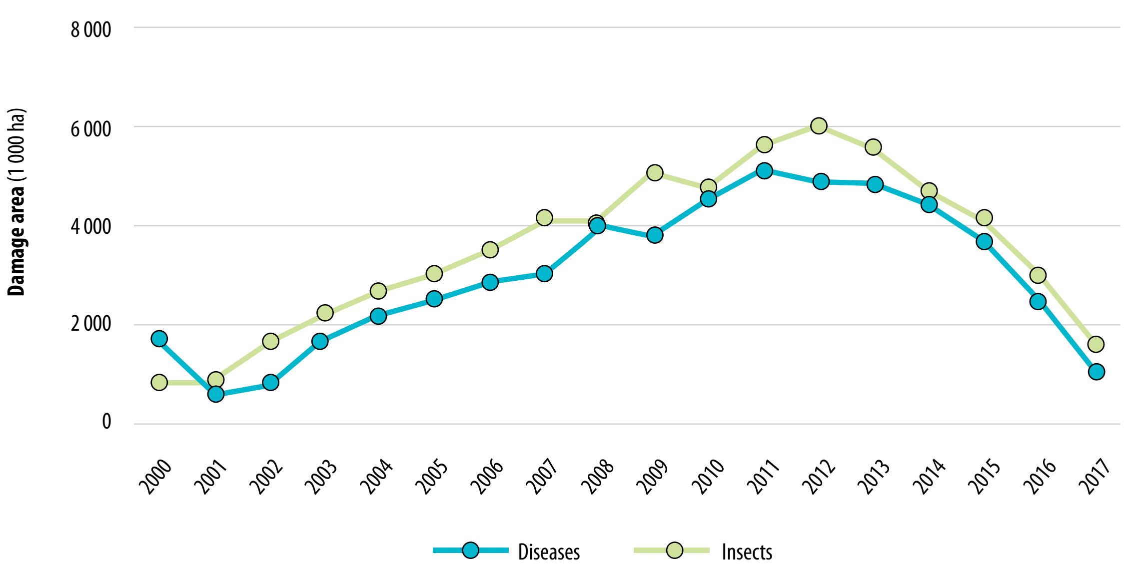
The Forest Service of the USDA also has designated surveys on forest health that are conducted within its Forest Health Protection program. A long serving one is the Major Forest Insect and Disease Conditions in the United States reporting (USDA 2023b, LaBau *et al.* 2007). These reports are publicly available. They contain detailed information about the area affected by various pests and pathogens across the United States, from 1920s onwards. The reporting assesses mortality and defoliation. The Major Forest Insect and Disease Condition reporting is based on targeted surveys, which are generally done from airplanes (aerial detection), but can also be supported by ground surveys and remote sensing (satellite).

Yet, as the Major Forest Insect and Disease Condition reporting is not based on representative sampling methods, the results are not directly comparable between years. Whereas the FIA system provides figures that are comparable across the years as well across different regions within the United States. Given their different purpose, the damage estimates between the two surveys will naturally differ. Figure 4.10 shows the recent FRA report on area of forest affected by insects and diseases in the United States, which stems from the FIA reporting. Figure 4.11 shows the area of forest (in acres) with tree mortality caused by insects and diseases based on the Major Forest Insect and Disease Condition reports.

The availability of several surveys (e.g. NFIs and assessments of specific causes of damage) can enrich set of sources that can be used for the international reporting, for example, the Major Forest Insect and Disease Condition survey also has species-specific information on not only on mortality, but also on forest area affected by various pests (bark beetles, moths, sawflies etc.). However, given that the objectives and methodologies of different survey programs are not always comparable, special attention should be paid when using them for compiling national data for international reporting, where representative figures at the country level are required.

FIGURE **4.10**

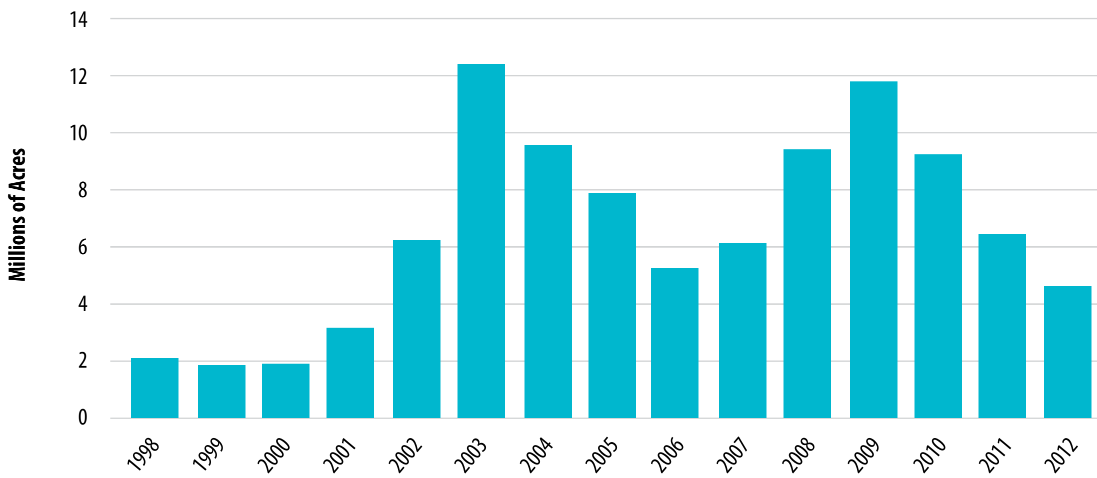
Area of forest damage in the United States caused by the group insects and diseases (FRA data, based on FIA reporting)



Data source: FAO 2020.

FIGURE **4.11**

Area of forest with tree mortality caused by insects and diseases in the United States



Source: Results of the Major Forest Insect and Disease Condition reporting for 2012 (USDA 2023b) https://www.fs.usda.gov/foresthealth/.

Literature

Bechtold, W.A. & Patterson, P.L. (2005). The enhanced forest inventory and analysis program--national sampling design and estimation procedures (No. 80). USDA Forest Service, Southern Research Station.

CFS. (2023a). Canadian Forest Service: information page on Canadian NFI and its results (site visited 26.3.2023): https://nfi.nfis.org/en/

CFS. (2023b). Canadian Forest Service: field guide of Canadian NFI. ISBN 978-1-100-11330-2. Available at (site visited 26.3.2023): https://d1ied5g1xfgpx8.cloudfront.net/pdfs/29402.pdf

FAO. (2020): Global Forest Resources Assessment data download center: https://fra-data.fao.org/assessments/fra/2020

Fridman, J., Holm, S., Nilsson, M., Nilsson, P., Ringvall, A. & Ståhl, G. (2014). Adapting National Forest Inventories to changing requirements - the case of the Swedish National Forest Inventory at the turn of the 20th century. Silva Fennica vol. 48 no. 3 article id 1095. http://dx.doi.org/10.14214/sf.1095

Korhonen, K.T., Ahola, A., Heikkinen, J., Henttonen, H.M., Hotanen J.-P., Ihalainen, A., Melin, M., Pitkänen, J., Räty, M., Sirviö, M. & Strandström M. (2021). Forests of Finland 2014–2018 and their development 1921–2018. Silva Fennica 55 (5) https://doi.org/10.14214/sf.10662

LaBau V.J., Bones, J.T., Kingsley, N.P., Lund, H.G. & Smith, W.B. (2007). A history of the forest survey in the United States: 1830–2004. FS-877. Washington, DC: U.S. Department of Agriculture, Forest Service. 82 p. Available at (visited 26.3.2023): https://www.fs.usda.gov/emc/rig/documents/HFSbook_FINAL_07_0625.pdf

SLU. (2023a). Swedish Agrigultural University SLU. NFI field guide (site visited 26.3.2023): https://www.slu.se/globalassets/ew/org/centrb/rt/dokument/faltinst/nfi_fieldwork_instructions_eng.pdf

SLU. (2023b). Swedish Agrigultural University SLU. Information on the Swedish NFI (visited 26.3.2023): https://www.slu.se/en/Collaborative-Centres-and-Projects/the-swedish-national-forest-inventory/

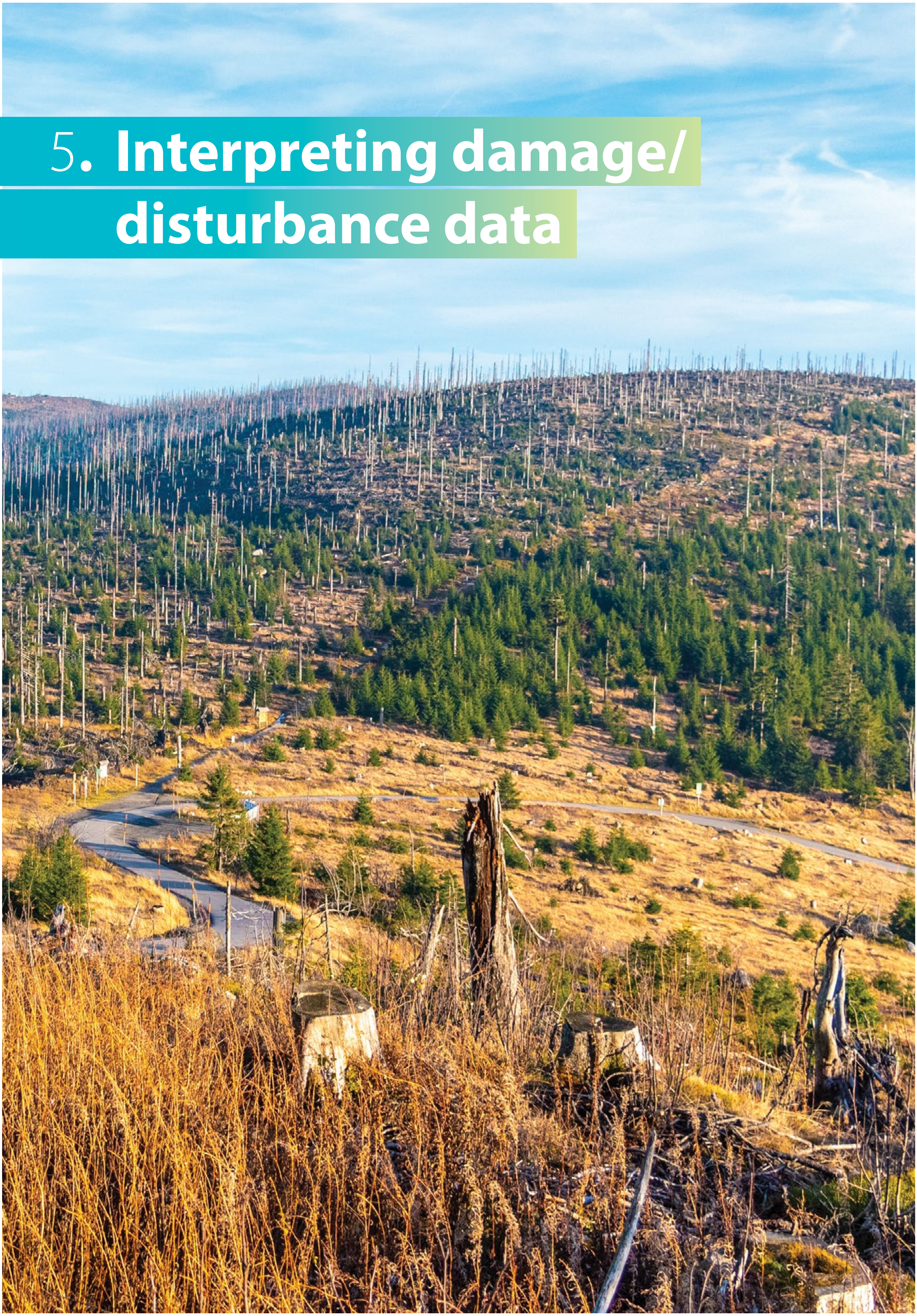
Statistics Poland. (2022). Statistical Yearbook of Forestry. Available at (site visited 26.3.2023): https://stat.gov.pl/download/gfx/portalinformacyjny/en/defaultaktualnosci/3328/12/5/1/statistical_yearbook_of_forestry_2022.pdf

Talarczyk, A. (2014). National Forest Inventory in Poland. Baltic Forestry 20(2): 333-340. https://www.researchgate.net/publication/279102556_National_Forest_Inventory_in_Poland (visited 26.3.2023)

USDA (2023a). Information sites on the Forest Inventory and Analysis program: https://www.fs.usda.gov/research/inventory/FIA (visited 26.3.2023)

USDA (2023b). Information site on the Major Forest Insect and Disease Condition reporting. https://www.fs.usda.gov/foresthealth/ (visited 26.3.2023)

5. Interpreting damage/ disturbance data



5. Interpreting damage/ disturbance data

Guy Robertson, Stefanie Linser, Michael Köhl, Andrzej Talarczyk

Data interpretation is the process of analysing, understanding, and making sense of numerical data that has been collected, aggregated and presented to draw subsequent conclusions and implications. The purpose of data interpretation is to extract specific information for decision-making and subsequent actions.

Data interpretation is preceded by collecting and organizing data. It assigns meaning to statistical estimates and visualizations and derives conclusions. This process is essential for understanding patterns and trends in the data, identifying areas that require further investigation, and informing decision-making on management and policy level. When interpreting the data, the origin of the data as well as the chosen evaluation procedures must be considered. This is especially true when data are collected for only a subset of the total population and therefore cannot be generalized.

Data interpretation is a critical process, as depending on the particular view of the interpreter it may be subjective. Apart from personal or organizational biases, further challenges for data interpretation include poor data quality resulting in inaccurate or misleading conclusions, as well as complex data sets which require specific statistical or analytical expertise. Therefore, it is inevitable to observe some principles in interpretation.

The following chapter focuses on the process of interpretating data emerging from damage/disturbance reporting, and how resulting interpretations may be used. Key messages include: (1) damage/disturbance data are directly dependent on complex and often divergent measurement protocols; (2) reported data are often incomplete and/or inconsistent and these shortcomings need to be explicitly recognized in analysis and interpretation; and (3) convincing interpretations will require synthetic analysis, incorporating additional data and reference information outside the narrow scope of particular damage/disturbance data, particularly those presented at aggregate spatial scales. The chapter concludes with several examples of interpretations of damage/disturbance data in a synthetic context.

5.1 Steps in interpretation of damage/ disturbance data

Once the source data have been organized, the next step is to interpret the results. It is important to consider the limitations of the data and the potential sources of bias that may have influenced the results. Interpreting damage and disturbance data involves four steps to draw legitimate, transparent, and bias-free conclusions.

Step 1: Assemble the information needed

First, the available statistical estimates and the graphical output needed to draw conclusions are collected. Important additional information includes:

- **Sampling frame/ Population covered**: a description of the sampling frame or the (sub-) population covered. This information is of particular importance when damage/disturbance data are assessed by special surveys conducted in a limited area where damage occurred. The interpretation has to refer to the population covered by the data and should not extend beyond this area.
- **Sample completeness**: for UNECE-reporting of damage/ disturbance the completeness of sample (response rates) have been found to be critical for some regions or damage causes. Therefore, the sample completeness has to be considered in data interpretation.
- **Double counting**: some causes of damage usually occur together, such as drought and bark beetle infestations. Therefore, the data must be analysed to identify whether there may be double counting. It is advisable to make a consistency check based on the total area of forest affected by damage/disturbance. The sum of the areas reported for individual causes of damage/disturbance must not exceed the total forest area affected by damage/ disturbance. Due to national differences in reporting, this consistency check has to be done country by country.
- The **nomenclature systems** of the reporting countries may differ (see chapter 3). This concerns among others the question of threshold values, differences in the timespan in which the occurrence of a damage/ disturbance is assigned to the current assessment or the reporting of tree- or area-related damage/ disturbance. When interpreting the data, the comments in the country reports and, if necessary, the recording instructions of individual countries should be consulted.
- **Spatial and temporal variation**. Damage/disturbance processes often exhibit high degrees of spatial and temporal variation that confound statistical analysis and the identification of trends or deviations from trend.

- **Statistical implications associated with aggregation**. Even if broadly consistent time series data are available at a wide scale, the process of aggregation introduces issues in interpretation that must be recognized. Changes that are significant at smaller spatial scales may well be offset or otherwise obscured in aggregate data series describing larger spatial scales. This observation is also true for temporal scales, particularly in the case of NFIs relying on rolling samples with relatively long plot return schedules averaged over time to derive periodic reports. Spatial or temporal aggregates may obscure an essential aspect of damage/disturbance processes: their high variance.
- Discerning **baselines for comparison**. Suitably consistent and long-term time series needed to establish baselines for comparison are relatively rare, especially across multiple countries or regions.
- **Causal attribution** in dynamic systems. Damage/disturbance processes depend upon numerous factors, including historical land-use and management regimes and dynamic forest processes as forest stands mature and change. When attributing change to specific causes (climate change, for example), these other factors must be accounted for.

Step 2: Develop findings

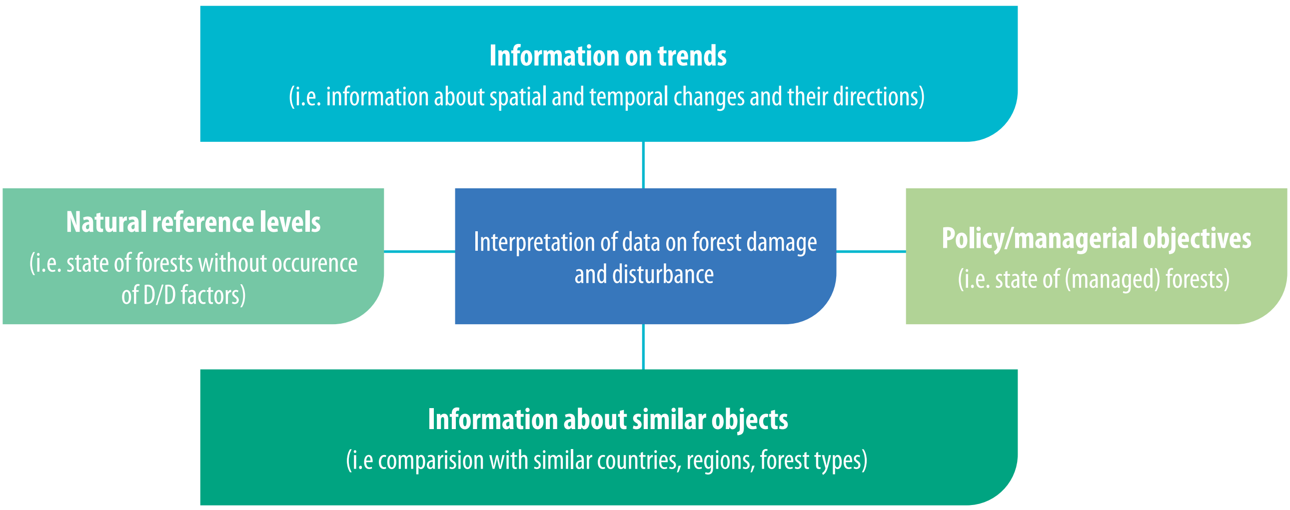
Findings are observations about data. They are the statements that summarize the important points, including trends, patterns or lack of patterns. Developing findings is a process in which results are cross-validated (e.g. by comparing with known standards or guidelines, with other results of the data set, or with auxiliary data) and in which quality assurance/quality control results (e.g. comments in the national reporting documents) are analysed.

Developing findings demands additional information (baselines for comparison), that helps adding meaning to the collected data. Possible sources for interpretation of forest damage/disturbance data (see Figure 5.1) include:

- Natural reference levels, i.e. state of forests without occurrence of damage/disturbance factors;
- Policy/managerial objectives, i.e. state of (managed) forests envisaged as optimal (or acceptable) for serving assigned functions,
- Information on trends, i.e. information about spatial and temporal changes and their directions
- Information about similar objects, i.e. comparison with similar countries, regions, forest types.

FIGURE **5.1**

Interpretation of data



Step 3: Develop conclusions

Conclusions provide an explanation of the context of the data results and highlight implications for future actions. There are many opportunities for interpretation at large spatial scales, opportunities that will benefit from enhanced data reporting and harmonization. First among these opportunities is the enhanced ability to identify damage/disturbance processes that warrant additional analysis using disaggregated data and/or additional information in a synthetic fashion. This approach is particularly important when attributing change to specific causes.

Additionally, the ability to derive aggregates at regional, and broader spatial scales may reveal important changes that are not directly apparent from country-level data series. Note that this sort of analysis may not always require direct comparability between country level statistics, just as long as those statistics are consistent over time and allow for reliable estimation of rates of change. While the aggregate data series may not be suitable for statistical hypothesis testing and related analysis, they can still provide a foundation for synthetic interpretation.

Conclusions involve attribution to causes. Since forest damage is the result of complex impact chains, potential causes include, among others, extreme weather events, climate change, silvicultural treatments, site suitability, invasive pests, or pollution. The combination of different causes can lead to an aggravation of the effects.

Similarly, the consequences of damage/disturbance can be interpreted in many ways. Interpretive approaches range from altered ecosystem processes leading to restoration of natural forest cover or adaptation to climate change, to economic impacts for forest owners or the timber market. Selective choice of causes and consequences can lead to biased interpretations. Therefore, when interpreting results, it is essential to always consider economic (e.g., loss of value), ecological (e.g., resilience, adaptation), and socioeconomic (e.g., jobs, recreation, protective effects) aspects equally.

Step 4: Develop recommendations

Recommendations are based on findings and conclusions. They can take two forms: action that should be taken and further information that should be gathered.

5.2 Examples

The following examples will help illustrate some of the challenges and opportunities for using damage/disturbance data in synthetic analysis focused on change detection.

5.2.1 Forest fires in the United States

In the last few decades wildland fire in the western United States has emerged as a pressing concern for both forest managers and the general public. Fire extent and severity have been increasing. Fire suppression costs account for a large and growing proportion of the Forest Agency budgets. Recent fire seasons have seen a number of catastrophic fires resulting in a growing number of deaths and extensive damage to human settlements. Increasing drought and summer-time heat conditions are an underlying factor linked to climate change.

The National Interagency Fire Center (NIFC) compiles data on wildland fires (number of fires and total area burned) for the United States[22]. These data are the main source for aggregate wildland fire data in the United States. Likewise, these are the numbers reported to FAO FRA. The primary data sources used by NIFC to derive aggregate measures come from state and federal "situation reports," which are produced by local units as fire incidents arise. Not all fires are reported, with inclusion being determined by size (over 40 hectares) but also by the amount and type of suppression effort applied. The actual thresholds and requirements are quite complex and reflect immediate fire management concerns more than they do information needs for either scientific analysis or broad-scale aggregations to describe fire behaviour. Nonetheless, these data have a number of advantages in more general reporting settings—they are relatively simple and widely used, and they have been compiled on an annual and consistent basis since 1983. Also, The NIFC data are timelier than fire data emerging from the United States' NFI, which relies on a ten-year plot return cycle in the fire-prone western states. Previous-year NIFC data at the state and national levels, on the other hand, can be available as early as June of the following year. However, for a number of reasons, the NIFC data requires care when interpreted at aggregate levels.

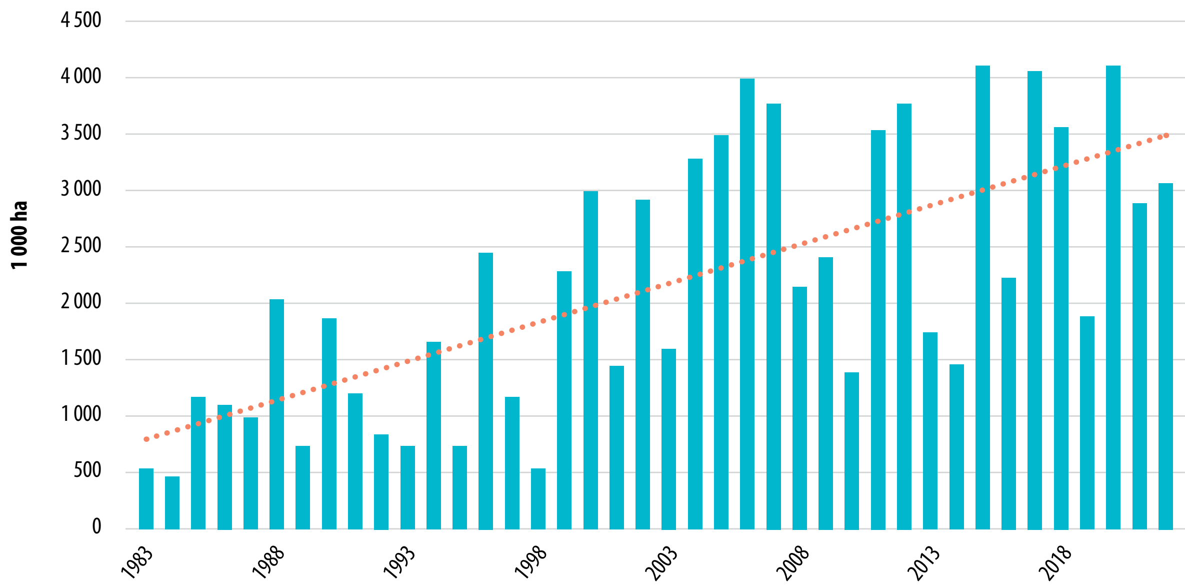
In the first place, NIFC reports *wildland* fire totals, which include grassland and brushland fire along with forest fires. As such, these numbers are not directly comparable with forest specific numbers produced elsewhere, nor are they comparable to estimates produced by the United States'. NFI, which covers forest lands only. Still, the NIFC data contains the numbers commonly referenced in United States' national reporting, and not surprisingly since overall wildland fire is the variable of principal public interest, not whether that fire occurs on forests, woodlands or grasslands as defined in the NFI. Fires in forests account for slightly over half of all fire areas, at least in recent decades (Koch and Ellenwood, 2020), but this percentage is subject to wide annual variation.

Although an increasing trend is clearly discernible in Figure 5.2, there is a high degree of temporal variation, with recent annual levels fluctuating between a low of 1.4 million ha. (in 2010) and high of 4.1 million ha. (in 2015). Spatial variation (not shown here) is likewise high, particularly with the inclusion of Alaska, the country's largest state and the location of large fires affecting remote boreal forests. In years when Alaska

22 https://www.nifc.gov/

FIGURE **5.2**

Area burned in wildland fires in the United States, 1983-2022



Source: National Interagency Fire Center (https://www.nifc.gov/).

exhibits large fires, the state tends to dominate the national aggregate fire statistics. High variance in turn indicates the care that must be taken when identifying overall trends and average conditions in national or regional aggregate data.

Establishing a baseline for comparison and identifying underlying causes for change leads to more fundamental challenges. The data in Figure 5.2 support the assumption that there now is considerably more wildland fire in the United States than in the last century. This, however, is not the case. Figure 5.3 shows the same NIFC data for 1983 onward as shown in Figure 5.2, but it also includes data on wildland burn area for prior years, going back to 1926. These earlier data, developed by the USDA Forest Service (Peterson and Barret 2021, USDA Forest Service, 2011), are of unknown provenance and are not statistically consistent with the NIFC data. Nonetheless, even a very approximate comparison shows that there may have been as much as four times more burnt area in the early years of the last century than is evident today. This finding is supported by a broad consensus among forest scientists and mangers that wildland fire was much more prevalent in the past, prior to the introduction of extensive fire suppression in the first half of the last century, particularly in regions where ecosystems originally adapted to low intensity fires on a relatively short return cycle are common (Peterson and Barret 2021, Moritz *et al.* 2018). As a result, constructing a baseline for comparison based on the supported, post-1983 data does not appear to be a viable option, but neither does using prior data, even if its provenance was better understood.

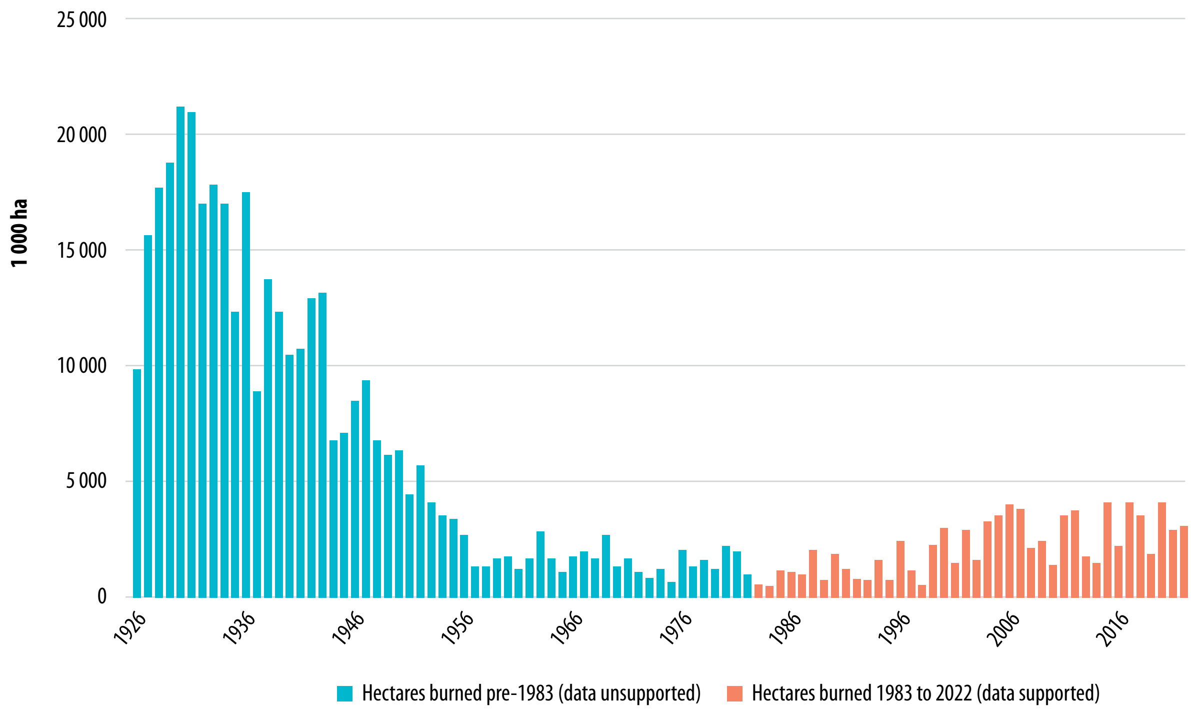
The history and current trajectory of wildland fire in the western United States is complex and place dependent. However, owing to the broad-scale success of fire-suppression efforts, the fire behaviour witnessed since 1983 must generally be interpreted in the context of substantially altered forest systems characterized by increasing (and increasingly homogeneous) fuel loadings in the absence of periodic fire.

At the same time, various markers of fire behaviour point to the impact of climate change over and above what would be expected in its absence (Abatzoglou and Williams 2016 and other). These include increasing fire intensity, length of fire season, and area burned in large fires that escape initial suppression efforts. Additionally, climatic factors associated with wildland fire, such as drought and extreme heat events, are rising (Koch and Ellenwood 2020). This additional information, over and above that provided by the NIFC data, indicate multiple causal agents, notably climate change and fire suppression, interacting in a dynamic fashion to produce the fire behaviour witnessed in recent years.

While the NIFC burn area data that constitutes the most likely variable for international reporting supports this interpretation, additional information is needed to identify causal factors, management implications, and departures from historical levels. Single variable time series may indicate the need for further analysis, but the interpretation of these data requires additional information to understand casual dynamics as well as temporal and spatial variation.

FIGURE 5.3

Area burned in wildland fires in the United States, 1926-2020



Source: 1983-2021 National Interagency Fire Center[23]. 1926-1982 USDA Forest Service.

Note: Data includes all wildland fire, including that occurring on grass and brushlands).

5.2.2 Storm damage in the European Union

Forest in Europe cover 35% of the total land area and have a wide range of ecological, social and economic functions that continue to grow in importance (Forest Europe, 2020). Storms have caused damage to pan-European forests throughout history, during the past 70 years, 130 major storm events hit parts of Europe, damaging forest area (Figure 5.4) and timber volumes (Figure 5.5) (DFDE database; Forest Europe, 2020). These damages have increased markedly and now account for more than 50% of primary damage to European forests (Corvol, 2009; Gardiner *et al.* 2010 and 2013; Ferretti *et al.*, 2020; Schelhaas, 2003). It is expected that climate change will result in continued increases in storm damages in Europe (Lindner *et al.*, 2010).

The total area of forest damaged by storm, wind and snow (including drought, mudflow, avalanche and other identifiable abiotic factors except fire) is the present indicator for aggregate weather damage reporting in the UNECE region, and it is the only severe-weather related measure reported at global scale by the FAO FRA. However, considering decision makers' interest in instituting well-organized phytosanitary activities and in avoiding market distortions, measures of damaged volumes and the proportion of those volume that are salvage timber may also be taken into consideration.

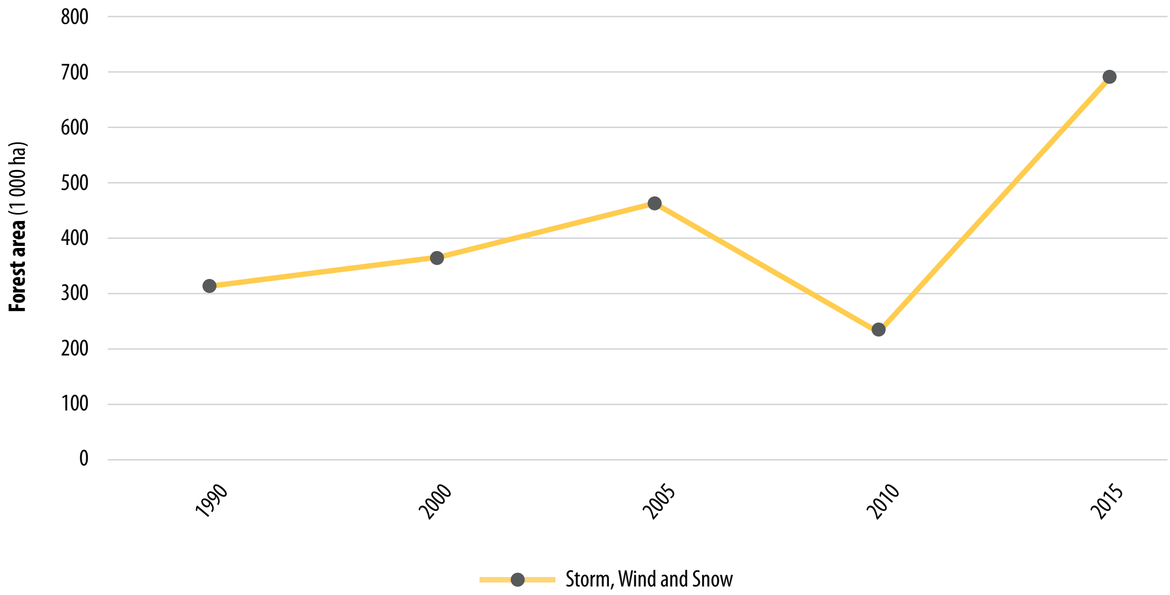
To properly plan phytosanitary measures, timber storage, logistics for timber transport or reforestation activities, consistent, harmonized information is needed. To avoid market distortions due to misinformation on the area of damaged forests and on the resulting volumes of damaged timber, it is expected that this information includes not only the size of the damaged area but also the volumes of damaged timber, preferably from the local to national level.

Responses of forest managers, forest owners and researchers to European storm events have provided much data and information. However, a complete picture of destructive storm events in European forests is difficult, as a large amount of the data and information is available only on a regional or even local scale and is scattered over many sources and not regularly monitored or reported based on harmonized measurement methods (Gardiner, 2010).

23 https://www.nifc.gov/

FIGURE **5.4**

Area of forest with damage by storm, wind and snow as continuously reported by 10 European countries



Source: Forest Europe (2020): State of Europe's Forests Report. Ministerial Conference on the Protection of Forests in Europe – FOREST EUROPE. Bratislava, Slovakia. https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf, Table 18.

With increasing climate change, and a growing age of forest stock, storm damage in Europe is very likely to continue to rise. Therefore, the need for well-coordinated management responses will rise along with it. Such responses will require data and related information that is reported at the national, European Union, and the pan-European level in a harmonized and comparable fashion to guarantee a fair and prompt distribution of various kinds of countermeasures (for instance cross-border assistance, compensation payments, reforestation subsidies or tax relief).

Based on the request by the European Commission, the European Forest Institute (EFI) has created an extensive Database on Forest Disturbances in Europe (DFDE)[24] to better understand the influence and impacts of destructive storm episodes, and as a basis for a report to the European Commission (Gardiner *et al.*, 2013). The authors of the DFDE categorized storm damage in three components:

- Primary damage: Initial mechanical damage to the trees caused by the storm.
- Secondary damage: Subsequent damage following the initial windstorm. This is mostly from bark beetles, but can emerge as well from other biotic factors or abiotic factors such as fire, snow/ice and even additional storm damage.
- Tertiary damage: Loss of production in shortened forest rotations and other long-term constraints on forest operations.

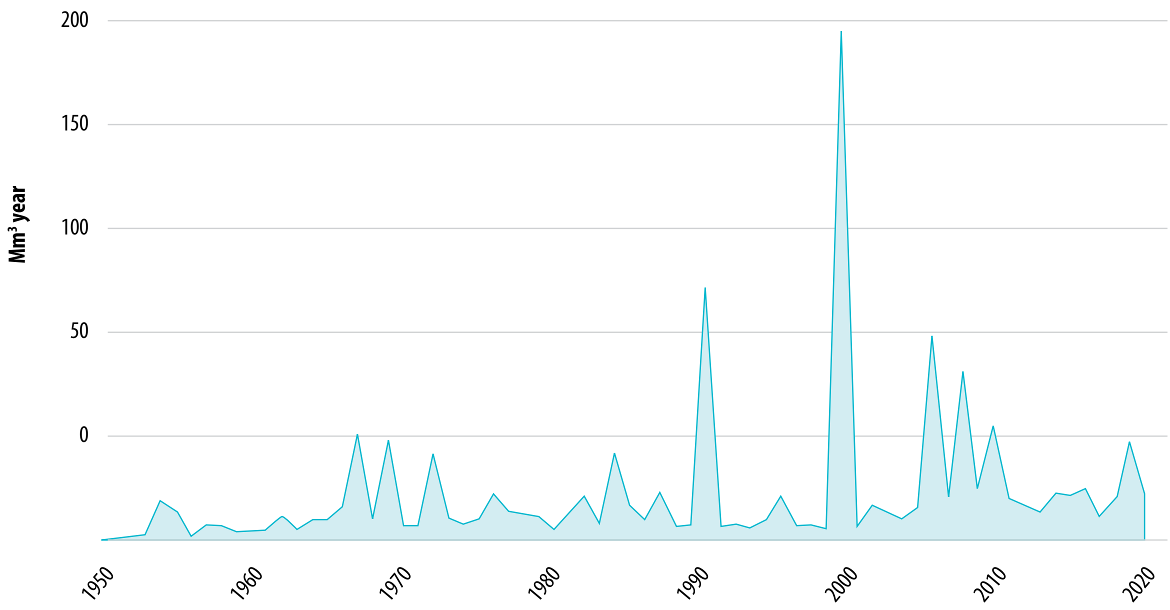
The DFDE contains information for each damaging event with regard to primary damage (m^3), secondary damage (m^3), estimated growing stock (m^3), percentage of growing stock initially damaged (primary damage), removals (m^3) and value (in Euro) in year of forest damage. The DFDE contains information on around 170 storm events, 60 from 1800 to 1900 and annually from 1901 on, but in some years with very low amounts of damaged volumes. Figure 5.5 shows that the impact of damaging storm events increased in the past 35 years. However, in the interpretation of the damage in volume, it should be also considered that in the analysed period the overall volume and age significantly increased. According to SoEF 2020 (Forest Europe, 2020), the growing stock of European forests has increased by 50% since 1990.

For weather-related disturbance in the Global Forest Resource Assessment of FAO and the Joint UNECE/FAO/Forest Europe Pan-European Data Collection (JPEDC), the joint questionnaire records only the area of forest damaged (and not the timber volume, for example). The respective indicator 2.4 on forest damage contains a sub-category for "area of forests damaged by storm, wind and snow". However, the respective reporting notes request joint data on storm, wind, snow, drought, mudflow, avalanche and other identifiable abiotic factors – except fire.

24 Database on Forest Disturbances in Europe (DFDE): https://dfde.efi.int/db/dfde_app.php

FIGURE **5.5**

Volume (Mm³) of wood damaged by storms as reported in European countries from 1950–2019



Source: Patacca, M., Lindner, M., Lucas-Borja, M. E., Cordonnier, T., Fidej, G., Gardiner, B., & Schelhaas, M. J. (2023). Significant increase in natural disturbance impacts on European forests since 1950. Global change biology, 29(5), 1359-1376. DOI: 10.1111/gcb.16531.

In the most recent JPEDC (2020), only 25 of 46 pan-European countries reported any data on the "area of forest with damage by storm, wind and snow" (Forest Europe, 2020, Annex 8 - Table 17). Table 18 in the same source report displays the resulting information for the years 1990, 2000, 2010, 2015. In 1990 only 15 of 46 countries reported the respective data. Comparable data for all four reference years was only available for 10 of 46 countries and thus does not provide a representative picture for all of Europe.

Despite they are done according to entirely different methodologies, and have different coverage, both (DFDE and JPEDC) sources indicate the increase of damaged areas and volumes in recent decades. When interpreting these data, the conclusion could be drawn that the pace of damage reported by the DFDE exceeds the one in the JPEDC. Although the detailed reasons for this discrepancy cannot be determined easily, and regardless of which source is analysed, additional information is necessary for interpreting collected data and presenting it in a larger (and possibly more complete) context.

5.2.3 Bark beetles in the German mountain range Harz

The Harz is a low mountain range in Germany, characterized by a rich variety of flora and fauna. At the highest elevations, from about 800 m to the timberline at 1000 m, spruce forests predominate, while at lower elevations up to 700 m, beech forests dominate. At middle altitudes from 700 to 800 m, mixed beech-spruce forests would occur under natural conditions. In the Harz there is one national park, one biosphere reserve and four legally independent nature parks.

At the end of the 1940s, due to intensive clear-cutting for reparation payments in connection with Second World War, the Harz could only be afforested with spruce plantations. However, the resulting monocultures attracted bark beetles, especially when the trees were weakened by other stress factors - such as climate change in particular. Meanwhile 14,700 hectares (= 72%)[25] of its total spruce forest area of 20,500 hectares were destroyed by the bark beetle by 2020 (Figure 5.6). The perception of nature conservation, tourism, or business representatives on large-scale mortality, particularly with respect to the need for active mitigation measures such as sanitary fellings, is not uniform. How this disturbance is interpreted, and what conclusions and indications are made can be seen from different perspectives in the following examples from the press (wording original, unofficial translation).

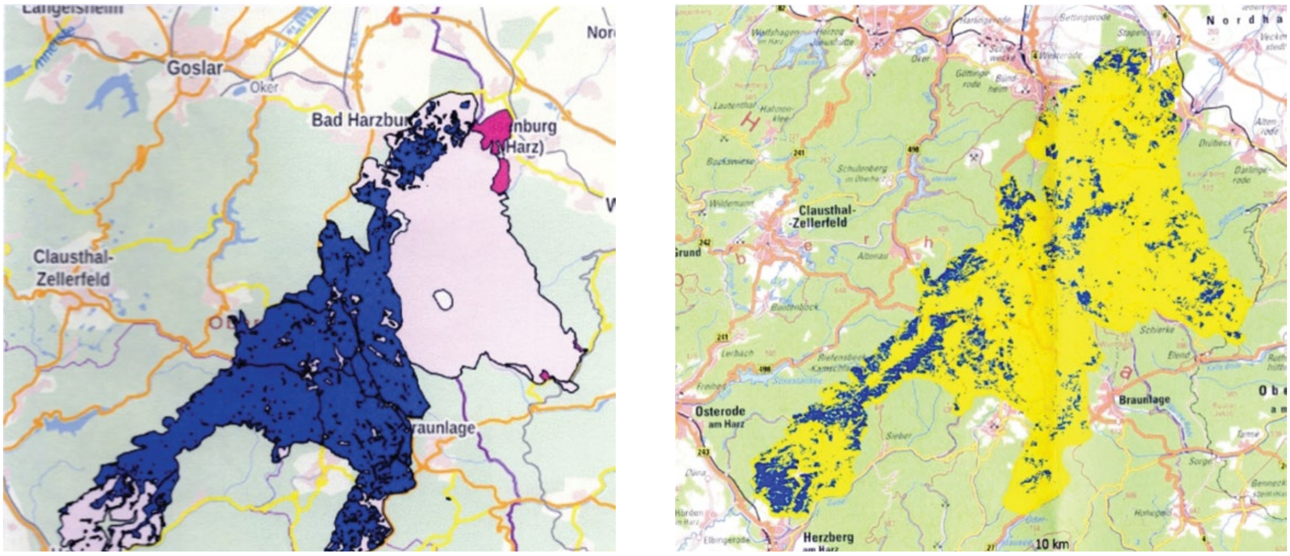
Nature conservation: Let nature be nature

"In line with the motto of the national park "Let nature be nature", nature is allowed to develop freely in large parts of the

25 https://www.harzer-waldsterben.de/

FIGURE **5.6**

The transnational Harz National Park in Lower Saxony and Saxony-Anhalt as of 2006



Source: Bundesamt für Kartographie u. Geodäsie (Federal Agency for Cartography and Geodesy), on: https://www.harzer-waldsterben.de/.

Note: As recently as 2003, the spruce stands - highlighted in blue - in the Harz National Park (Lower Saxony) were completely intact. The area highlighted in blue on the right map shows the remaining spruce forest areas (2022) not yet infested by the bark beetle.

national park. Former commercial forests with their human-dominated spruce monocultures are allowed to become wild natural forests again. An initially perhaps alienating, but also fascinating forest change is taking place. Nature has different standards of time and order than we humans do. Dead spruces are a sign of the change to wilderness and an important basis of life for many creatures, as food, hiding place or nursery. That is why the dead spruces remain standing and lying in the national park forest. Between their silver trunks, new life is germinating everywhere - more species-rich, more diverse and more robust than before. A new wilderness is growing up."[26]

Tourism: The uncontrolled tree death could cause considerable damage to tourism

"The Harz forests look how the layman imagines a lunar landscape. The accumulation of nothing: breakage, rubble, undergrowth and the dominant color brown. In the vacation resort of Schierke, which is bordered by the national park, the situation is viewed with concern. "This uncontrolled tree death could cause considerable damage to tourism," fears local mayor Christiane Hopstock. She has nothing against the national park. But then comes a big BUT: "Does forest conversion really have to be so radical?" There are two large groups of guests in Schierke, she says: older people and young families. "They walk through the dead forests once, but certainly not twice," says Hopstock."[27] [28]

Forestry-Carbon: The Harz National Park is rapidly becoming a uniform, huge area of deadwood

"The effects on the economy and tourism are also devastating. But especially the ecological consequences up to the negative CO_2 - balance are massive. Up to 5 million tons of carbon dioxide (CO_2) are released by the decaying dead wood over the years.

The Harz National Park has deliberately refrained from bark beetle control since 2006 as part of its basic philosophy of "let nature be nature". The supposed acceleration of forest conversion by the pest, towards mixed forests, is desired there. The philosophy "Let nature be nature" of the national park should actually apply more extensively to the entire animal and plant world (fauna and flora) and all natural processes. But currently an important native game species, the red deer, which also lives in the national park, is hunted massively. Without targeted control of the bark beetle, the forest sector will face the same dead wood areas again in a few decades at the latest, as can already be observed. If the spruce areas

26 Source: https://www.nationalpark-harz.de

27 Sources: https://www.weser-kurier.de/region/tourismus-im-harz-leidet-unter-dem-borkenkaefer-doc7esa68i1cqo1fuux3f6u

28 Source: https://www.mz.de/mitteldeutschland/gezieltes-sterben-tote-fichten-und-bangen-um-touristen-im-nationalpark-harz-1576294

renew themselves, which according to our knowledge is only possible on partial areas, and the bark beetle continues not to be controlled there, the drama will start all over again on these areas when the spruce is 50 years old or older."[29]

Timber market: When the spruces fall in the forest, timber industries benefit

The recent significant increase in the compulsory use of the forest resources due to forest damage and an increased order situation in the timber market from of Germany and abroad led to contrary developments in the forestry and timber industry. For example, wood consumption and prices for sawn timber rose sharply. The timber industry benefited from lumber exports mainly from buyers in China and the U.S., while large volumes of raw lumber were shipped mainly to China: In the period between 2015 and 2020, the volume of raw wood exports more than tripled. During the same period, timber imports decreased by one-third.

Forestry suppliers of raw wood, on the other hand, are currently hardly benefiting from growing wood consumption. Raw wood prices - as measured by the index of producer prices of harvested wood products - have been rising moderately for several months, but in June 2021 they were still far below the level of 2015. In 2021, on the other hand, producer prices for processed wood rose at an above-average rate. In particular, the prices for softwood lumber increased extremely, in July 2021 these were 90% above the prices of January 2021.[30]

29 https://www.harzer-waldsterben.de/

30 www.holzkurier.com

Literature

Abatzoglou, J.T.; Williams, A.P. (2016). Impact of anthropogenic climate change on wildfire across western U.S. forests. Proceedings of the National Academy of Sciences of the United States of America. 113(42): 11770–11775.

Corvol A. 2009. Grands vents et chablis, XVIe-XIXe siècles : aspects historiques. In: Birot Y., Landmann G., Bonhême I. Eds., La forêt face aux tempêtes. Editions Quae, 15-27

Ferretti, M.; Waldner, P.; Vertraeten, A.; Schmitz, A.; Michel, A.; Zlindra, D.; Marchetto, A., Hansen, K.; Pitar, D.; Gottardini, E.; Calatayud, V.; Haeni, M.; Schaub, M.; Kirchner, T.; Hiederer, R.; Potocic, N.; Timmermann, V.; Ognjenovic, M.; Schuck, A.; Held, A.; Nikinmaa, L., Köhl, M.; Marchetti, M.; Linser, S. (2020): Criterion 2: Maintenance of Forest Ecosystem Health and Vitality. In: State of Europe's Forests 2020 Report. Ministerial Conference on the Protection of Forests in Europe – FOREST EUROPE. Bratislava, Slovakia.

Forest Europe (2020): State of Europe's Forests 2020. Forest Europe Liaison Unit : Bratislava, Slovakia.

Gardiner, B.; Schuck, A.; Schelhaas, M.-J.; Orazio, C.; Blennow, K.; Nicoll, B. (eds.) (2013): Living with Storm Damage to Forests. What Science Can Tell Us 3. European Forest Institute. Joensuu, Finland

Koch, F.H. ; Ellenwood, J.R. (2020). Indicator 3.16: Area and percent of forest affected by abiotic agents (e.g., fire, storm, land clearance) beyond reference conditions. U.S. Forest Sustainability Indicators, USDA Forest Service. https://www.fs.usda.gov/research/inventory/sustainability.

Lindner, M., Maroschek, M.; Netherer, S.; Kremer, A.; Barbati, A.; Garcia-Gonzalo, J.; Seidl, R.; Delzon, S.; Corona, P.; Kolstro, M.; Lexer, M.J.; Marchetti, M. (2010): Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and management 259: 698-709.

Moritz, M.A.; Topik, C.; Allen, C.D.; Hessburg, P.F.; Morgan, P.; Odion, D.C.; Veblen, T.T.; McCullough I.M. (2018). A Statement of Common Ground Regarding the Role of Wildfire in Forested Landscapes of the Western United States. Fire Research Consensus Working Group Final Report. https://pubs.er.usgs.gov/publication/70217618.

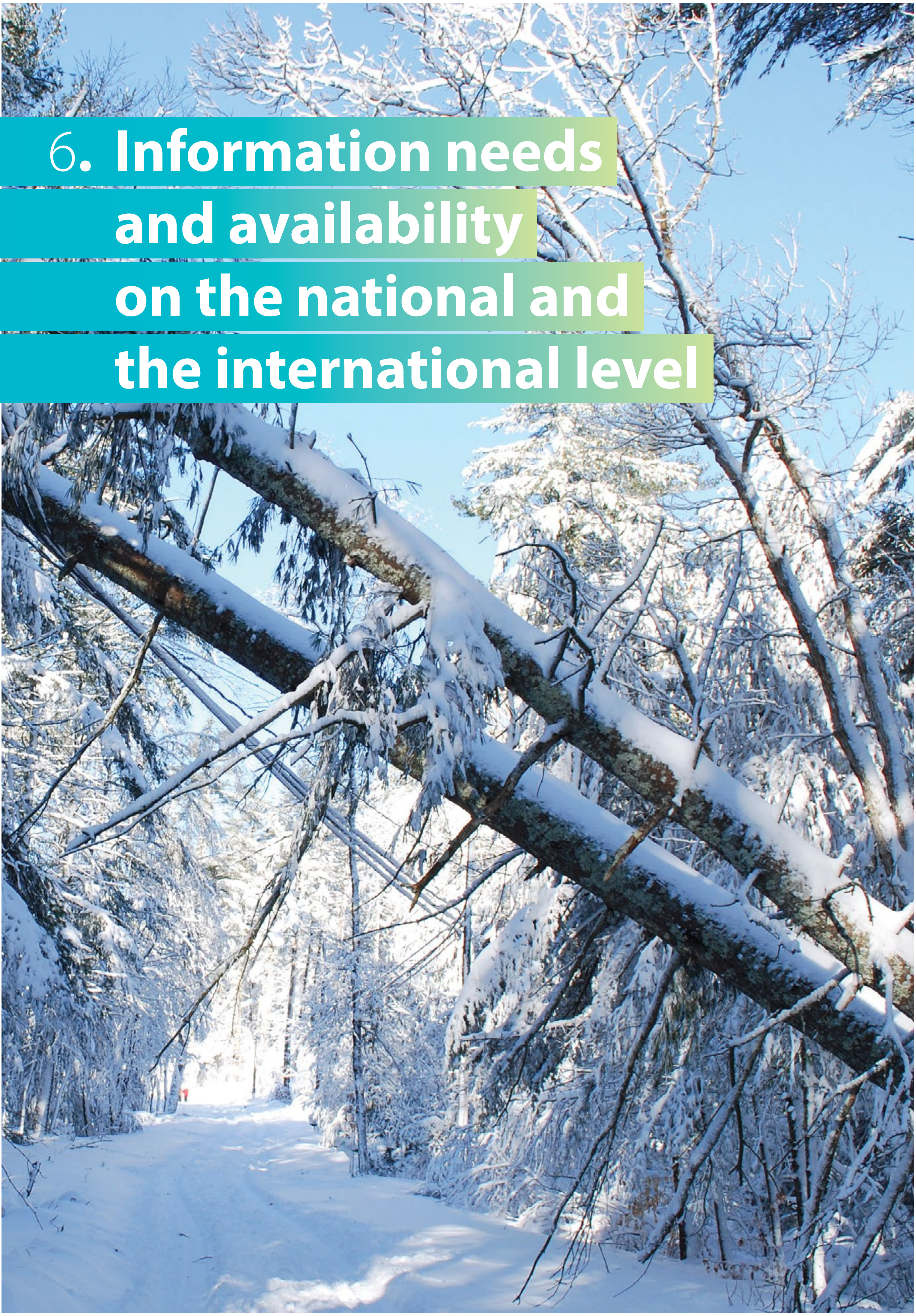
Patacca, M., Lindner, M., Lucas Borja, M. E., Cordonnier, T., Fidej, G., Gardiner, B., & Schelhaas, M. J. (2023). Significant increase in natural disturbance impacts on European forests since 1950. Global change biology, 29(5), 1359-1376. DOI: 10.1111/gcb.16531

Peterson, D.W.; Barret, T.M. (2021). Fire Disturbances. Chapter 4 in Barrett, T. M.; Robertson, G. C., eds. Disturbance and sustainability in forests of the Western United States. Gen. Tech. Rep. PNW-GTR-992. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 231 p. https://www.fs.usda.gov/research/treesearch/62126.

Schelhaas, M.-J., Nabuurs, G.-J., & Schuck, A. (2003): Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biology, 9(11), 1620–1633. doi:10.1046/j.1365-2486.2003.00684.x

USDA Forest Service. (2011). National Report on Sustainable Forests—2010. G. Robertson, Editor. FS-979. Washington D.C.: USDA Forest Service. 212 pp. https://www.fs.usda.gov/research/treesearch/54685.

6. Information needs and availability on the national and the international level



6. Information needs and availability on the national and the international level

Stefanie Linser and Michael Köhl

The following chapter presents information needs and information assessed on the national level relevant to forest damage/disturbance reporting in the UNECE region drawing upon project-survey results concerning current FAO FRA reporting practices.

To improve international and national reporting as well as an additional revision of damage/disturbance related indicators, an analysis of the submitted national responses was envisaged to establish an initial basis for further methodological and procedural arrangements regarding forest damage/disturbance.

6.1 Objectives

According to the described context of forest damage/disturbance (see chapter on Conceptual Foundations), the survey aimed to assess the information needs for international reporting on forest damage/disturbance.

The analysis of the responses to the questions asked in the survey contributed to the following objectives:

1. Identification of needs, gaps and opportunities on reporting and assessment of forest damage/disturbance in the UNECE region for FRA reporting.
2. Comparison of current international reporting formats with information potential of national assessment systems in the UNECE region and identification of options for their improvement.
3. Development of recommendations for current best practice reporting schemes (see chapter 8).

Furthermore, the analysis contributed to highlighting implications and requirements for the interface of science, policy and practice to meet state-of-the-art prerequisites.

6.2 Methodology

The questionnaire on forest damage and disturbance was elaborated by the UNECE/FAO Team of Specialists (ToS) on monitoring Sustainable Forest Management and issued by the UNECE/FAO Forestry and Timber Section in September 2021 (UNECE/FAO, 2021) to the related National Correspondents (NC) of the FAO Global Forest Resources Assessment.

The questionnaire addressed the following areas of interest:

- Part IA: Information needs for global FRA reporting on forest damage/disturbance (analysed in chapter 5)
- Part IB: Information needs on pan-European reporting on forest damage/disturbance (see chapter 3)
- Part II: Definitions and assessment methods applied at the national level (analysed in chapter 6)
  - II.a Damage/Disturbance
  - II.b Thresholds
  - II.c Time of occurrence
  - II.d Multiple causes
  - II.e Forest area damage/disturbance

The questionnaire aimed to identify and to understand the information needs expressed to international reporting and challenges of national forest damage/disturbance reporting. In order to achieve this purpose, a mixed method research design was applied, since the survey contained quantitative closed questions along with the possibility of open-end comments to certain questions. The online survey was conducted via the web application "Survey Monkey".

Since quantitative data can help to understand qualitative data, the quantitative data was first analysed. Questions guiding the analysis comprised:

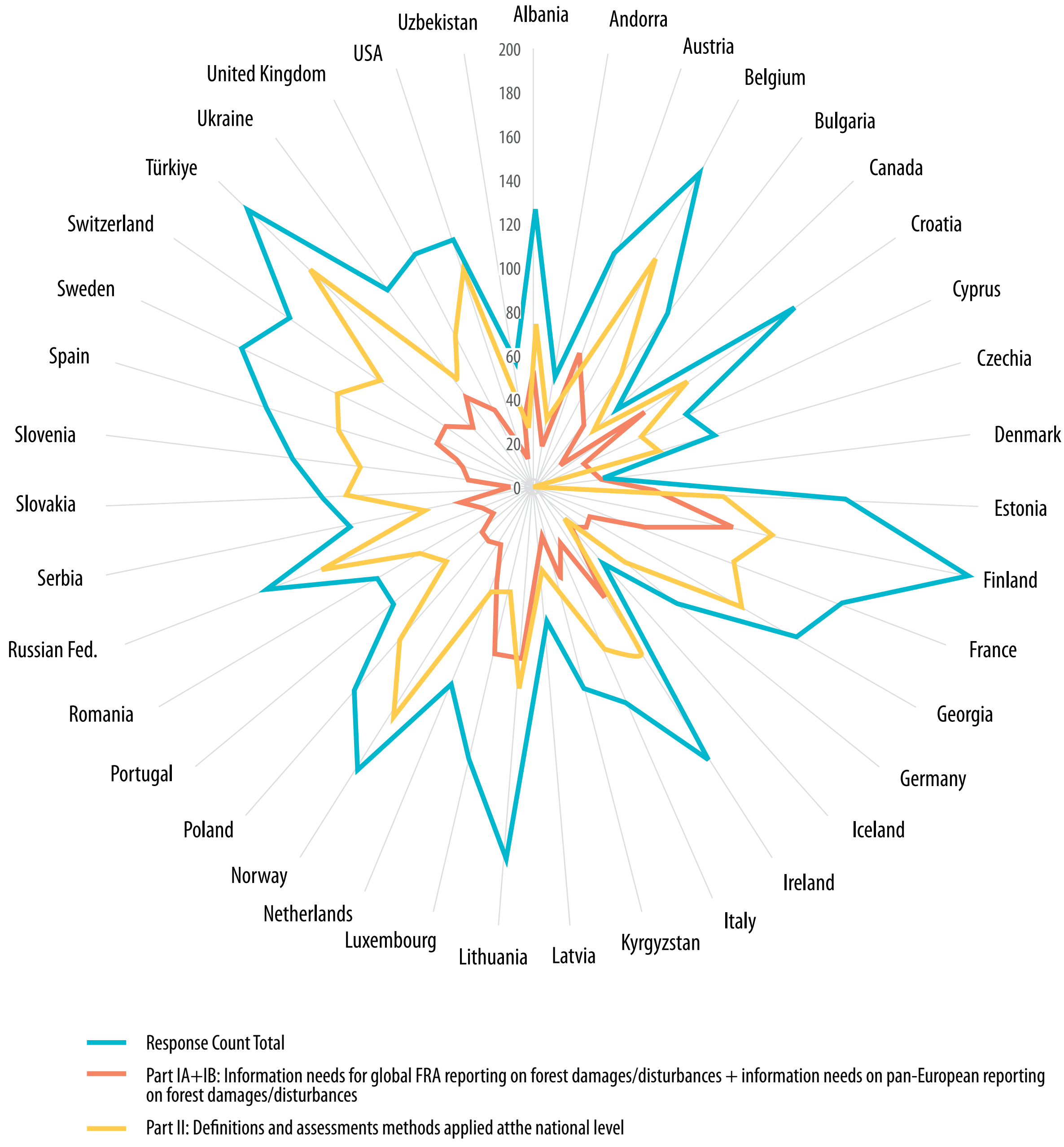
- What are the most common responses to a given question?
- Which responses will address further information for the next FRA?
- Which time periods for monitoring and reporting are considered sufficient?
- Which respondents are most affected by a given issue?

6.3 Response counts to the survey and background

The online questionnaire was sent to the national FRA correspondents of the 56 UNECE member States. Responses were obtained from 39 countries. The forest area of all 56 UNECE countries comprises 1 714 mil ha. The forest area of

FIGURE **6.1**

Response counts of the replying countries in total and with regard to various parts of the questionnaire



Data Source: UNECE/FAO, 2021.

those 39 UNECE countries which replied to the online survey comprises 1 685 mil ha. With a 98 per cent share of the UNECE forest area covered, the survey responses are highly representative for the UNECE region.

All responding countries replied to questions in part IA (Information needs for Global FRA and pan-European reporting) and part II (Definitions and assessment methods applied at the national level). From the maximum of 200 possible responses, on average 112 responses were provided by the survey participants. Figure 6.1 shows the number of responses by responding countries to the questionnaire.

6.4 Reporting on forest damage/disturbance for global FRA

In the FAO Global Forest Resources Assessment 2020 (FRA 2020) countries were asked to report on fires and disturbances[31]. Damage/disturbance agents reported in the FRA included insects, diseases, severe weather events and other factors. The reference unit was the forest area affected by fire and by other damage/disturbance (by agent and in total). FRA 2020 (FAO, 2020) requested annual data on damage/disturbance from 2000 to 2017 (see Chapter 4 for more information).

Based on the current international reporting in FRA 2020, the National Correspondents were asked eight questions related to the information needs of the UNECE countries.

Damage/disturbance reporting in FRA 2020 focused on a limited set of general categories: Insects, diseases, severe weather events, fire, and other. Concerning the level of detail of the currently specified causes of damage/disturbance, a slight majority of responses[32] regarded the level of detail insufficient, proposing additional damaging agents for reporting. Those additional agents include the primary cause of damage, detailed information on abiotic damaging agents (storms, snow and ice, drought, forest fires per type of forest fire). Likewise, more specifications on biotic damaging agents (game classified by grazing, browsing, fraying, scaling, bark beetles, species of other insects, species of fungi, types of diseases) as well as area damaged by human induced damages.

The information on forest damage/disturbance in FRA 2020 was collected for individual years and covered the period 2000 to 2017. Regarding the sufficiency of this time period just over half of the respondents recommended to extend the time period for all damaging agents reported to match the period back to 1990 for which other FRA attributes are presented.

Countries covering three quarters of the UNECE forest area indicated that damage/disturbance reporting merely on country level is sufficient in FRA, and there is no need for additional thematic reporting units beside country level for reported forest damage/disturbance.

However, other countries proposed the following additional thematic reporting units/objects: main tree species, mixed/single species stands, protected forest areas, forests available for wood supply, altitude classes, or biomes.

In FRA 2020, the total forest area affected by damage/disturbance is reported. Slightly more than half of the responses recommend including other reporting attributes to obtain more information on the scope and severity of damaging events. Additional reporting attributes proposed are volume of growing stock affected, market value affected and forest age of the affected area.

The need to distinguish between damages and disturbances in FRA was expressed by countries representing nearly three quarters of the UNECE forest area. A distinction could be made between damage and disturbance in FRA regarding ecological, economic and social aspects. This could, for example, satisfy information needs that relate to damaging events in protected forest areas that do not have any economic implications, in contrast to damaging events in forests available for wood supply.

Countries covering more than three quarters of the UNECE forest area saw no need to report in FRA on damaged trees subject to salvage logging. However, countries covering one fifth of the UNECE forest area suggested an additional reporting on the volume, the marketed volume, and the marketed value of salvage timber as this information is of high economic interest for timber market developments.

Forests can be affected by several damage/disturbance processes often interacting with each other. These can be assigned to primary and secondary categories using: the chronological sequence or the severity of impact. A broad majority expressed no need for a distinction to be made between primary and secondary or multiple causes of damage/disturbance in FRA reporting, as it is seen to be particularly difficult to obtain this information.

The current FRA reporting does not set any threshold for the intensity and scale to qualify the damage/disturbance for reporting. Countries covering two thirds of the UNECE forest area responded that minimum threshold values for reporting on the scale (extent) of forest area affected by damage/disturbance should be specified, as small-scale damage/disturbance could be part of the natural development. Ecological, economic and social effects are only apparent in damaged forest areas of a certain size. Additionally, several countries (with a small share of the UNECE forest area) recommended thresholds for the intensity of damage/disturbance. Suggested are thresholds ranging from at least 25, 30 or 60 per cent of affected area or alternatively several intensity classes.

6.5 Definitions and assessment methods applied at the national level

In the following, the results of the UNECE/FAO ToS survey are presented as part II of the survey, devoted to definitions and assessment methods applied at the national level by the responding countries as a basis for the harmonization of future damage/disturbance assessments.

31 The definition of "Disturbance" in FRA2020 corresponds to a definition of "Damage" in the 2020 pan-European reporting.

32 The information on majorities and minorities in this chapter relates to the share of forest area covered by the responding countries.

6.5.1 National assessments regarding general aspects of forest damage/disturbance

Two thirds of the replying countries reported that there was a linguistic distinction of negatively connoted damage and value-neutral connoted disturbance in corresponding terms used in the national context and in national languages. Nine of those countries, with a share of 68 per cent of the UNECE forest area, apply a distinction between disturbance and damage in their national forest damage reporting which is based mostly on economic and ecological impacts.

Countries representing 93 per cent of the UNECE forest area use thresholds that must be reached or exceeded for damage/disturbance to be monitored as such, including more than 10, 25 or 50 per cent of trees affected, more than 5, 10, 25, 40, 60 per cent of the forest area affected, more than a certain amount of salvage timber, loss of economic value and loss of yield or wood quality.

Countries representing three quarters of the UNECE forest area record the time at which a damage/disturbance occurred. Few countries reported that they only record damage that occurred within a defined time period prior to the time of recording (10, 5 years). The causes of damage/disturbance are assessed on observational units like trees, plots, or stands. One third of the responding countries limit the number of causes assessed. The maximum number of causes mentioned range from one cause (main damage reason) up to twelve and more causes recorded in a single observation unit.

In case of more than one cause of damage/disturbance occurring on an observation unit, countries covering 54 per cent of the UNECE forest area distinguish between the primary cause and secondary or subsequent causes. A harmonized reporting system identifying multiple disturbance agents with priority ranking will be difficult to monitor without short-term national recording periods, allowing the detection of the subsequent agents.

The most widely applied criteria used to establish the ranking of damaging agents on an observation unit was the severity of the damage/disturbance with regard to vitality of trees on 51 per cent of the UNECE forest area.

6.5.2 National assessments regarding forest area-related damage/disturbance

Information on area-related damage/disturbance attributes related to terrain is available in more than half of the responding countries. Human causes like mechanical silvicultural damages or mining are most frequently monitored and assessed by countries covering nearly 90 per cent of the UNECE forest area, followed by landslide/debris flow, flooding and avalanches/snow, each available on 70 per cent of the UNECE forest area. Information on damaging attributes related to stand conditions are available for up to 98 per cent of the UNECE forest area. Most of the responding countries monitor at least the areas damaged by forest fires and insects.

Attributes like wind/storm, loss of vitality, phytopathogens or snow load, which might gain more importance in assessing the influence of climate change, are presently monitored in around three quarters of the UNECE forest area. This also applies to damages by game and livestock. Regional differences in importance are recognizable. Damage/disturbance to forest soils like soil compaction, are assessed in about half of the UNECE forest area by 11 countries.

6.5.3 National information on damage/disturbance detection to standing living trees

In NFIs, trees are the most commonly used observation unit for damage detection in the UNECE region. When recording damage/disturbance to standing trees, a distinction is made between living and dead trees. This section deals with the monitoring of damage/disturbance to standing living trees, the next section focus on standing dead trees.

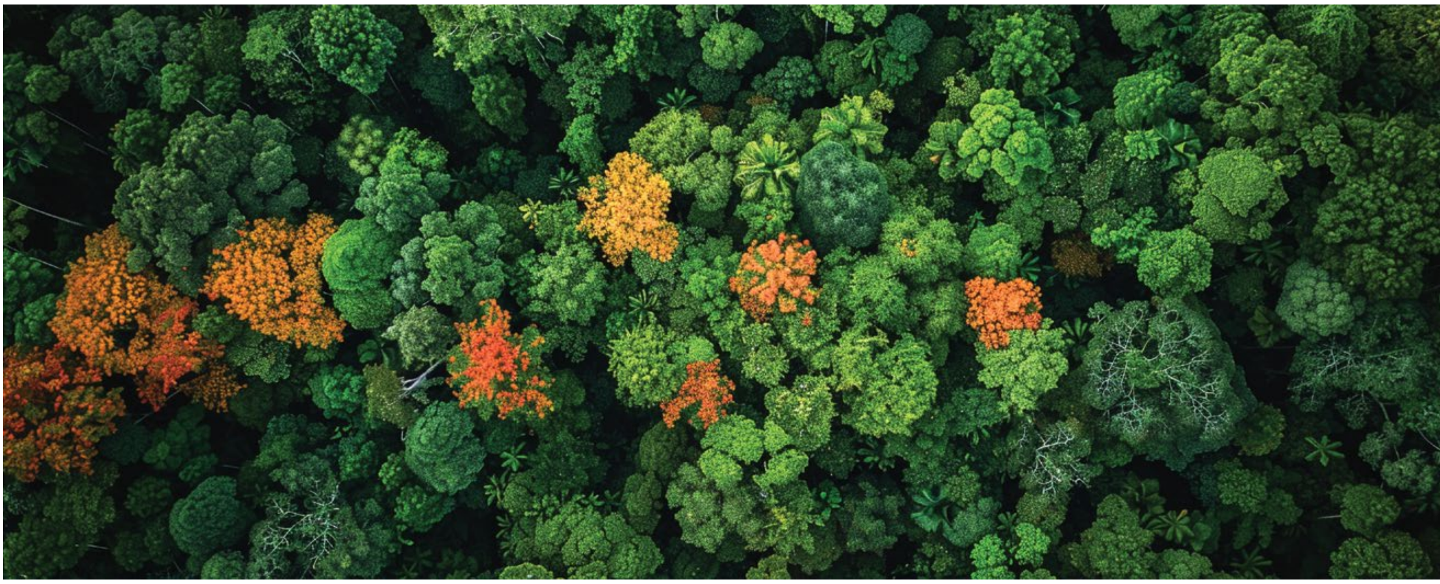
Damage/disturbance reporting on standing living trees is conducted by countries covering 78 per cent of the UNECE forest area. Most data are available for the main types of damage/disturbance (biotic, abiotic and human-induced), as well as for damage/disturbance caused by various types of insects. A high number of countries also monitor wind/storm damage/disturbance. Sixteen countries, representing about half of the UNECE forest area, record the location of the damage/disturbance on standing trees, e.g. in segments. Information on extent of damage on standing living trees is assessed by 21 responding countries. Assessments refer to the proportion of foliage or volume actually damaged or to relative classes (e.g., modest, average, intense). Some countries also define a minimum threshold area which must be exceeded to record damage to standing living trees.

The time of occurrence of damage/disturbance to standing living trees is also recorded by only a few pan-European countries and by the Russian Federation. Either the year of occurrence is estimated or the damage/disturbance has to have occurred in the time of the current monitoring period.

6.5.4 Damage/disturbance detection to standing dead trees

Deadwood is an essential component of forest ecosystems and provides microhabitats for a broad spectrum of species. Furthermore, deadwood is also an important forest carbon pool (Forest Europe, 2020). Premature death of trees may be caused by drought or other extreme weather events, or by outbreaks of insects, diseases and other pathogens in weakened forests.

Tree mortality level may also provide information on the lack of adaptability of forests to climate change. The monitoring of standing dead trees is therefore particularly important with regard to climate change, for forest biodiversity or forest



health assessments and for bark beetle countermeasures, like salvage logging. However, the data for standing dead trees is very scattered and heterogeneous.

Not even half of the responding countries assess the cause of mortality on standing dead trees. However, in the two countries with the largest forest areas – the Russian Federation and the United States – causes of tree mortality are assessed. The extent of damage on standing dead trees is assessed by 13 pan-European countries.

The primary cause of mortality on standing dead trees is assessed on 73 per cent of the UNECE forest area, at least for the main types – biotic and abiotic damages – with the subtypes of insects, diseases and fire.

The time of mortality of standing dead trees is recorded for 71 per cent of the UNECE area. The specific year of mortality is either directly reported or reported at time intervals of 5 years. Only for 23 per cent of the UNECE forest area is the status of wood decay reported, even though it is of ecological (habitats), economic (market value) and social (safety) importance.

Other characteristics assessed on standing dead trees like tree species, or broken stems are assessed by five countries.

6.5.5 Damage/disturbance of regeneration

Data on the extent and causes of damage/disturbance to regeneration are assessed by half of the responding pan-European countries. The most frequently mentioned causes of damage/disturbance to regeneration are wild ungulates, browsing, fungi, insects, and unfavourable microclimate (e.g. drought, frost).

6.5.6 Recovery from damage/disturbance and damage caused by invasive species

Information on the forest area that has recovered from forest damage/disturbance is available for 68 per cent of the UNECE forest area. Information on the time frame for the consideration of recovery from damages/disturbance is very scattered. Sixteen countries reported that no specific time period is given. In seven pan-European countries the period is different for different causes of damage/disturbance and varies between 3 and 5 years. Information on damage/disturbance caused by invasive species was collected by eleven countries, representing 89 per cent of the UNECE forest area, focusing either on information on trees damaged/disturbed by invasive biotic pathogens and insects or on information on forest regeneration pushed back by invasive plant species.

Literature

FAO Database: Global Forest Resources Assessment. Available online at: https://fra-data.fao.org. Data accessed: 18.9.2023

FAO (2020). FAO Global Forest Resources Assessment 2020. FAO: Rome, Italy.

Forest Europe (2020). State of Europe's Forests 2020. Forest Europe Liaison Unit: Bratislava, Slovakia.

UNECE/FAO (2021). Questionnaire on Reporting and assessment of biotic and abiotic forest damages/disturbances in the UNECE region. Manuscript, available at Joint UNECE/FAO Forestry and Timber Section.

7. Innovative tools in line with methodologies for regionally consistent forest damage assessment

7. Innovative tools in line with methodologies for regionally consistent forest damage assessment

Frank Koch and Andrzej Talarczyk

This chapter examines innovative tools and approaches for forest damage/disturbance assessment at multiple scales. The objectives of such assessments are:

- Identify sources and define the extent of forest damage/disturbance;
- Identify meaningful departures from expected conditions and system dynamics;
- Identify specific management responses to damage/disturbance and initiate them at appropriate scales;
- Acquire information for the better understanding of the conditions that might favour damage/disturbance occurrence and for identifying potential risk areas;
- Ultimately, enhance the understanding of forest ecosystem dynamics after damage/disturbance to guide subsequent policy and management action.

The overarching goal for this chapter is to outline how to accomplish these objectives to maximize compatibility, reliability and interpretability of damage/disturbance information assembled from across the UNECE region. This requires analytical methods that can be implemented similarly by every UNECE country. The methods must be applicable to data sources available universally, or if not, data measured and recorded in a consistent way. Innovation is important, but so are cost-effectiveness and feasibility. Methods that are perceived as costly or technically challenging may fail to get adequate buy-in from policy makers, even if the potential outputs are highly appealing.

Herein, aspects of current and emerging tools and data sources are described that can satisfy these criteria. Satellite-based remote sensing is proposed as a key component of a coordinated, regional-level approach to assessment. Merits and limitations of remotely sensed data – particularly multispectral satellite imagery – for characterizing forest damage/disturbance are discussed, followed by an overview of recent technological developments that have increased the utility of these data: time series-based analytical algorithms, cloud computing, and modelling techniques that employ artificial intelligence methods, such as machine learning and deep learning. A critical challenge for remote sensing is determining the cause of an identified occurrence of forest damage/disturbance. The last part of the chapter describes potential methods and data sources that could be applied for causal attribution to show how these might be integrated into a stepwise, systematic approach for regional-scale analysis.

7.1 Mapping forest damage/disturbance with remote sensing

Over the last few decades, there have been hundreds of applications of remote sensing for mapping and characterizing forest damage/disturbance. Typically, these have been targeted at specific geographic regions or categories of causal agents. Altogether, these examples provide limited guidance for a unified approach to forest damage/disturbance assessment, either because of a narrow focus and spatial extent or insufficient resolution (in some regard) of the underlying data.

To achieve the objective of a unified approach for an assessment across an area as large as the UNECE region, the emphasis must be on creating large-scope (e.g., global or continental) geospatial databases of forest damage/disturbance occurrences through time. One way to address this need is to adopt a phased strategy that starts with mapping of all such occurrences in a region of interest, irrespective of what caused them. Thus, causal attribution is a distinct process step. A highly relevant example of this was described in Senf and Seidl (2021b), who mapped the disturbance regimes of European forests between 1986 and 2016. Using >30,000 Landsat images and a variety of supporting and reference data, they created a data set that tracked the status of each forested location (i.e., a 30-m pixel) in continental Europe over the analytical period.

While there have been similar efforts, Senf and Seidl (2021b) provided a useful prism for understanding the elements that are likely to be critical for a consistent forest damage/disturbance assessment across the UNECE region. The most salient aspects deal with a few interrelated concepts: analytical approaches and algorithms; cloud computing platforms and workflows; and causal attribution. Below, each of these topics is discussed, with examples from current research.

7.2 A geospatial framework to facilitate regionally consistent assessment

Despite the increasing availability of detailed data about forests (Lausch *et al.* 2018), forest damage/disturbance reporting in the UNECE region – as in other parts of the world – is still presented mainly in terms of simple metrics: the total amount or extent of damage/disturbance in countries caused by each of a small set of agents, primarily fire, storms/wind, insects and diseases (see Chapters 3 and 4).

Problematically, this type of generalized approach does not provide ecological context. What did a forest stand look like before the recorded damage/disturbance, and what did it look like afterwards? These are essential questions when attempting to understand whether ecosystem dynamics are affected significantly by damage/disturbance events.

It is important to recognize that some degree of tree mortality is a constant presence in all forest systems, as are instances of acute and chronic forest decline, i.e., decreases in forest vitality commonly signalled by tree canopy loss (Cohen *et al.* 2016, Das *et al.* 2016). Therefore, what is relevant for assessment is to detect where the damage/disturbance deviates from expected patterns (Lambert *et al.* 2013, Trumbore *et al.* 2015).

If forest damage/disturbance events are tracked geographically, and preferably through time, it can be easier to identify meaningful patterns. Indeed, geographical pattern is critical, in particular, since the area where the damage/disturbance occurs has important implications for policy response. "Tracked geographically", is meant to suggest that the events are mapped as unique geospatial features. This would enable analyses such as the detection of spatial clusters among similar types of forest damage/disturbance events, or the identification of spatially anomalous events in geographical areas where they do not occur typically. While on some level, summary reporting by countries can provide useful geographical information, national borders are of lesser importance in an ecological sense. Moreover, they can obscure regional-scale patterns that may extend across borders.

The notion of adopting a shared geospatial framework to facilitate consistent regional assessment is not ground-breaking. Conceptual and methodological guidance has long been available (e.g., Coops *et al.* 2006, Scott and Rajabifard 2017). In some cases, the values that individual countries report about forest damage/disturbance for large-scope summaries are based on underlying geospatial data.

For example, the European Forest Fire Information System (EFFIS) was designed as a region-wide geographical information system (GIS) for regularly updated information on fire perimeters as well as a historical spatial database that individual countries can use for analysis and reporting needs (San-Miguel-Ayanz *et al.* 2012).

Across the many categories of forest damage/disturbance, issues of consistency – especially consistency of interpretation – remain because of differences between countries in nomenclature, data collection protocols and characteristics of the recorded data features, such as minimum thresholds of damage/disturbance that are reported (see Chapter 5). Nevertheless, a shared geospatial framework can serve to organize available data for further analyses that can address such differences and exploit any commonalities.

7.3 Remote sensing as an integral analytical component

Satellite-based remote sensing can provide – in combination with other data sources – a foundation for consistent regional assessment, with some important caveats described below. Remote sensing encompasses a variety of platforms and sensor types that can be applied for forest damage/disturbance assessment (for overviews, see Lausch *et al.* 2017, Gao *et al.* 2020, Lechner *et al.* 2020). Across platforms, the most common type of sensor is an optical imaging system that records data in multiple spectral bands, with each band covering a different portion of the electromagnetic spectrum, especially visible and near-infrared wavelengths; the number of spectral bands can range from 3-15 (multispectral) to hundreds (hyperspectral) (Lechner *et al.* 2020). Satellite-based optical sensors offer wall-to-wall geographical coverage of an area of interest, along with a systematic, raster-based (i.e., pixel-based) geospatial framework (Lausch *et al.* 2018). This framework also supports time series and trend analysis, making such sensors useful for applications such as forest monitoring (Tuominen *et al.* 2009, Lechner *et al.* 2020).

Historically, the design of satellite optical sensors has involved trade-offs in terms of spatial, spectral and temporal resolution due to costs and technological limitations (Tuominen *et al.* 2009, Cohen *et al.* 2016, Lausch *et al.* 2016). For example, individual satellite-sensor systems that have short revisit times (e.g., 1-2 days for MODIS) typically collect data with coarse spatial resolution (≥250 m) (Sulla-Menashe *et al.* 2014). In contrast, the latest generation of satellite hyperspectral sensors (e.g., PRISMA) have moderate to high spatial resolution (8-30 m) to complement their spectral capabilities, but revisit times of a few weeks or longer (Vangi *et al.* 2021).

With respect to forest damage/disturbance at a regional scale, much of the research in the last two decades has focused on multispectral satellite imagery with medium spatial resolution, most commonly Landsat imagery. One of the primary reasons is because the Landsat data archive extends back 50 years. Landsat-4, the first mission with a ≈30-m resolution sensor, launched in 1982, meaning that the technical characteristics of the images have been relatively constant for 40 years (Masek *et al.* 2020), although older images are generally inferior in quality to those captured with the improved sensors of later Landsat missions.

Furthermore, the need for radiometric, atmospheric, and topographic correction is a persistent concern, as is availability of cloud-free imagery in some geographical regions (Banskota *et al.* 2014). The Copernicus programme of the EU developed the Sentinel-2 mission in part to improve upon the revisit time (in addition to the spatial and spectral resolution) of the Landsat sensors (Drusch *et al.* 2012). In turn, a Harmonized Landsat and Sentinel-2 (HLS) product allows observation of the global land surface every 2-4 days (Claverie *et al.* 2018). These regular revisits enable the implementation of rolling time intervals for analysis and reporting. Despite the emergence of Sentinel-2 and other complements or alternatives to Landsat, it seems unlikely that another data source will fully displace it in the near term for contemporary forest damage/disturbance mapping, which typically requires a sufficient historical data record to serve as a baseline (Francini *et al.* 2022b).

A critical limitation of optical remote sensing, especially at a medium spatial resolution, is that it primarily looks at the forest canopy. Subcanopy vegetation may be obscured year-round in conifer-dominated forests and during much of the growing season in hardwood-dominated forests. Optical remote sensing is probably most effective at identifying and characterizing damage when there are many images available on anniversary dates (i.e., recorded at the same time in multiple years) and, ideally, in multiple seasons.

Still, remote sensing technologies evolve rapidly, and their overall costs tend to decrease, so feasible solutions can be expected to be developed in the future that will be based on other types of sensors. In particular, active sensors, which emit pulses of energy and then measure the amount of energy that is returned, provide qualitatively different information from what is collected by "passive" optical sensors (Lausch *et al.* 2017). For instance, some countries have carried out national programmes of wall-to-wall high-resolution airborne laser scanning (ALS) – a type of lidar – which could supply reliable and consistent data on structural changes in forest stands and size of forest damage/disturbance, both in terms of area and timber volume (Nilsson *et al.* 2017, Beland *et al.* 2019, Maltamo *et al.* 2021).

Another as-yet underexplored technology is synthetic aperture radar (SAR), which has the possibility of operating under cloudy weather conditions and can provide information on moisture and stand structure (Plank 2014, Tanase *et al.* 2019, Torres *et al.* 2021). It appears that future remote sensing solutions for forest damage/disturbance detection and assessment are likely to be integrative, combining different technologies. A recent illustration of the possibilities with respect to integration was provided by Francini *et al.* (2022a), who combined Landsat imagery with data from GEDI, a lidar sensor aboard the International Space Station, to map forest disturbances in Italy over four decades. Forthcoming satellite missions are expected to deploy multisensor technology (e.g., lidar and multispectral imaging on one platform) that will enable such integrations directly (Lausch et al. 2017).

Moreover, a growing trend among remote sensing programmes has been the implementation of constellations of multiple satellites, frequently with different sensor types (e.g., the multispectral and SAR satellites in the Sentinel constellation). Because the satellites operate as a coordinated system, data integration (or "fusion") is relatively straightforward (Lechner *et al.* 2020).

A disadvantage of any type of remote sensing in the forest damage/disturbance context is that it can only provide indirect measurement of the phenomena of interest. What is recorded is the spectral response – or returned signal, for active systems such as lidar or radar – associated with an apparent damage/disturbance occurrence. Thus, some degree of uncertainty remains, particularly with respect to the cause of the observed occurrence. Furthermore, not all damage/disturbance is equally detectable by remote sensing means. A combination with ground-based monitoring may be necessary to identify the causal agent (e.g., type of pathogen). On the other hand, remote sensing approaches have pronounced benefits in terms of cost efficiency for data acquisition over large areas. Nonetheless, remote sensing is merely a partial foundation. Examination of contemporary remote sensing-based methods for damage/disturbance mapping should demonstrate the necessity for a hybrid approach that integrates a diversity of data sources, including field survey.

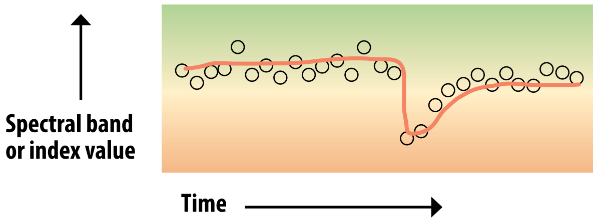
7.4 Analytical approaches and algorithms

The Landsat archive has become a central feature of forest mapping and monitoring throughout the UNECE region and globally (e.g., Hermosilla *et al.* 2015, Oeser *et al.* 2017, White *et al.* 2017, Schroeder *et al.* 2017, Zhao *et al.* 2018, Wulder *et al.* 2020, Schleeweis *et al.* 2020, Senf and Seidl 2021b). Various analytical approaches have emerged that exploit the archive's decades-long data history, with trajectory-based approaches being especially prominent. One of the most well-known of these is the LandTrendr (Landsat-based detection of Trends in Disturbance and Recovery) algorithm (Kennedy *et al.* 2010). Expanding on traditional two-date change detection approaches, LandTrendr introduced the concept of extracting trajectories of spectral data on a by-pixel basis from Landsat time series (LTS) stacks. Typically, these stacks consist of a representative image for each year in the series, ideally acquired on anniversary or near-anniversary dates. In some cases, image compositing techniques are necessary to maximize cloud-free observations (see Banskota *et al.* 2014, Gómez *et al.* 2016).

Details of LandTrendr are outlined in Kennedy *et al.* (2010), but a core methodological aspect is the use of a regression-based temporal segmentation approach to model a pixel's spectral time series. This smooths some of the finer-scale variation ("noise") in the time series signal but retains enough detail to capture both rapid and slow changes in the spectral trajectory. The organizing principle is that different types of forest change tend to exhibit characteristic spectral trajectories before, during, and after the change occurred (Figure 7.1). This makes it possible to distinguish disturbance from non-disturbance events as well as map them in both time and space.

FIGURE **7.1**

Conceptual representation of the spectral trajectory of a forested pixel (e.g., from a Landsat image)



In Figure 7.1, each circle represents the pixel's values for one band or index at a point in time along the trajectory. For the first half of the trajectory, the pixel's values follow a flat trend, indicating little change to spectral response and thus forest cover. Then, a sharp decrease in the values may correspond to a fast-developing disturbance event (e.g., fire), followed by subsequent forest recovery, although at a level less than in the first half of the trajectory.

There are alternatives to LandTrendr that use a similar approach to evaluate LTS data stacks (Banskota *et al.* 2014). For mapping forest damage/disturbance occurrences, commonly used alternatives include the Vegetation Regeneration and Disturbance Estimates through Time (VeRDET), Vegetation Change Tracker (VCT), Breaks for Additive Seasonal and Trend (BFAST), and Continuous Change Detection and Classification (CCDC) algorithms (Huang *et al.* 2010, Verbesselt *et al.* 2010, Lambert *et al.* 2013, Cohen *et al.* 2017, Zhu 2017, Francini *et al.* 2022b).

Another option is the Shapes algorithm, which fits regression splines to LTS data stacks, modeling each pixel's time series as one of seven smoothed trajectories ("shapes") based on historical forest disturbance dynamics (Moisen *et al.* 2016, Schleeweis *et al.* 2020). One recent algorithm, Jumps Upon Spectrum and Trend (JUST), works with image data that are unequally spaced through time, thus avoiding the difficulty of finding data from anniversary dates (Ghaderpour and Vujadinovic 2020). Trajectory-based approaches have even shown some promise for mapping relatively low-severity forest damage/disturbance (Coops *et al.* 2020, Gao *et al.* 2020).

Although the algorithms were developed primarily using LTS data stacks, they can be applied to data from other optical sensors as long as those data can be compiled into a consistent time series. Notably, nearly all of these algorithms were developed to look at single spectral bands or derived indices such as the Normalized Difference Vegetation Index (NDVI), the three indices of the Tasseled Cap transformation (i.e., brightness, greenness and wetness) and the Normalized Burn Ratio (NBR), which is used for wildfire detection and mapping (Cohen *et al.* 2010, 2016, 2017, Banskota *et al.* 2014, Hirschmugl *et al.* 2017, Oeser *et al.* 2017, White *et al.* 2017, Midekisa *et al.* 2017, Bright *et al.* 2020). Combining analyses performed with multiple bands or indices requires application of artificial intelligence methods such as machine learning (described in more detail in section 7.6).

No matter the algorithm or data source, remote sensing-based detection of forest changes over large spatial scales requires substantial reference data for validation and veracity testing. In most cases, sufficient reference data (e.g., from field surveys) are not available, especially with respect to 25- or 30-year time series of images over a large geographical area.

TimeSync, a software application associated with LandTrendr but applicable to other algorithms, addresses this limitation through an independent, human-interpreted segmentation of the same image data stack used by the algorithm. Generally, human interpretation is supported by high- or very high-resolution imagery or other ancillary data sets (Cohen *et al.* 2010, Banskota *et al.* 2014, Cohen *et al.* 2016, Schroeder *et al.* 2017, Zhao *et al.* 2018, Schleeweis *et al.* 2020, Senf and Seidl 2021b). This sort of approach, whether it involves TimeSync or not, leverages the ability of humans to assess changes more accurately than automated algorithms, and is considered appropriate practice for generating reference data to supplement field-based observations (Olofsson *et al.* 2014).

7.5 Cloud computing platforms and workflows

When the United States Geological Survey made the entire Landsat image archive freely available in 2008, this signalled the start of a "big data" era for remote sensing. Many other satellites have been launched in the years since, with a wide assortment of sensors and scientific objectives, and often under an open access data policy (Casu *et al.* 2017, Kennedy *et al.* 2018).

The remarkable increase in available remote sensing data necessitated the development of technologies that could provide sufficient capacity for data storage, processing, and analysis. This has led to greater demand for high-performance computing (HPC), most of which now occurs on distributed cloud computing platforms (Lechner *et al.* 2020).

Cloud computing platforms give users HPC capacity in a virtual environment, eliminating the need for them to maintain their own hardware and software (Amani *et al.* 2020). Among the cloud computing platforms that facilitate geospatial analysis and data processing, the best-known is Google Earth Engine (Gorelick *et al.* 2017, Gomes *et al.* 2020).

The Google Earth Engine (GEE) platform combines an efficient computational infrastructure with an extensive data catalogue that includes the entire Landsat image archive (1984-current) and those of several other satellite sensors (e.g., Sentinel-1, -2, -3 and -5P). It also includes global data sets for weather, topography and human population distribution, as well as numerous, more specialized data sets contributed by users (Gorelick *et al.* 2017, Gomes *et al.* 2020).

This combination of computing power and vast data availability shows that the GEE platform is well suited to analyses utilizing algorithms like LandTrendr and BFAST (Hamunyela *et al.* 2020) as well as applications of artificial intelligence methods, especially since users do not need abundant programming expertise for implementation (Gorelick *et al.* 2017).

While GEE is currently the most popular of the cloud-based geospatial platforms there are other options, such as Sentinel Hub, that follow similar frameworks and offer similar capabilities (Lastovicka *et al.* 2020).

As an open-source project of the FAO Forestry Programme, the SEPAL platform[33] may be of particular interest regarding efforts to coordinate forest damage/disturbance assessment across the UNECE region. It is also part of Open Foris[34], a suite of open-source software tools for environmental and land monitoring. The SEPAL platform is a combination of GEE and software tools that provide an array of geospatial and image processing functions for users with little or no coding experience (Gomes *et al.* 2020). Because of its linkage to GEE, users have access to the GEE data catalogue. The SEPAL platform does not provide access to the LandTrendr algorithm, but it does feature the BFAST algorithm for trajectory-based analyses (Verbesselt *et al.* 2010, Banskota *et al.* 2014, Hirschmugl *et al.* 2017).

As with all remote sensing-related technologies, the cloud computing paradigm continues to evolve. Approaches such as fog, mist, and edge computing are beyond the scope of this chapter, but these concepts are likely to become increasingly familiar to people tasked with broad-scale assessments utilizing large amounts of geospatial data (Barik *et al.* 2020).

7.6 Artificial intelligence and machine learning in forest monitoring

The arrival of high-volume and high-quality data-sets, advanced technologies (e.g., microsatellite constellations, high-resolution cameras, lidar and other active sensor systems, unmanned aerial vehicles) and increased computational capacity at reasonable cost have stimulated the evolution of artificial intelligence-related research and practical applications (Taylor *et al.* 2020).

Artificial intelligence (AI) refers to the use of computer systems for tasks that traditionally required human intelligence, such as pattern recognition and anomaly detection. Machine learning (ML) techniques are a subset of AI methods that are often used for analysis of high-volume data sets, including remote sensing data (Stupariu *et al.* 2022). Frequently used ML techniques include support vector machines, artificial neural networks, boosted regression trees and random forests (Baumann *et al.* 2014, Ozdogan 2014, Belgiu and Drăguţ 2016, Wegmueller and Townsend 2021, Solórzano and Gao 2022). AI and ML techniques are distinctly data driven. A representative sample of input data is used to develop ("train") a model for subsequent prediction or classification tasks.

AI and ML applications have become increasingly common across many aspects of forest monitoring. For example, the Global Forest Watch initiative[35] strives to monitor deforestation and illegal logging around the world using AI-based analytical workflows applied to satellite imagery.

More generally, AI- and ML-based statistical algorithms are utilized for many fundamental forest-monitoring tasks such as plant inventory and identification, phenology monitoring, forest classification and mapping, forest resource quantification (e.g., biomass estimation), assessment of anthropogenic threats (e.g., effects of polluting agents) and modelling of soil moisture, vegetation evapotranspiration and other aspects that govern water-use efficiencies of forest ecosystems (Shivaprakash *et al.* 2022).

There are production-verified examples of AI being used for analysing combined multispectral images and lidar data to provide accurate, cost-effective insights into forest conditions. Such products (e.g., Overstory[36]) facilitate tree species identification, determination of tree height, growth rate and vitality, detection of insect infestations as well as change detection.

Furthermore, AI and ML techniques have been incorporated directly into efforts to monitor and assess impacts of key forest damage/disturbance agents. For instance, wind is responsible for more than 50 per cent of all damage by volume in European forests (Schelhaas *et al.* 2003, Forzieri *et al.* 2020b). Highly accurate image classification algorithms such as convolutional neural networks – also referred to as deep learning algorithms (Christin *et al.* 2019) – provide rapid automatic detection and mapping of wind-damaged forest areas (Hamdi *et al.* 2019).

33 https://sepal.io

34 https://openforis.org

35 https://www.wri.org/initiatives/global-forest-watch

36 https://www.overstory.com

Likewise, ML algorithms facilitate rapid mapping of burned forest areas to assess damage extent and formulate forest-restoration strategies (Zhang *et al.* 2023).

One illustration of an AI-powered solution for real- or near-real-time fire monitoring is the Vesta Mark 2 advanced model, developed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the New South Wales Rural Fire Service, which predicts the speed and behaviour of eucalypt forest fires, helping save lives and property (Cruz *et al.* 2022).

Another emerging topic of research is utilization of satellite synthetic aperture radar (SAR) data to detect forest disturbance in near-real time. This has been motivated especially by the Copernicus Sentinel-1 mission, which provides cloud-free SAR imagery worldwide on a 6- or 12-day repeat cycle.

AI and ML have proven crucial for interpreting these data, as demonstrated by their integration into analytical systems operated by research agencies (e.g., Centre d'Etudes Spatiales de la Biosphère, CESBIO). It has been shown that, if properly calibrated, these Sentinel-1 SAR-based methods employing AI outperformed optical sensor-based methods in several aspects in tropical forests, especially in very cloudy areas (Doblas Prieto *et al.* 2023).

It is anticipated that future combined optical-SAR systems will have excellent detection capabilities, thus constituting a promising and feasible approach for forthcoming forest-monitoring systems. New SAR-based algorithms have demonstrated potential for mapping even low-intensity forest disturbances, such as illegal selective logging (Aquino *et al.* 2022).

There is a growing expectation that forest monitoring systems will go beyond merely reporting current or recent conditions, becoming decision support systems that enable managers to identify threats before they appear or detect them early enough to respond properly, thus making risk management more efficient and cost-effective. AI-based technologies are crucial to this end, allowing the integration of information from varied sources.

For example, the World Resources Institute (WRI), in collaboration with the Central Africa Regional Program for the Environment (CARPE), used spatial modelling and AI to understand what factors influence deforestation in the Democratic Republic of the Congo and to map where future forest loss is most likely to occur (Shivaprakash *et al.* 2022).

Large amounts of in situ data are required to train and calibrate AI algorithms effectively (Stupariu *et al.* 2022). There are still significant gaps in this respect which will need to be filled to further improve the accuracy of AI-based solutions. Another obstacle is that AI-based monitoring is labour- and resource-intensive. Fortunately, initiatives such as FAO's SEPAL platform provide easy-to-use tools to reduce the effort required to get actionable monitoring information.

The resource demands of high-throughput analyses and processing make them dependent on the few commercial cloud-based computing platforms that are available. It is likely that future satellites will carry on board some kind of AI-based pre-processing engines to improve quality and efficiency of image acquisition and utilization.

It is critical to find ways to link these sophisticated technologies and research results to business, and thereby create some financial or policy incentives to apply AI in forest monitoring. There are many interesting research projects in this area, but it remains to be seen which of them will make a difference in terms of providing tangible benefits to policymakers.

7.7 Accuracy of damage/disturbance maps from remote sensing

Because forest damage/disturbance occurrences are depicted indirectly via spectral information for optical sensors – or returned signals for active sensors (e.g., lidar) – errors are inevitable. Some actual occurrences will be missed (omission errors) and some non-events will be misclassified as damage/disturbance (commission errors). Furthermore, an indirect representation cannot fully capture the impact on individual trees in a disturbed location (pixel).

Even if a disturbed location is identified successfully, the timing of the observed damage/disturbance may be recorded inaccurately. This is a recognized weakness of trajectory-based algorithms (Cohen *et al.* 2010). Such approaches are also prone to errors caused by the difficulty of differentiating low-severity forest damage/disturbance from background variation, or "noise" (Ozdogan 2014, Schroeder *et al.* 2017, Zhao *et al.* 2018, Schleeweis *et al.* 2020, Senf and Seidl 2021b). Stated simply, remote sensing-based forest damage/disturbance mapping will be more successful at finding high-severity occurrences despite sophisticated analytical approaches.

Nonetheless, in their work mapping the forest disturbance regimes of Europe, Senf and Seidl (2021b) asserted that they were generally successful at distinguishing between undisturbed areas, non-stand-replacing disturbances (i.e., partial canopy loss) and stand-replacing disturbances (i.e., complete canopy loss). This terminology has also been used by others (e.g., Ahmed *et al.* 2017, White *et al.* 2017, Coops *et al.* 2020, Shikhov *et al.* 2020). The distinction between stand-replacing and non-stand-replacing damage/disturbance is potentially meaningful for regional-scale assessment and reporting.

There are longer-term ecological implications that are relevant to sustainable forest management, such as the prospects for forest recovery after disturbance. As might be expected, applications of remote sensing in this regard have mostly focused on stand-replacing damage/disturbance occurrences because their data signatures are usually more obvious, such as an abrupt and substantial decrease in spectral values (Coops *et al.* 2020). In some cases, it is possible to distinguish low-severity, non-stand-replacing disturbances (e.g., from defoliating insect outbreaks) using a trajectory-based approach, but the lack of information on forest structure provided by optical remote sensing remains an obstacle to detecting gradual or subtle changes (Coops *et al.* 2020, Sanchez-Lopez *et al.* 2020). This emphasizes the value of integrating data from active sensors, if available, when mapping forest damage/disturbance (Sanchez-Lopez *et al.* 2020).

7.8 Attributing damage/disturbance to agents and processes

Attribution of causal agents is the most difficult aspect of a remote sensing-based approach to mapping forest damage/disturbance (Sebald *et al.* 2021). The indirect measurements provided by remotely sensed data come with ambiguities that extend beyond detection of damage/disturbance occurrences. For example, even if an observation of forest damage/disturbance can be associated definitively with fire, it may be unclear whether it was caused by wildfire or prescribed fire. Sometimes, there can be clues about the cause from the primary data set (e.g., an LTS data stack) used for mapping. For instance, forest damage/disturbance events with characteristic spatial signatures include hurricanes and other storms, which commonly exhibit pronounced directional patterns (McDowell *et al.* 2015). Nonetheless, causal attribution almost always requires application of true ancillary data, i.e., external data that provide information that cannot be determined simply by looking at the properties and patterns of events mapped from remotely sensed data.

The technical advances in cloud-based computing and artificial intelligence (see section 7.6) that have enabled better forest damage/disturbance mapping in the last decade have also facilitated causal attribution with ancillary data (Baumann *et al.* 2014, Hermosilla *et al.* 2015, Cohen *et al.* 2016, Oeser *et al.* 2017, Bright *et al.* 2020, Schleeweis *et al.* 2020, Senf and Seidl 2021c, Sebald *et al.* 2021). Of course, no single ancillary data set depicts all relevant causal agents and processes (but see Patacca *et al.* 2021 regarding DFDE2, an updated Database on Forest Disturbances in Europe, and Chapter 5 of this study). Like damage/disturbance mapping itself, causal attribution typically requires the integration of multiple predictors extracted from different data sets, and in turn, an emphasis on artificial intelligence methods (Kennedy *et al.* 2010, Cohen *et al.* 2016, Schroeder *et al.* 2017).

Indeed, taking advantage of this methodological overlap, some researchers have combined forest damage/disturbance mapping and attribution rather than treating them as distinct analytical steps (e.g., Schroeder *et al.* 2017). Regardless, all causal attribution efforts involve probabilistic modelling. Thus, there is a degree of uncertainty in any causal label assigned to a mapped damage/disturbance occurrence, just as there is uncertainty as to whether it is an actual occurrence.

7.9 Using ancillary data to aid causal attribution

It is impractical to describe every data set that has been or could be used for the causal attribution of forest damage/disturbance. Fortunately, the causal agents with the largest impact footprints across the UNECE region (i.e., fire, wind/storms, insects and diseases) have the most robust supporting data.

For example, fires are the one type of damage/disturbance for which global data are available: the Global Fire Atlas dataset (Andela *et al.* 2019) compiled by NASA and the GlobFire database (Artés *et al.* 2019) of the European Commission's Joint Research Centre (JRC). However, neither of these is targeted specifically at forest fires, nor do they include small or short-duration fires. In contrast, EFFIS, which is also managed by the JRC, centralizes national forest fire data from a network of European, Middle Eastern and North African countries, thus providing users with access to detailed historical and current data on forest fires across the region. The largest countries in the UNECE region – Russian Federation, United States and Canada – are not covered by EFFIS, but these countries have their own fire information systems (Eidenshink *et al.* 2007, Hall *et al.* 2020, Kotel'nikov *et al.* 2020).

The FORWIND database, which consists of ~90,000 records (i.e., georeferenced polygons) of wind disturbances during the period 2000-2018, is the first comprehensive, spatially explicit database of wind/storm disturbances for Europe (Forzieri *et al.* 2020b). Despite its size, FORWIND is estimated to contain only ≈30% of damaging windstorms recorded in Europe during this period (Forzieri *et al.* 2020b). The United States does not have an exact equivalent to FORWIND, but a Storm Events Database from the National Centers for Environmental Information (NCEI) can be queried for wind-related disturbances (Letson *et al.* 2021). Shikhov *et al.* (2020) presented a database of severe windthrow events in Russian forests for the period 1986-2017. Theoretically, these data also could be integrated with FORWIND.

As of today, there is no region-wide source of spatially explicit data about insect or disease disturbances in European forests. The JRC is developing a Database of European Forest Insect and Disease Disturbances (DEFID2) that will be similar in format to the FORWIND database (Forzieri *et al.* 2020a). It is expected to cover the period 1981-present. Geographically, records are expected to cover Europe, northern Africa and the Middle East. Such databases strongly depend on collaboration with external data providers. Notably, the design of the DEFID2 was inspired by the national Insect and Disease Survey (IDS) database of the United States Forest Service. This suggests that they will integrate reasonably well, which also can be expected for the Canada's Forest Insect and Disease Survey, as it follows similar protocols (Hall *et al.* 2016).

Besides the previous examples, a few general categories of ancillary data are common to most attribution efforts discussed in this chapter. Nearly all analyses, regardless of scale, feature some representation of land cover, including forest cover, either as a way to mask out non-forest areas (e.g., Oeser *et al.* 2017) or to refine the attribution process in some fashion. A second category consists of topographic variables (e.g., slope, aspect, terrain ruggedness index) derived from digital elevation data (Schroeder *et al.* 2017, Murillo-Sandoval *et al.* 2018, Schleeweis *et al.* 2020, Sebald *et al.* 2021).

Particularly for climate-associated forest disturbances, a third general category includes variables (e.g., temperature, precipitation, snow conditions) derived from coarse-scale meteorological data (Oeser *et al.* 2017, Forzieri *et al.* 2021, Hislop *et al.* 2021, Sebald *et al.* 2021). For example, Senf and Seidl (2021a) used ERA5-Land reanalysis data in an assessment of the impact of the 2018 drought on forest disturbance regimes in Europe. Developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), the ERA5-Land data consist of 50 variables that depict water and energy cycles in terrestrial environments, available globally from 1950 to present with a spatial resolution of ≈9 km (Muñoz-Sabater *et al.* 2021).

In another analysis, Senf and Seidl (2021c) developed a model that, for each disturbance patch in their European data set, predicted the probability that the disturbance was caused by either wind or fire. Lacking a spatially comprehensive data set that could be used for calibration and attribution, they combined disparate sources: the FORWIND and EFFIS databases as well as the original Database on Forest Disturbances in Europe (DFDE), which includes a non-spatial but exhaustive collection of windthrow events (Schelhaas *et al.* 2003). This was the first such attribution effort performed for all of Europe.

Distinct from these sorts of data sets – most of which are pre-processed, quality controlled, updated with regularity, and publicly available – another category of ancillary data that is often seen as instrumental to the causal attribution process is high-resolution multispectral imagery captured by aircraft or satellites (Baumann *et al.* 2014, Hermosilla *et al.* 2015, Oeser *et al.* 2017, Huo *et al.* 2019, Schleeweis *et al.* 2020, Senf and Seidl 2021b). The images are used in a couple of contexts: as reference data for confirming disturbances mapped from medium-resolution imagery and attempting to determine their causal agents (Oeser *et al.* 2017, Huo *et al.* 2019, Schleeweis *et al.* 2020) or for accuracy assessment (validation) of the results of attribution modeling and mapping efforts (Baumann *et al.* 2014, Huo *et al.* 2019). Regardless of context, a major distinction between these images and other ancillary data lies in how they are utilized. In short, high-resolution images are used for causal attribution because they show features that would be impossible to discern from medium-resolution imagery. This can be especially important in regions with low accessibility, such as the interior of Alaska in the USA (Pastick *et al.* 2019). Given current analytical capabilities, however, doing so requires a substantial amount of human (i.e., non-automated) interpretation. For this reason, high-resolution images usually have been applied for a subset of the full area of interest in previous studies.

In countries with dedicated aerial survey programmes (e.g., the IDS programme in the United States), targeted overflights by airplane, helicopter, or drone can provide corroborative information with respect to insect and pathogen activity in forests (Meddens *et al.* 2013, Coops *et al.* 2020). But perhaps the most important type of ancillary data for causal attribution of forest damage/disturbance remains the NFIs of individual countries. Because they include measurements at the level of individual trees and forest stands, NFIs provide critical information about forest damage/disturbance that is unlikely to be available from any other data source. Indeed, there are examples of NFI data being used with little or no additional data to summarize forest damage/disturbance trends at a regional or national scale (Wulff *et al.* 2013, Díaz-Yáñez *et al.* 2016, Henttonen *et al.* 2017, Enderle *et al.* 2018, Ojha *et al.* 2020, Fitts *et al.* 2022)

However, NFI data are probably most useful in combination with other data sources. For instance, the North American Forest Dynamics (NAFD) project has a template for forest damage/disturbance assessment in the conterminous United States similar to that outlined by Senf and Seidl (2021b) for their work in Europe, with a 25-year period of interest (1986-2010) and the Landsat data archive as the primary data source. The culmination of the "third phase" of the NAFD project was a new spatial data set, the NAFD-ATT (North American Forest Dynamics-Attribution) data.

The attribution process involved an assortment of supporting data, including examples mentioned here: plot data from Forest Inventory and Analysis (FIA), United States of America's NFI; damage polygons from the IDS database; fire occurrence data from the Monitoring Trends in Burn Severity (MTBS) programme; National Land Cover Data (NLCD); and data sets generated in prior disturbance assessments (see Schleeweis *et al.* 2020 for details). The NAFD-ATT data assigned disturbances to one of four causal categories: fire, wind, harvest, conversion from forest, or stress, with stress being any event resulting in gradual loss of forest canopy, such as insect, disease, or drought damage (which co-occur regularly). Nationwide, harvest was the most frequently observed disturbance type. Although harvest is not considered forest damage or disturbance in most of the UNECE region, its prominence in the United

States of America underlines the importance of accounting for it during causal attribution efforts.

7.10 Putting it together: a possible template for a unified regional approach

The preceding sections described primary elements of an approach to consistent, coordinated forest damage/disturbance assessment across a country or a region, utilizing remote sensing data as a foundation. As noted earlier, this foundation is only a partial template. Lausch *et al.* (2018) listed reasons why, historically, remote sensing has seldom been integrated into national or regional forest health monitoring efforts: (1) previously developed technologies do not record certain forest indicators or record them with insufficient quality; (2) complex and large remote sensing data often have high technical and personal requirements for storage, processing, analysis, etc.; (3) processing and analysis further requires extensive training, skill, and access to software and high spatial and spectral resolution data (for validation, training, etc.); and (4) the methodologies of forest inventory differ substantially from those of remote sensing approaches and thus require differing specialist competencies.

Although there has been significant progress towards addressing these issues, aspects of reason (1) remain true with respect to forest damage/disturbance assessment. Some causal agents (e.g., non-lethal tree pathogens or minor defoliators) will remain difficult to capture even with robust time series of high-resolution imagery.

Moreover, reason (4) cited by Lausch *et al.* (2018) – differing methodologies and specialist competencies for remote sensing versus forest inventory – is still a key consideration. If NFIs are recognized as important data sources for forest damage/disturbance assessment, then ways should be found to foster their development and maximize their utility in this context. Actually, this assertion should extend to any data source that can aid in assessment, not just NFIs.

Therefore, a hybrid approach can be suggested. The main components of a possible hybrid approach are illustrated in Figure 7.2, parts of which are adapted from Oeser *et al.* (2017). The diagram is an idealized representation, focusing on the geographic area depicted in a single image or scene, captured by a satellite optical sensor. There are two primary data sources: a time series of remote sensing data and corresponding ground truth data for the target scene. Based on current sensors, it might be easiest to imagine a time series consisting of medium-resolution, multispectral images from a single satellite programme (e.g., Landsat), but as technologies improve, it might incorporate hyperspectral, high spatial resolution or integrated multisensory data. Preferably, the time series would span 25 years or more, with the data captured on consistent, near-anniversary dates (i.e., corresponding to the peak of vegetation growth). The ground truth data may come from NFIs and/or other monitoring programmes. They may be associated with field plots or summarized at the survey unit level, preferably by measurement year. Furthermore, the target scene might cross national boundaries, requiring a merge of data from more than one source (e.g., NFIs from neighbouring countries). Regardless, the goal is to be able to link, spatiotemporally, any disturbance/damage occurrences recorded in the ground truth data to locations (pixels) in the remote sensing time series.

The approach has three mandatory steps (ovals): forest masking, damage/disturbance mapping, and causal attribution. There is also an optional step, damage/disturbance type classification, positioned between the latter two mandatory steps. Application of the remote sensing time series in these steps is depicted with blue arrows, while application of the ground truth data is depicted using red arrows. The relative weight (i.e., line width) of the arrows is meant to indicate the expected importance of each data source for the associated step. In addition, other data sources, many of which have been mentioned in this chapter, are likely to play varying roles in each step. For example, land cover data (e.g., from Copernicus Global Land Service) might be used to facilitate forest masking. Because the exact roles of these ancillary data sets are unspecified, their linkages are depicted generally (with grey arrows).

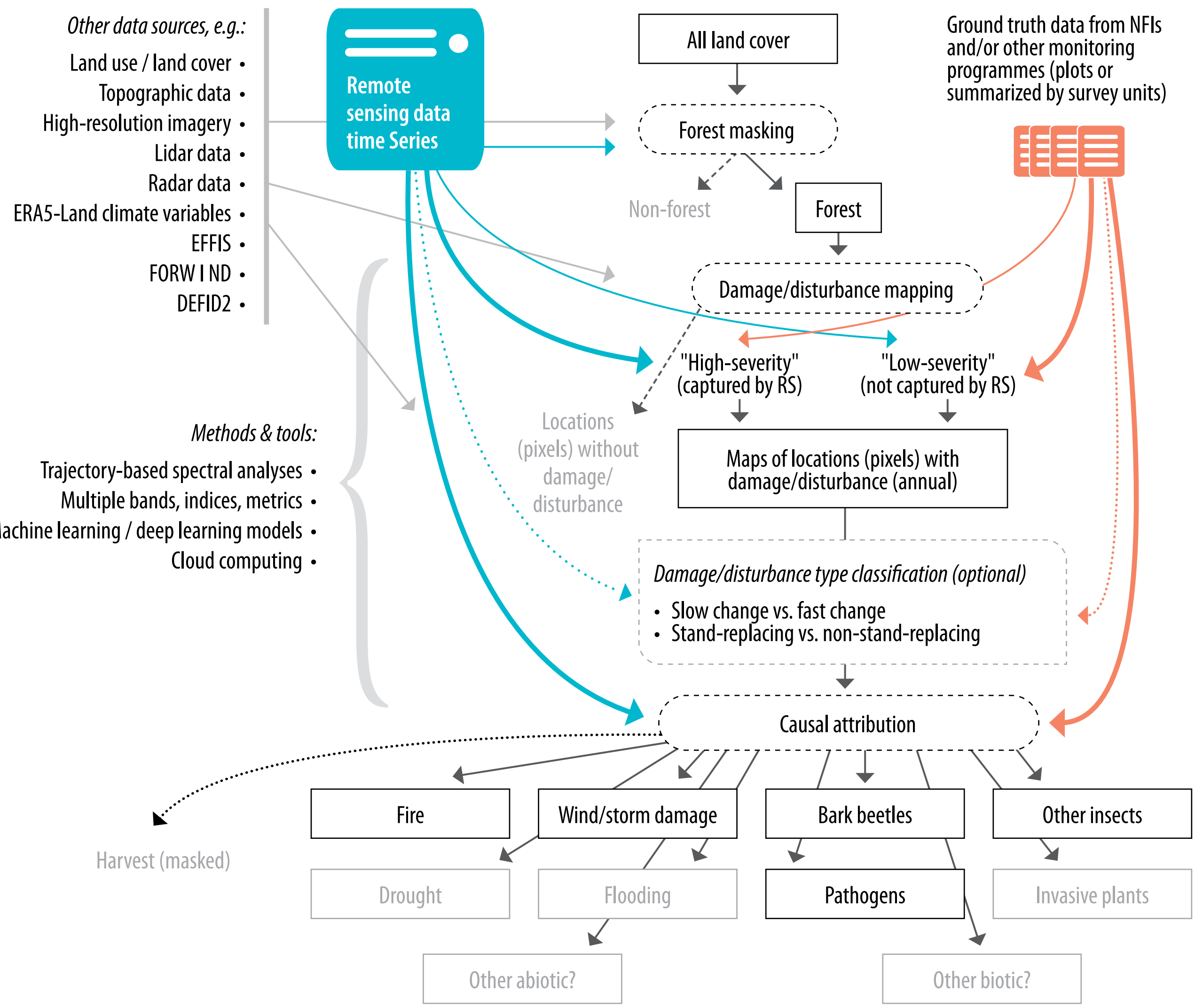
Moving beyond the critical first step of distinguishing forest from non-forest, the rest of the diagram in Figure 7.2 deals with concepts and methods presented in this chapter. For instance, damage/disturbance mapping (the second step) is likely to rely heavily on trajectory-based analyses of spectral band and derived index values from an optical image time series. However, recognizing that such analyses are likely to miss some cases of low-severity damage/disturbance, a separate path for mapping low-severity instances is outlined, using primarily the ground truth data. In turn, occurrences extracted from the ground truth data would feed into machine learning (or deep learning) models operating at a regional scale to map both high- and low-severity damage/disturbance locations on an annual basis. Retaining the severity information can be helpful in subsequent stages of the analytical process.

The step of damage/disturbance type classification assumes that the annual maps of locations (pixels) with damage/disturbance are arranged and analysed as time series. Although optional, this step is justified by research showing the benefits of type classification during causal attribution. For example, fire and wind damage/disturbance are usually signalled by an abrupt loss of forest canopy (i.e., a fast change), while insect or disease damage/disturbance are signalled by gradual canopy loss (i.e., a slow change) (Moisen *et al.* 2016, Schleeweis *et al.* 2020).

The final step is causal attribution. The simplified depiction of this step in Figure 7.2 belies its difficulty, as has been discussed previously. In keeping with convention, harvested locations are distinguished and set aside. The causal agents in the black text boxes are those recognized as the most prominent in a country/region. The agents in grey text boxes represent other causal agents that might be of regional interest. For example, drought has emerged as an important agent for forest damage/disturbance in much of Europe (Schuldt *et al.* 2020, Senf *et al.* 2020, Senf and Seidl 2021a), and one that many UNECE countries would like to see reported consistently (see Chapter 3). Of course, drought impacts in forests usually are manifested as insect outbreaks or other forest health issues, so how best to capture drought as a causal agent remains unresolved. Nevertheless, the drought example highlights a key question that must be answered for any regionally coordinated approach to work: what forest damage/disturbance agents and processes represent top priorities for

FIGURE **7.2**

Conceptual diagram of a hybrid approach to forest damage/disturbance assessment



Source: Oeser *et al.* (2017), adapted.

a country or region? Policy makers and analysts must come to some sort of agreement on the way forward with respect to drought and any other causal agents or processes deemed important.

Literature

Ahmed, O. S., M. A. Wulder, J. C. White, T. Hermosilla, N. C. Coops, and S. E. Franklin. (2017). Classification of annual non-stand replacing boreal forest change in Canada using Landsat time series: a case study in northern Ontario. Remote Sensing Letters 8:29–37.

Amani, M., A. Ghorbanian, S. A. Ahmadi, M. Kakooei, A. Moghimi, S. M. Mirmazloumi, S. H. A. Moghaddam, S. Mahdavi, M. Ghahremanloo, S. Parsian, Q. Wu, and B. Brisco. (2020). Google Earth Engine cloud computing platform for remote sensing big data applications: a comprehensive review. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 13:5326–5350.

Andela, N., D. C. Morton, L. Giglio, R. Paugam, Y. Chen, S. Hantson, G. R. Van Der Werf, and J. T. Anderson. (2019). The Global Fire Atlas of individual fire size, duration, speed and direction. Earth System Science Data 11:529–552.

Aquino, C., E. T. A. Mitchard, I. M. McNicol, H. Carstairs, A. Burt, B. L. Puma Vilca, M. Obiang Ebanéga, A. Modinga Dikongo, C. Dassi, S. Mayta, M. Tamayo, P. Grijalba, F. Miranda, and M. Disney. (2022). Reliably mapping low-intensity forest disturbance using satellite radar data. Frontiers in Forests and Global Change 5:1018762.

Artés, T., D. Oom, D. de Rigo, T. H. Durrant, P. Maianti, G. Libertà, and J. San-Miguel-Ayanz. (2019). A global wildfire dataset for the analysis of fire regimes and fire behaviour. Scientific Data 6:296.

Banskota, A., N. Kayastha, M. J. Falkowski, M. A. Wulder, R. E. Froese, and J. C. White. (2014). Forest monitoring using Landsat time series data: a review. Canadian Journal of Remote Sensing 40:362–384.

Barik, R. K., R. Priyadarshini, R. K. Lenka, H. Dubey, and K. Mankodiya. (2020). Fog computing architecture for scalable processing of geospatial big data. International Journal of Applied Geospatial Research 11:1–20.

Baumann, M., M. Ozdogan, P. T. Wolter, A. Krylov, N. Vladimirova, and V. C. Radeloff. (2014). Landsat remote sensing of forest windfall disturbance. Remote Sensing of Environment 143:171–179.

Beland, M., G. Parker, B. Sparrow, D. Harding, L. Chasmer, S. Phinn, A. Antonarakis, and A. Strahler. (2019). On promoting the use of lidar systems in forest ecosystem research. Forest Ecology and Management 450:117484.

Belgiu, M., and L. Drağuţ. (2016). Random forest in remote sensing: a review of applications and future directions. ISPRS Journal of Photogrammetry and Remote Sensing 114:24–31.

Bright, B. C., A. T. Hudak, A. J. H. Meddens, J. M. Egan, and C. L. Jorgensen. (2020). Mapping multiple insect outbreaks across large regions annually using Landsat time series data. Remote Sensing 12:1655.

Casu, F., M. Manunta, P. S. Agram, and R. E. Crippen. (2017). Big Remotely Sensed Data: tools, applications and experiences. Remote Sensing of Environment 202:1–2.

Christin, S., É. Hervet, and N. Lecomte. (2019). Applications for deep learning in ecology. Methods in Ecology and Evolution 10:1632–1644.

Claverie, M., J. Ju, J. G. Masek, J. L. Dungan, E. F. Vermote, J. C. Roger, S. V. Skakun, and C. Justice. (2018). The Harmonized Landsat and Sentinel-2 surface reflectance data set. Remote Sensing of Environment 219:145–161.

Cohen, W. B., S. P. Healey, Z. Yang, S. V. Stehman, C. K. Brewer, E. B. Brooks, N. Gorelick, C. Huang, M. J. Hughes, R. E. Kennedy, T. R. Loveland, G. G. Moisen, T. A. Schroeder, J. E. Vogelmann, C. E. Woodcock, L. Yang, and Z. Zhu. (2017). How similar are forest disturbance maps derived from different Landsat time series algorithms? Forests 8:98.

Cohen, W. B., Z. Yang, and R. Kennedy. (2010). Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync — Tools for calibration and validation. Remote Sensing of Environment 114:2911–2924.

Cohen, W. B., Z. Yang, S. V. Stehman, T. A. Schroeder, D. M. Bell, J. G. Masek, C. Huang, and G. W. Meigs. (2016). Forest disturbance across the conterminous United States from 1985-2012: the emerging dominance of forest decline. Forest Ecology and Management 360:242–252.

Coops, N. C., C. Shang, M. A. Wulder, J. C. White, and T. Hermosilla. (2020). Change in forest condition: characterizing non-stand replacing disturbances using time series satellite imagery. Forest Ecology and Management 474:118370.

Coops, N. C., M. A. Wulder, and J. C. White. (2006). Identifying and describing forest disturbance and spatial pattern: data selection issues and methodological implications. Pages 31–61 in M. A. Wulder and S. E. Franklin, editors. Understanding Forest Disturbance and Spatial Pattern: Remote Sensing and GIS Approaches. 1st edition. CRC Press (Taylor and Francis), Boca Raton, FL, USA.

Cruz, M. G., N. P. Cheney, J. S. Gould, W. L. McCaw, M. Kilinc, and A. L. Sullivan. (2022). An empirical-based model for predicting the forward spread rate of wildfires in eucalypt forests. International Journal of Wildland Fire 31:81–95.

Das, A. J., N. L. Stephenson, and K. P. Davis. (2016). Why do trees die? Characterizing the drivers of background tree mortality. Ecology 97:2616–2627.

Díaz-Yáñez, O., B. Mola-Yudego, R. Eriksen, and J. R. González-Olabarria. (2016). Assessment of the main natural disturbances on Norwegian forest based on 20 years of national inventory. PLoS ONE 11:e0161361.

Doblas Prieto, J., L. Lima, S. Mermoz, A. Bouvet, J. Reiche, M. Watanabe, S. Sant Anna, and Y. Shimabukuro. (2023). Inter-comparison of optical and SAR-based forest disturbance warning systems in the Amazon shows the potential of combined SAR-optical monitoring. International Journal of Remote Sensing 44:59–77.

Drusch, M., U. Del Bello, S. Carlier, O. Colin, V. Fernandez, F. Gascon, B. Hoersch, C. Isola, P. Laberinti, P. Martimort, A. Meygret, F. Spoto, O. Sy, F. Marchese, and P. Bargellini. (2012). Sentinel-2: ESA's optical high-resolution mission for GMES operational services. Remote Sensing of Environment 120:25–36.

Eidenshink, J., B. Schwind, K. Brewer, Z.-L. Zhu, B. Quayle, and S. Howard. (2007). A project for Monitoring Trends in Burn Severity. Fire Ecology 3:3–21.

Enderle, R., B. Metzler, U. Riemer, and G. Kändler. (2018). Ash dieback on sample points of the national forest inventory in south-western Germany. Forests 9:25.

Fitts, L. A., G. M. Domke, and M. B. Russell. (2022). Comparing methods that quantify forest disturbances in the United States' national forest inventory. Environmental Monitoring and Assessment 194:304.

Forzieri, G., B. Eckhardt, P. Beck, and A. Cescatti. (2020a). Database of European Forest Insect & Disease Disturbances – DEFID2 – protocol for data collection. European Commission, Joint Research Centre, Ispra, Italy.

Forzieri, G., M. Girardello, G. Ceccherini, J. Spinoni, L. Feyen, H. Hartmann, P. S. A. Beck, G. Camps-Valls, G. Chirici, A. Mauri, and A. Cescatti. (2021). Emergent vulnerability to climate-driven disturbances in European forests. Nature Communications 12:1–12.

Forzieri, G., M. Pecchi, M. Girardello, A. Mauri, M. Klaus, C. Nikolov, M. Rüetschi, B. Gardiner, J. Tomastik, D. Small, C. Nistor, D. Jonikavicius, J. Spinoni, L. Feyen, F. Giannetti, R. Comino, A. Wolynski, F. Pirotti, F. Maistrelli, I. Savulescu, S. Wurpillot-Lucas, S. Karlsson, K. Zieba-Kulawik, P. Strejczek-Jazwinska, M. Mokroš, S. Franz, L. Krejci, I. Haidu, M. Nilsson, P. Wezyk, F. Catani, Y. Y. Chen, S. Luyssaert, G. Chirici, A. Cescatti, and P. S. A. Beck. (2020b). A spatially explicit database of wind disturbances in European forests over the period 2000-2018. Earth System Science Data 12:257–276.

Francini, S., G. D'Amico, E. Vangi, C. Borghi, and G. Chirici. (2022a). Integrating GEDI and Landsat: spaceborne lidar and four decades of optical imagery for the analysis of forest disturbances and biomass changes in Italy. Sensors 22:2015.

Francini, S., R. E. McRoberts, G. D'Amico, N. C. Coops, T. Hermosilla, J. C. White, M. A. Wulder, M. Marchetti, G. S. Mugnozza, and G. Chirici. (2022b). An open science and open data approach for the statistically robust estimation of forest disturbance areas. International Journal of Applied Earth Observation and Geoinformation 106:102663.

Gao, Y., M. Skutsch, J. Paneque-Gálvez, and A. Ghilardi. (2020). Remote sensing of forest degradation: a review. Environmental Research Letters 15:103001.

Ghaderpour, E., and T. Vujadinovic.(2020). Change detection within remotely sensed satellite image time series via spectral analysis. Remote Sensing 12:1–27.

Gomes, V., G. Queiroz, and K. Ferreira. (2020). An overview of platforms for big Earth observation data management and analysis. Remote Sensing 12:1253.

Gómez, C., J. C. White, and M. A. Wulder. (2016). Optical remotely sensed time series data for land cover classification: A review. ISPRS Journal of Photogrammetry and Remote Sensing 116:55–72.

Gorelick, N., M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau, and R. Moore. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment 202:18–27.

Hall, R. J., G. Castilla, J. C. White, B. J. Cooke, and R. S. Skakun. (2016). Remote sensing of forest pest damage: a review and lessons learned from a Canadian perspective. Canadian Entomologist 148:S296–S356.

Hall, R. J., R. S. Skakun, J. M. Metsaranta, R. Landry, R. H. Fraser, D. Raymond, M. Gartrell, V. Decker, and J. Little. (2020). Generating annual estimates of forest fire disturbance in Canada: the National Burned Area Composite. International Journal of Wildland Fire 29:878–891.

Hamdi, Z. M., M. Brandmeier, and C. Straub. (2019). Forest damage assessment using deep learning on high resolution remote sensing data. Remote Sensing 11:1976.

Hamunyela, E., S. Rosca, A. Mirt, E. Engle, M. Herold, F. Gieseke, and J. Verbesselt. (2020). Implementation of BFASTmonitor Algorithm on Google Earth Engine to support large-area and sub-annual change monitoring using earth observation data. Remote Sensing 12:2953.

Henttonen, H. M., P. Nöjd, and H. Mäkinen. (2017). Environment-induced growth changes in the Finnish forests during 1971–2010 – An analysis based on National Forest Inventory. Forest Ecology and Management 386:22–36.

Hermosilla, T., M. A. Wulder, J. C. White, N. C. Coops, and G. W. Hobart. (2015). Regional detection, characterization, and attribution of annual forest change from 1984 to 2012 using Landsat-derived time-series metrics. Remote Sensing of Environment 170:121–132.

Hirschmugl, M., H. Gallaun, M. Dees, P. Datta, J. Deutscher, N. Koutsias, and M. Schardt. (2017). Methods for mapping forest disturbance and degradation from optical Earth observation data: a review. Current Forestry Reports 3:32–45.

Hislop, S., A. Haywood, M. Alaibakhsh, T. H. Nguyen, M. Soto-Berelov, S. Jones, and C. Stone. (2021). A reference data framework for the application of satellite time series to monitor forest disturbance. International Journal of Applied Earth Observation and Geoinformation 105:102636.

Huang, C., S. N. Goward, J. G. Masek, N. Thomas, Z. Zhu, and J. E. Vogelmann. (2010). An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. Remote Sensing of Environment 114:183–198.

Huo, L. Z., L. Boschetti, and A. M. Sparks. (2019). Object-based classification of forest disturbance types in the conterminous United States. Remote Sensing 11:477.

Kautz, M., A. J. H. Meddens, R. J. Hall, and A. Arneth. (2017). Biotic disturbances in Northern Hemisphere forests – a synthesis of recent data, uncertainties and implications for forest monitoring and modelling. Global Ecology and Biogeography 26:533–552.

Kennedy, R. E., Z. Yang, and W. B. Cohen. (2010). Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr - Temporal segmentation algorithms. Remote Sensing of Environment 114:2897–2910.

Kennedy, R. E., Z. Yang, N. Gorelick, J. Braaten, L. Cavalcante, W. B. Cohen, and S. Healey. (2018). Implementation of the LandTrendr algorithm on Google Earth Engine. Remote Sensing 10:691.

Kotel'nikov, R. V., E. A. Lupyan, S. A. Bartalev, and D. V. Ershov. (2020). Space monitoring of forest fires: history of the creation and development of ISDM-Rosleskhoz. Contemporary Problems of Ecology 13:795–802.

Lambert, J., C. Drenou, J. P. Denux, G. Balent, and V. Cheret. (2013). Monitoring forest decline through remote sensing time series analysis. GIScience and Remote Sensing 50:437–457.

Lastovicka, J., P. Svec, D. Paluba, N. Kobliuk, J. Svoboda, R. Hladky, and P. Stych. (2020). Sentinel-2 data in an evaluation of the impact of the disturbances on forest vegetation. Remote Sensing 12:1914.

Lausch, A., E. Borg, J. Bumberger, P. Dietrich, M. Heurich, A. Huth, A. Jung, R. Klenke, S. Knapp, H. Mollenhauer, H. Paasche, H. Paulheim, M. Pause, C. Schweitzer, C. Schmulius, J. Settele, A. K. Skidmore, M. Wegmann, S. Zacharias, T. Kirsten, and M. E. Schaepman. (2018). Understanding forest health with remote sensing, Part III: Requirements for a scalable multi-source forest health monitoring network based on data science approaches. Remote Sensing 10:1120.

Lausch, A., S. Erasmi, D. J. King, P. Magdon, and M. Heurich. (2016). Understanding forest health with remote sensing-Part I-A review of spectral traits, processes and remote-sensing characteristics. Remote Sensing 8:1029.

Lausch, A., S. Erasmi, D. J. King, P. Magdon, and M. Heurich. (2017). Understanding forest health with Remote sensing-Part II-A review of approaches and data models. Remote Sensing 9:129.

Lechner, A. M., G. M. Foody, and D. S. Boyd. (2020). Applications in remote sensing to forest ecology and management. One Earth 2:405–412.

Letson, F. W., R. J. Barthelmie, K. I. Hodges, and S. C. Pryor. (2021). Intense windstorms in the northeastern United States. Natural Hazards and Earth System Sciences 21:2001–2020.

Maltamo, M., P. Packalen, and A. Kangas. (2021). From comprehensive field inventories to remotely sensed wall-to-wall stand attribute data-a brief history of management inventories in the Nordic countries. Canadian Journal of Forest Research 51:257–266.

Masek, J. G., M. A. Wulder, B. Markham, J. McCorkel, C. J. Crawford, J. Storey, and D. T. Jenstrom. (2020). Landsat 9: Empowering open science and applications through continuity. Remote Sensing of Environment 248:111968.

McDowell, N. G., N. C. Coops, P. S. A. Beck, J. Q. Chambers, C. Gangodagamage, J. A. Hicke, C. ying Huang, R. Kennedy, D. J. Krofcheck, M. Litvak, A. J. H. Meddens, J. Muss, R. Negrón-Juarez, C. Peng, A. M. Schwantes, J. J. Swenson, L. J. Vernon, A. P. Williams, C. Xu, M. Zhao, S. W. Running, and C. D. Allen. (2015). Global satellite monitoring of climate-induced vegetation disturbances. Trends in Plant Science 20:114–123.

Meddens, A. J. H., J. A. Hicke, L. A. Vierling, and A. T. Hudak. (2013). Evaluating methods to detect bark beetle-caused tree mortality using single-date and multi-date Landsat imagery. Remote Sensing of Environment 132:49–58.

Midekisa, A., F. Holl, D. J. Savory, R. Andrade-Pacheco, P. W. Gething, A. Bennett, and H. J. W. Sturrock. (2017). Mapping land cover change over continental Africa using Landsat and Google Earth Engine cloud computing. PLOS ONE 12:e0184926.

Moisen, G. G., M. C. Meyer, T. A. Schroeder, X. Liao, K. G. Schleeweis, E. A. Freeman, and C. Toney. (2016). Shape selection in Landsat time series: a tool for monitoring forest dynamics. Global Change Biology 22:3518–3528.

Muñoz-Sabater, J., E. Dutra, A. Agustí-Panareda, C. Albergel, G. Arduini, G. Balsamo, S. Boussetta, M. Choulga, S. Harrigan, H. Hersbach, B. Martens, D. G. Miralles, M. Piles, N. J. Rodríguez-Fernández, E. Zsoter, C. Buontempo, and J. N. Thépaut. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth System Science Data 13:4349–4383.

Murillo-Sandoval, P. J., T. Hilker, M. A. Krawchuk, and J. Van Den Hoek. (2018). Detecting and attributing drivers of forest disturbance in the Colombian Andes using Landsat time-series. Forests 9:269.

Nilsson, M., K. Nordkvist, J. Jonzén, N. Lindgren, P. Axensten, J. Wallerman, M. Egberth, S. Larsson, L. Nilsson, J. Eriksson, and H. Olsson. (2017). A nationwide forest attribute map of Sweden predicted using airborne laser scanning data and field data from the National Forest Inventory. Remote Sensing of Environment 194:447–454.

Oeser, J., D. Pflugmacher, C. Senf, M. Heurich, and P. Hostert. (2017). Using intra-annual Landsat time series for attributing forest disturbance agents in Central Europe. Forests 8:251.

Ojha, S. K., K. Naka, and L. D. Dimov. (2020). Assessment of disturbances across forest inventory plots in the southeastern United States for the period 1995-2018. Forest Science 66:242–255.

Olofsson, P., G. M. Foody, M. Herold, S. V. Stehman, C. E. Woodcock, and M. A. Wulder. (2014). Good practices for estimating area and assessing accuracy of land change. Remote Sensing of Environment 148:42–57.

Ozdogan, M. (2014). A practical and automated approach to large area forest disturbance mapping with remote sensing. PLoS ONE 9:e78438.

Pastick, N. J., M. T. Jorgenson, S. J. Goetz, B. M. Jones, B. K. Wylie, B. J. Minsley, H. Genet, J. F. Knight, D. K. Swanson, and J. C. Jorgenson. (2019). Spatiotemporal remote sensing of ecosystem change and causation across Alaska. Global Change Biology 25:1171–1189.

Patacca, M., M.-J. Schelhaas, S. Zudin, and M. Lindner. (2021). Database on Forest Disturbances in Europe (DFDE) - history, state of the art, and future perspectives - technical report. European Forest Institute / Project I-Maestro.

Plank, S. (2014). Rapid damage assessment by means of multi-temporal SAR — a comprehensive review and outlook to Sentinel-1. Remote Sensing 6:4870–4906.

San-Miguel-Ayanz, J., E. Schulte, G. Schmuck, A. Camia, P. Strobl, G. Liberta, C. Giovando, R. Boca, F. Sedano, P. Kempeneers, D. McInerney, C. Withmore, S. S. de Oliveira, M. Rodrigues, T. Durrant, P. Corti, F. Oehler, L. Vilar, and G. Amatulli. (2012). Comprehensive monitoring of wildfires in Europe: the European Forest Fire Information System (EFFIS). Pages 87–108 in J. Tiefenbacher, editor. Approaches to Managing Disaster - Assessing Hazards, Emergencies and Disaster Impacts. InTech.

Sanchez-Lopez, N., L. Boschetti, A. T. Hudak, S. Hancock, and L. I. Duncanson. (2020). Estimating time since the last stand-replacing disturbance (TSD) from spaceborne simulated GEDI data: A feasibility study. Remote Sensing 12:1–25.

Schelhaas, M. J., G. J. Nabuurs, and A. Schuck. (2003). Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biology 9:1620–1633.

Schleeweis, K. G., G. G. Moisen, T. A. Schroeder, C. Toney, E. A. Freeman, S. N. Goward, C. Huang, and J. L. Dungan. (2020). US national maps attributing forest change: 1986–2010. Forests 11:653.

Schroeder, T. A., K. G. Schleeweis, G. G. Moisen, C. Toney, W. B. Cohen, E. A. Freeman, Z. Yang, and C. Huang. (2017). Testing a Landsat-based approach for mapping disturbance causality in U.S. forests. Remote Sensing of Environment 195:230–243.

Schuldt, B., A. Buras, M. Arend, Y. Vitasse, C. Beierkuhnlein, A. Damm, M. Gharun, T. E. E. Grams, M. Hauck, P. Hajek, H. Hartmann, E. Hiltbrunner, G. Hoch, M. Holloway-Phillips, C. Körner, E. Larysch, T. Lübbe, D. B. Nelson, A. Rammig, A. Rigling, L. Rose, N. K. Ruehr, K. Schumann, F. Weiser, C. Werner, T. Wohlgemuth, C. S. Zang, and A. Kahmen. (2020). A first assessment of the impact of the extreme 2018 summer drought on Central European forests. Basic and Applied Ecology 45:86–103.

Scott, G., and A. Rajabifard. (2017). Sustainable development and geospatial information: a strategic framework for integrating a global policy agenda into national geospatial capabilities. Geo-spatial Information Science 20:59–76.

Sebald, J., C. Senf, and R. Seidl. (2021). Human or natural? Landscape context improves the attribution of forest disturbances mapped from Landsat in Central Europe. Remote Sensing of Environment 262:112502.

Senf, C., A. Buras, C. S. Zang, A. Rammig, and R. Seidl. (2020). Excess forest mortality is consistently linked to drought across Europe. Nature Communications 11:1–8.

Senf, C., and R. Seidl. (2021a). Persistent impacts of the 2018 drought on forest disturbance regimes in Europe. Biogeosciences 18:5223–5230.

Senf, C., and R. Seidl. (2021b). Mapping the forest disturbance regimes of Europe. Nature Sustainability 4:63–70.

Senf, C., and R. Seidl. (2021c). Storm and fire disturbances in Europe: distribution and trends. Global Change Biology 27:3605–3619.

Shikhov, A. N., A. V. Chernokulsky, I. O. Azhigov, and A. V. Semakina. (2020). A satellite-derived database for stand-replacing windthrow events in boreal forests of European Russia in 1986-2017. Earth System Science Data 12:3489–3513.

Shivaprakash, K. N., N. Swami, S. Mysorekar, R. Arora, A. Gangadharan, K. Vohra, M. Jadeyegowda, and J. M. Kiesecker. (2022). Potential for artificialintelligence (AI) and machine learning (ML) applications in biodiversity conservation, managing forests, and related services in India. Sustainability 14:7154.

Solórzano, J. V., and Y. Gao. (2022). Forest disturbance detection with seasonal and trend model components and machine learning algorithms. Remote Sensing 14:803.

Stupariu, M.-S., S. A. Cushman, A.-I. Pleşoianu, I. Pătru-Stupariu, and C. Fürst. (2022). Machine learning in landscape ecological analysis: a review of recent approaches. Landscape Ecology 37:1227–1250.

Sulla-Menashe, D., R. E. Kennedy, Z. Yang, J. Braaten, O. N. Krankina, and M. A. Friedl. (2014). Detecting forest disturbance in the Pacific Northwest from MODIS time series using temporal segmentation. Remote Sensing of Environment 151:114–123.

Tanase, M. A., L. Villard, D. Pitar, B. Apostol, M. Petrila, S. Chivulescu, S. Leca, I. Borlaf-Mena, I. S. Pascu, A. C. Dobre, D. Pitar, G. Guiman, A. Lorent, C. Anghelus, A. Ciceu, G. Nedea, R. Stanculeanu, F. Popescu, C. Aponte, and O. Badea. (2019). Synthetic aperture radar sensitivity to forest changes: A simulations-based study for the Romanian forests. Science of the Total Environment 689:1104–1114.

Taylor, R., C. Davis, J. Brandt, M. Parker, T. Stäuble, and Z. Said. (2020). The rise of big data and supporting technologies in keeping watch on the world's forests. International Forestry Review 22:129–141.

Torres, P., M. Rodes-Blanco, A. Viana-Soto, H. Nieto, and M. García. (2021). The role of remote sensing for the assessment and monitoring of forest health: A systematic evidence synthesis. Forests 12:1–35.

Trumbore, S., P. Brando, and H. Hartmann. (2015). Forest health and global change. Science 349:814–818.

Tuominen, J., T. Lipping, V. Kuosmanen, and R. Haapane. (2009). Remote sensing of forest health. Pages 29–52 in P.-G. Ho, editor. Geoscience and Remote Sensing. InTech.

Vangi, E., G. D'Amico, S. Francini, F. Giannetti, B. Lasserre, M. Marchetti, and G. Chirici. (2021). The new hyperspectral satellite PRISMA: imagery for forest types discrimination. Sensors 21:1182.

Verbesselt, J., R. Hyndman, G. Newnham, and D. Culvenor. (2010). Detecting trend and seasonal changes in satellite image time series. Remote Sensing of Environment 114:106–115.

Wegmueller, S. A., and P. A. Townsend. (2021). Astrape: a system for mapping severe abiotic forest disturbances using high spatial resolution satellite imagery and unsupervised classification. Remote Sensing 13:1634.

White, J. C., M. A. Wulder, T. Hermosilla, N. C. Coops, and G. W. Hobart. (2017). A nationwide annual characterization of 25 years of forest disturbance and recovery for Canada using Landsat time series. Remote Sensing of Environment 194:303–321.

Wulder, M. A., T. Hermosilla, G. Stinson, F. A. Gougeon, J. C. White, D. A. Hill, and B. P. Smiley. (2020). Satellite-based time series land cover and change information to map forest area consistent with national and international reporting requirements. Forestry 93:331–343.

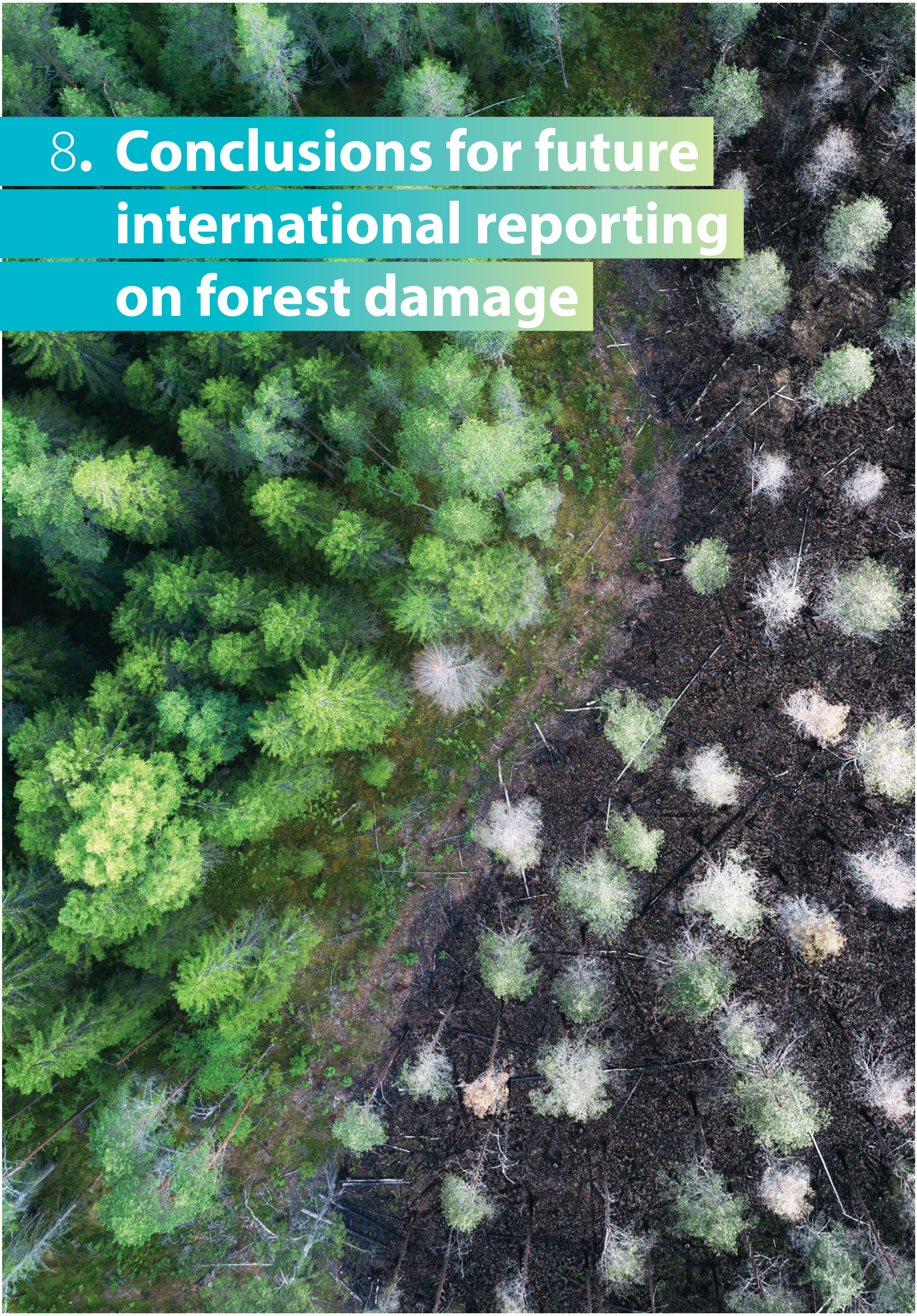
Wulff, S., C. Roberge, A. Ringvall, S. Holm, and G. Ståhl. (2013). On the possibility to monitor and assess forest damage within large scale monitoring programmes – a simulation study. Silva Fennica 47:1000.

Zhang, S., M. Bai, X. Wang, X. Peng, A. Chen, and P. Peng. (2023). Remote sensing technology for rapid extraction of burned areas and ecosystem environmental assessment. PeerJ 11:e14557.

Zhao, F., C. Huang, S. N. Goward, K. Schleeweis, K. Rishmawi, M. A. Lindsey, E. Denning, L. Keddell, W. B. Cohen, Z. Yang, J. L. Dungan, and A. Michaelis. (2018). Development of Landsat-based annual US forest disturbance history maps (1986–2010) in support of the North American Carbon Program (NACP). Remote Sensing of Environment 209:312–326.

Zhu, Z. (2017). Change detection using Landsat time series: A review of frequencies, preprocessing, algorithms, and applications. ISPRS Journal of Photogrammetry and Remote Sensing 130:370–384.

8. Conclusions for future international reporting on forest damage



8. Conclusions for future international reporting on forest damage

Forest damage and disturbance deserve special attention in international reporting as they have significant impact on sustainability, linking social, environmental and economic aspects of forests, and their future. On the one hand, damage prevention and mitigation as well as the restoration of damaged forest represents an important basis for safeguarding the diverse forest functions. On the other hand, damages and disturbances are determined by their damaging agents as well as their spatial and temporal occurrence that are subject to complex cause-effect relationships.

The further development of international reporting is understood as a process that respects the following principles:

- Identify and promote best practices and state-of-the-art technical innovations.
- Foster communication between countries and international forest experts.
- Build on and include existing reporting processes, notably FRA and the Joint pan-European Data Collection on Forests and Sustainable Forest Management.
- Commit to an incremental process of continuous improvement focused on key variables, specific problem areas, or promising innovations.

In addition to the technical aspects that should be addressed to improve international reporting on forest damage/disturbance, it is particularly desirable to further develop cooperation and communication among all actors involved.

8.1 Concept of damage/disturbance

While the term disturbance of ecosystem functions refers to processes, the term damage is related to ecosystem services and functions. When a "disturbance" becomes a "damage" in a managed forest is dependent on the chosen assessment criteria (e.g., water supply, value of standing timber). For international reporting, this raises the problem of how to set the criteria that establish when a disturbance becomes damage. These criteria depend on the perspectives and the demand of goods and services provided by forests.

When considering harmonization across space and time, the value-neutral measures associated with disturbance may be suited better for harmonized data reporting at regional and global scales. However, a viable compromise could be a report format that combines conceptually forest damage and disturbance. This does not exclude the possibility of distinguishing between damage and disturbance for specific ecosystem goods and services.

8.2 Periodicity

On damage/disturbance, international reporting thrives on topicality and continuity. This became evident in the 2020 SoEF which did not yet include the drastic forest damages observed in Central Europe in 2018, since the recent available data for this study were from before autumn 2018 (deadline for 2020 data collection). Therefore, the reporting periods for damage/disturbance could be adjusted to include information made available on recent events.

FRA offers the possibility of annual reference year reporting in the regular periodical data collection cycle. Since the 2025 cycle of the JPEDC, this approach can be also applied in the forest damage related reporting under indicator 2.4. Furthermore, some of the countries can report more comprehensive and frequent data to international processes than they do presently (Chapter 5).

8.3 Thresholds

The analyses have shown that countries apply no uniform thresholds for damage/disturbance. This is partly because the intensity of damage/disturbance is often assessed in response to specific conditions and purposes.

While the introduction of uniform thresholds would increase consistency and transparency in reporting, it could also lead to a decrease of reported information and/or erroneous conclusions. It is understood that countries define thresholds on their own responsibility based on their expertise and understanding of local conditions, which highly affects the comparability of data. Likewise, the criteria used by countries for reporting thresholds of damage should be highlighted in the analysis and presentation of results.

8.4 Double counting

Double counting poses a serious problem to reporting consistency and data validation. The introduction of the total area on which damage/disturbance occurs provides a partial remedy. It is recommended to distinguish between primary damage and consequential damage/disturbance. The question of what is meant by primary damage/disturbance can be answered differently, i.e. by using the temporal sequence of occurrence or by referring to an attribute based on quantitative values. An example would be the affected volume or number of affected trees. It should be left to the countries to decide which assessment approach to use.

8.5 Completeness vs specificity

Current international reporting on forest damage/disturbance aims at providing complete coverage on forest damage, both in terms of areas and damaging/ disturbing factors. Many of the reporting countries would already have more detailed data available for reporting, but they are making it broader for the purpose of the FRA reporting (for example "snow", "wind", "drought" etc. are bundled into "extreme weather") (see Chapter4). This would also bring more insight into what type of "extreme weather" (for instance) has affected the forests as this varies significantly between regions: snow is a common damage agent in Northern Europe whereas drought has the same role in Southern parts of Europe. Similarly, if the FRA category "insects" was additionally divided into sub-categories "bark beetles" and "defoliators", the data would give a more complete picture about what is affecting the forests.

To provide more specific information on, e.g. selected groups of insects, various abiotic factors and specific thresholds, an improved international reporting on forest damage should consider the inclusion of more specific (sub)indicators on particular types of damage and/or damaging agents.

The specificity of reporting will also need to consider scale which will play an integral role. In the current international reporting, forest damage is aggregated at the national level, however the improved interpretation of data would benefit from adjusted geographical scales.

8.6 Harmonization

International reporting is based on national data, which are assessed through systems that have evolved historically and are based on countries' respective capacities, resources and information needs. To eliminate resulting inconsistencies for international reporting, ways of harmonizing the data provided have long been explored. So far, an applicable and generally accepted solution could not be found for all harmonization issues.

International data-collection systems can be used - to some extent - in assessing forest damage/disturbance in either defining a unique data assessment standard for all countries (e.g. ICP Forests) or providing a uniform assessment system (e.g. EFFIS).

The use of international and regional data providers can be appropriate to provide consistent and comprehensive damage/disturbance data for international reporting.

8.7 Time allocation of damages

For consistent reporting, it is essential to establish a uniform nomenclature for the temporal allocation of the damage/ disturbance that occur. The introduction of a temporal framework which serves to distinguish between old and newly occurring damage/disturbance would be worth considering. For example, areas where damage/disturbance has occurred within the last 5 years of the international reporting cycle or between two national forest inventory dates could be distinguished from areas where damage/disturbance has already been reported. Reporting could also be expanded to include areas that have recovered from damage/disturbance.

8.8 Additional attributes to be included

To increase the informative value of damage/disturbance, the introduction of additional reporting variables should be reconsidered. Conceivable new attributes would be:

- Volume of growing stock affected
- Salvage timber (volume and value) accrued
- Market value affected
- Forest age of the affected area
- Attributes related to terrain
- Damage/disturbance of forest soils
- Damage/disturbance of regeneration
- Status of wood decay in dead trees
- Damage/disturbance caused by invasive species
- Management status of affected forest areas

Though, the possible extension of the portfolio of forest damage variables in the international reporting is always tempting, any decision in this regard should be preceded by the purpose and cost/benefit analysis, and consider the complementarity with the existing sets and processes.

8.9 Data Integration

Useful data about forests are increasingly available from a growing range of sources. Advances in remote sensing technologies have led to improvements in spectral, spatial and temporal resolution of optical imagery, as well as in active sensor systems (e.g., synthetic aperture radar) that provide information about forest structure even in cloudy conditions. Cloud-based computing platforms grant users the capacity to perform analyses in this emerging "big data" environment, especially through the application of AI techniques such as machine learning and deep learning. Nevertheless, remote sensing technologies offer only indirect measures of forests and trees. Field-based measurements, such as through NFIs, remain critical for the assessment of forest damage/

disturbance, perhaps foremost for identifying the agents or processes that cause damage/disturbance events.

It is a challenge to integrate these disparate data streams for consistent, reliable assessment of forest damage/ disturbance at a regional scale. One potential solution is a hybrid approach (see Figure 7.2) that combines two parallel data streams: a time series of remote sensing data (e.g., a stack of multispectral satellite images) and corresponding ground truth data from NFIs or other monitoring programmes. These two primary data streams can be supplemented by other data, such as from regional fire information systems or insect and disease disturbance databases (see Chapter 7 for more examples). The approach has two primary analytical phases. Initially, forest damage/disturbance occurrences, regardless of cause, are mapped spatially and through time. Then, these mapped occurrences are attributed to causal agents with as much specificity as possible. Both analytical phases are computationally intensive, and the results will still be subject to uncertainty, particularly regarding causal agents. However, cloud computing, artificial intelligence and an ever-expanding data suite greatly increase the opportunities for regional-level data integration.

8.10 Improve completeness of international reporting

The analyses in this study have shown that selected countries already avail of more information on damage/disturbance for international reporting (see chapter 3). International reporting on forest damage relies on voluntary data provision by participating countries and international data providers (IDPs), and has been carried out so far in relatively long periods (5 years).

Reporting on forest damage is only one component of comprehensive reporting, demanding a significant amount of resources in the participating countries and organizations. Possible improvement in responses rates on forest damage would require an increase of resources, dedicated to this task, to implement the reporting process as proposed below.

On the part of the data query, the following improvements can help to increase the response rates.

- Questionnaires should be easy to understand and adequately piloted and tested.
- Guidance, support and training material for participants should be provided to the extent possible.
- Participants should receive all possible support in compiling and reporting national information.

8.11 Refine international data collection on forest damage/disturbance

The analysis has shown that in addition to the completeness, accuracy, and complementarity of international reporting on forest damage/disturbance, the current overall format of the reporting may not entirely fit present and future needs. The latter might become very challenging in the future with the diversity of forest types and the expected changing climatic conditions.

A comprehensive review and refinement of the reporting on forest damage/disturbance in the UNECE region will become necessary to better align the purpose, format, frequency, and extent of this type of reporting to the requirements of forest policy, management, as well as the societal demands. This would need to consider existing reporting formats such as the forest damage assessment carried out in FRA and JPEDC.

Reporting on forest damages and disturbances in the UNECE region

The frequency and intensity of wildfires, storms and pest outbreaks has been increasing rapidly for several decades, highlighting the vulnerability of the world's forests and the impact of natural and human threats accelerated and intensified by climate changes.

Although disturbance and mortality are inherent to forest ecosystems, and forest disturbance has always been a concern in forest management, monitoring the extent of damage has become a key priority in recent decades.

Forests are vital carbon sinks for climate change mitigation and reservoirs of global biodiversity. This makes reliable information, data and accurate reporting of damage and disturbance even more important for effective policies ensuring the sustainable management of forests.

To ensure that this critical information is available to all, the United Nations Economic Commission for Europe (UNECE) and the Food and Agriculture Organization of the United Nations (FAO) have summarized in this publication the main dynamics and significance of forest damage, and their reporting in the UNECE region.

The publication invites readers to reflect on possible harmonized methodologies and reporting schemes. In this regard, it also underlines the collective effort that is essential for the forest sector.

Real-world scenarios, such as the analysis of forest damage and disturbance data, require state-of-the-art techniques beyond the usual statistical evaluation. Innovative technologies highlighted in this publication such as remote sensing, artificial intelligence and machine learning will need to be integral parts of any advances in forest damage assessment.

Reporting on forest damage is not just a technical exercise. It is a critical element of our shared commitment to biodiversity, climate resilience and livelihoods. Supporting comprehensive reporting will lay the foundation for safeguarding forest ecosystems for future generations.

This publication is an important step towards improving international reporting on forest damage and the result of a collaborative effort of national and international experts, supported by the secretariat.

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