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Forest disturbance and damage: Perspectives for forest monitoring and reporting

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ABSTRACT

In this forest perspectives paper, we explore issues and concepts involved in the enhancement of regional monitoring frameworks for reporting on forest disturbances and damages. First, we consider the different meanings of "forest disturbance" and "forest damage," terms that are often used interchangeably but have important differences in meaning and management implications. Human expectations, goals and concerns underlie both terms, especially forest damage, and they condition the data-gathering efforts and interpretations of resulting information. Accordingly, we also address the overall motivations for reporting forest disturbances and damages, the potentially impacted human expectations, and the general categories of impact and response. Next, we present some general observations on the ecological processes underlying forest disturbances and forest damages and the approaches used to measure them, noting the following challenges these processes pose for clear and consistent reporting across space and time: complexity of disturbance processes; attributing causality and distinguishing between proximate, intermediate and ultimate causes; spatial and temporal discontinuities; measurement protocol variations between countries. Both ecological processes and their related measurement techniques are particularistic, involving various and specific measurement techniques and protocols, and they do not always conform to conceptual generalizations. We conclude with a discussion on bridging the gap between concept and practical application of disturbance and damage monitoring and reporting. Despite challenges in aggregating diverse data on forest disturbances, doing so is crucial for improving scientific understanding, policy-making, and environmental management on regional and global scales.

Keywords

damage, damage indicators, disturbance, forest condition, forest monitoring, forest reporting

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INTRODUCTION

Due to global change, the frequency and intensity of storms, forest fires, diseases and insect calamities have been increasing in the past decades, highlighting the vulnerability of our forests (Seidl et al. 2014a; Ellis et al. 2022; Kautz et al. 2017). Serious losses of forest ecosystem health and vitality are often synonymously referred to as forest disturbance or forest damage. These forest disturbances and damages not only threaten the structural integrity of forests but also disrupt essential ecosystem services, including carbon sequestration and biodiversity conservation. Disturbances can lead to the release of stored carbon into the atmosphere, reducing forests' role as carbon sinks, while also fragmenting habitats and threatening species diversity, further impeding efforts to mitigate climate change and biodiversity loss (Ferretti et al, 2020; Gardiner et al., 2013). Furthermore, forest damages and disturbances have a significant impact on the wood supply chain (Ross, 2023).

This paper addresses important conceptual issues underlying forest disturbance and forest damage reporting in North America, pan-Europe, European Union, Caucasus and Central Asia, thus comprising most countries of the Northern Hemisphere. These issues are discussed in relation to the overarching goals of more fully reporting forest disturbance and forest damage at the national and the international level and better harmonizing reporting across large regions. Much of the impact of climate change and other natural and anthropogenic environmental stressors to forests will be expressed through disturbance and damage, and understanding forest disturbance processes at multiple scales, including at regional and global levels, 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).

Spatial and temporal scale is an important underlying issue for reporting, with our focus being on the eventual development of consistent, harmonized and informative forest disturbance and forest damage measures to be reported for single countries within larger regions like the European Union, pan-Europe, North America, Central Asia etc. Scale will play an integral role in forest disturbance and forest damage reporting efforts, and the interpretation of resulting data will likewise need to be tailored to the national and regional scales. In general, detail in terms of spatial distribution of particular forest disturbance processes and agents will be reduced. Precision will also be reduced, but accuracy, meaning the lack of systematic bias, will ideally be maintained. One point that has become increasingly clear over the preceding decades is that forest ecosystems are closely linked at varying spatial and temporal scales, including regional and even global scales. Achieving consistent measures of key forest disturbance processes across larger regions will not only allow comparison between countries and the identification of major trends affecting all, but will also support the development of strategies to maintain or restore essential forest ecosystem services, outputs, and characteristics in a changing world.

WHAT IS FOREST DISTURBANCE AND DAMAGE?

From a conceptual point of view, it is challenging to fashion a concise definition of forest disturbance or forest damage. It is tempting to simply say that these words refer to any process or agent that impedes the optimal or anticipated development of forests. However, the term “optimal” is value-laden and depends on the output(s) to be optimized (e.g. biodiversity conservation, timber production, or carbon sequestration). Furthermore, the endemic presence of certain disturbance processes may be compatible or even necessary for healthy forests. However, the term “healthy” is problematic in its value connotations. From a practical standpoint, there is a fair amount of agreement on what constitutes forest disturbance and forest damage. These are processes or agents that significantly impact forests through tree mortality and reduced growth (FAO 2020a; Gardiner et al. 2013; Köhl et al. 2020).

Criteria and Indicator (C&I) reporting frameworks provide examples of general categories commonly used in reporting disturbance and damage. A common distinction is between biotic disturbances (e.g. through insects, diseases, and animal) and abiotic disturbances (e.g., fire, drought, and storms). This agent-centered approach is used in the Montréal Process C&I framework for the Conservation and Management of Temperate and Boreal Forests, where biotic and abiotic disturbances are each given a separate indicator under an overarching forest health criterion (Montréal Process 2015). In its Global Forest Resource Assessment, FAO also organizes disturbance reporting by agents, reporting area measures for disturbance by fire, insects, diseases, severe weather events, and an optional “other” category to be further described in country specific notes (FAO 2020b). Forest Europe’s State of Europe’s Forests (SoEF) reporting, on the other hand, takes an impact-centered approach and provides five indicators related to forest ecosystem health and vitality: deposition and concentration of air pollutants, soil condition, defoliation, forest damage and forest land degradation, although the indicator on deposition identifies specific pollutants and the forest damage indicator is classified by the primary damaging agent (Ferretti et al. 2020). However, notwithstanding the logical structure of forest-related C&I frameworks, general categorizations of disturbance and damage only go so far, and reporting is largely driven by practical considerations of data availability, public concern, and the particular nature of specific disturbance processes, leading to challenges in achieving reliable information, data and accurate reporting.

In forest reporting activities and related discussions, “forest disturbance” and “forest 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 sensing activities; damage, on the other hand, involves the interpretation of disturbance information as it relates to negative impacts on human expectations. Figure 1 provides a simple stepwise schema for data gathering, information development, and value attribution. Note the distinction between disturbance and damage - under this simple distinction, tree mortality would be considered disturbance, and loss of merchantable wood volume would be considered damage. Since human expectations and the desire to avoid damage help determine policy and management concerns, and thereby forest data collection, the distinction is not complete, and the measures will inevitably be influenced a priori by human expectations regarding forests and their outputs—people measure what is important to them.

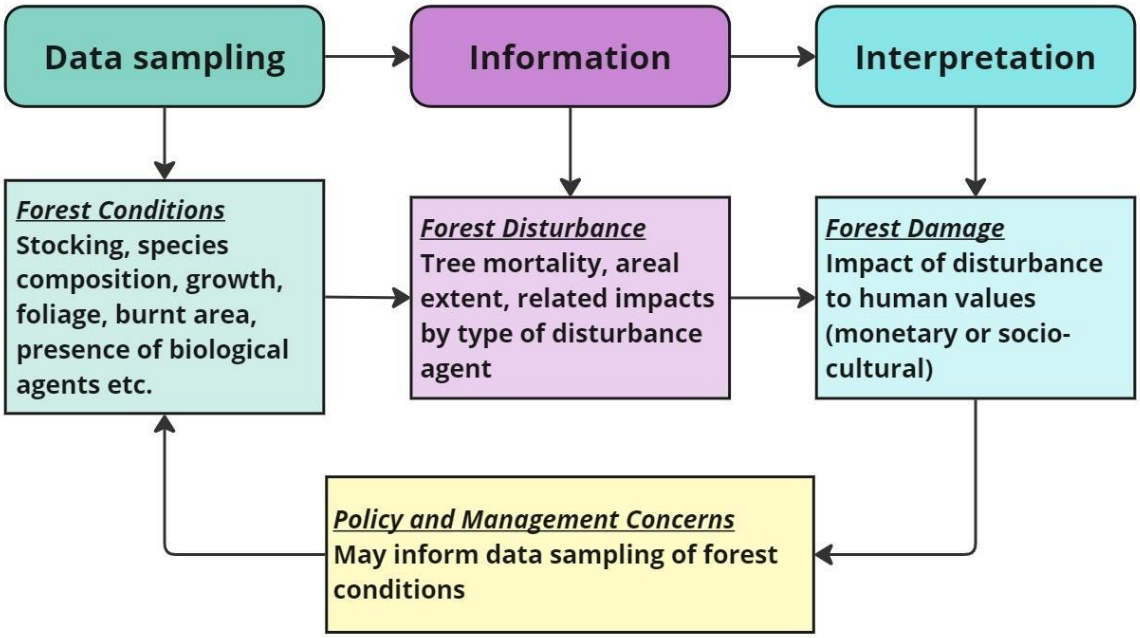

Figure 1: Simple stepwise schema relating forest conditions, forest disturbance and forest damage. Source: Own presentation.

Despite the blurred lines between forest disturbance and forest damage and their interchangeable usage in practical application, the distinction is nonetheless important. This is because (1) different people have different values associated with forests and may not agree on what constitutes forest damage and its negative connotations, (2) values may change over time and therefore compromise the comparability of damage measures taken in different time periods, especially if these values are incorporated in measurement protocols, through the use of thresholds for example, (3) values will likewise differ over space and forest type and thus may compromise comparability of damage measures between specific locations, countries and regions, and (4) a certain level of forest disturbance is endemic to all forest ecosystems and may be part of the natural, or even desired, development of these systems. This may be true even for catastrophic disturbances such as fire in fire-adapted forest ecosystems (Attiwill 1994; Gardiner et al. 2013; Lertzmann and Fall 1998; Thom and Seidl 2016). As a result, and especially when considering harmonization across space and time, the value neutral measures associated with forest disturbance are better candidates for foundational measures. Forest damage can then be assessed based on particular values in combination with outputs and thresholds associated with these values. In any case, the point here is not to insist on a rigorous separation of these two terms, but to remind ourselves that forest disturbance is not synonymous with forest damage at all times or for all people. Accordingly, this paper will generally use “forest disturbance” unless a specific negative impact is stressed, in which case “forest damage” will be used.

In addition to forest disturbance and forest damage, a third concept should be mentioned in this context, and that is “disaster”, denoting a force majeure that causes great damage or loss of life. Forest-related disasters vary in terms of type, severity, and extent, but all tend to overwhelm available local resources for response and countermeasures (FAO 2020a). While they can sometimes be predicted to a limited extent, these events can all carry an element of surprise and receive significantly greater public attention than more gradual forest disturbance processes that may be equally damaging. Therefore, the risks associated with forest disasters and their abrupt impacts require special mitigation and response strategies over and above those required by more gradual processes. Furthermore, the intensity of public perception and political focus strongly influences policy and management reactions. Additionally, disasters are usually concentrated over space and time and are not adequately reflected in annual spatial aggregates. Given the role that climate change can play in generating disasters whether through extreme weather events or increased susceptibility to fire, increases in the frequency and intensity of forest disasters are often interpreted as a negative indicator of the ecosystem’s response to changing climate conditions and the potential for further disasters in the future (Robinne 2021). This paper, however, does not rigorously treat disaster as a special category, instead simply noting that particularly abrupt and destructive forest disturbance events may require special consideration.

MOTIVES TO MEASURE FOREST DISTURBANCE AND DAMAGE

Monitoring and data generation for forests is a complex and expensive undertaking in general and, for reasons described below, is more so for forest disturbance in particular (Forzieri et al. 2020; Linser 2020; Senf and Seidl 2020). The primary objective of measuring forest disturbance is to inform actions to protect and enhance valued forest outputs or characteristics and to limit the damage associated with disturbance events. Traditionally, forest management has been focused mainly on timber production, game management, and firewood production in the more distant past, but many specific examples of management and monitoring for other valued outputs can be found, particularly since the second half of the 20th century (FAO 2020b). The values people associate with forests and forestry have changed with the development of human civilization, and the variety of values has increased significantly along with our understanding of the ways in which society and forests interact (Bastrup-Birk et al. 2016; Bengston 1994). The number and range of stakeholders interested in forests and forestry has also increased, with many of them having contradictory expectations regarding forest characteristics and forest-related products (Isoaho et al. 2019). In Figure 2 some general categories of human expectations associated with forests are listed.

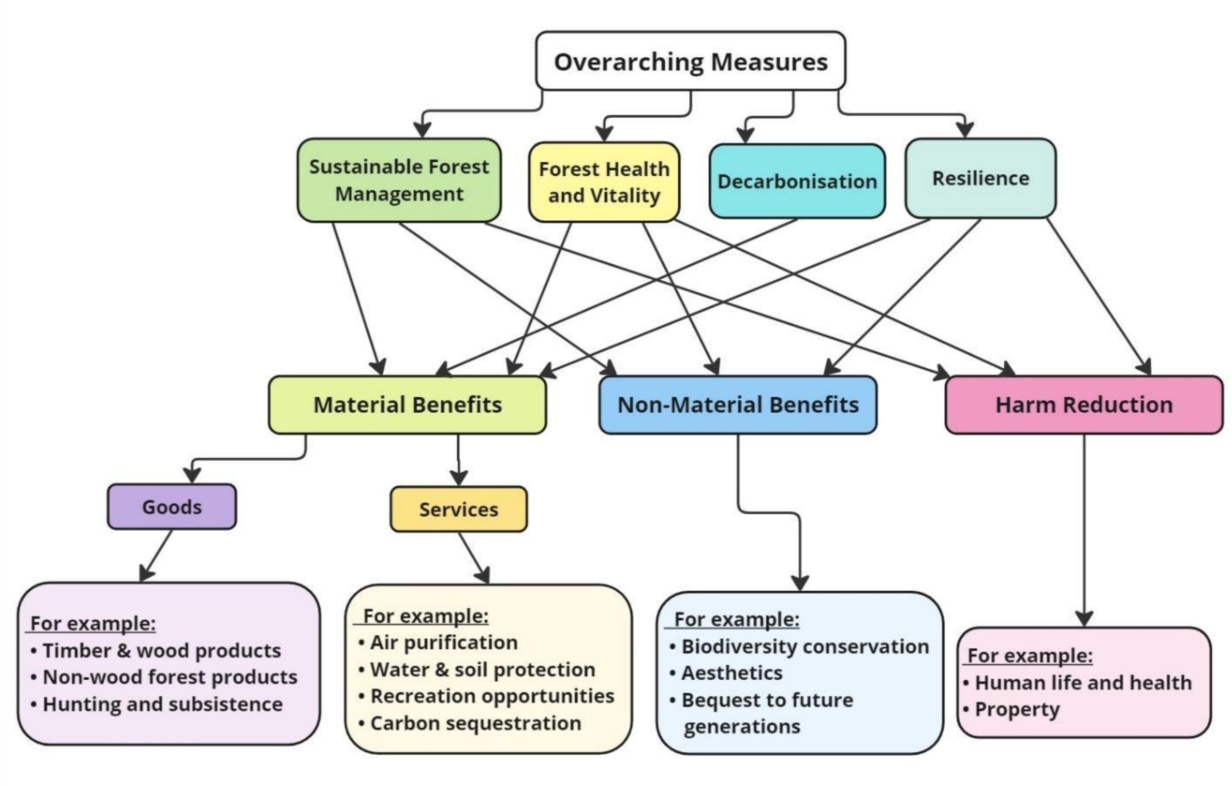

Figure 2: Categorization of human expectations motivating forest disturbance and forest damage monitoring and reporting. Source: Own presentation.

Since more specific values will arise in specific situations, these categories are meant to be comprehensive but not exhaustive. Assessments of forest damage often relate directly to these different values, especially in the case of timber production but also in relation to damaged ecosystem services. In addition, forest conditions are often described in terms of composite measures with implicit value connotations, such as “sustainability”, “health”, “vitality” or “resilience”, and disturbance impacts may also be evaluated against these measures. Furthermore, the effects of forest disturbances, particularly in the case of forest fire, can extend well beyond forest ecosystems and directly impact values not immediately associated with forest conditions and metrics. For instance, elevated concentrations of smoke in human settlements relatively distant from fires can seriously affect human health (Finlay 2012; Fowler 2003; Johnson et al. 2011). Likewise, socio-economic impacts following abrupt changes in supply and demand conditions (e.g. surplus of salvage timber) can also have distant effects extending to regional and even global markets (Brezina et al. 2024). And finally, deviations in forest disturbance regimes can provide early alert of major systemic changes associated with changing climate conditions, with significant implications for forest management and other actions to reduce greenhouse gas emissions or otherwise mitigate climate change and its impacts (Birdsey et al. 2019).

In addition to the value categories mentioned above, four specific objectives for undertaking forest disturbance and damage monitoring efforts are:

1. Targeted management response - identify sources and extent of specific disturbance impacts to direct policy and management response.
2. Scientific knowledge - increase understanding of forest ecosystems to guide policy and management action.
3. Broadscale change detection - identify major departures in disturbance regimes to support future planning and enhance understanding of broadscale ecological and geo-processes (notably in response to climate change).
4. Environmental accounting - support reporting to goals stipulated in international processes or to more localized environmental accounting efforts, notably those associated with carbon accounting.

Of these, the measurement of particular disturbances to target management response (number 1 above), is the oldest and perhaps most extensive justification used for expending effort on measurement. This objective is closely related to the concept of damage and is directed to specific forest outputs valued by humans in terms of maximizing gains and minimizing losses. Also, it is often directed to specific forest areas and specific disturbance events. Examples include tree mortality resulting from a local insect infestation or fire, the calculation of downed wood volume salvageable after a major storm event, or (urban) tree planting activities needed to replace trees lost to an insect infestation or to diseases like elm and ash dieback.

As complex systems, forests present considerable challenges to effective conservation and management, and the more knowledge we have of the role disturbance plays in the dynamics governing forest ecosystems (number 2), the better we can tailor our policies and actions to secure desired outcomes. Increasingly, the role of disturbance as an endemic process in many forest ecosystems has been recognized (Seidl et al. 2014b; Turner 2010), and an adequate understanding of these systems requires an understanding of disturbance processes and how they may affect, and be affected by, forest dynamics, including maturation (Gardiner et al. 2013). This observation is perhaps more evident in the management of large tracts of natural or semi-natural forests than in more intensively managed forest stands where damage is more controlled. Still the development and application of control measures in these managed forests relies on a thorough understanding of disturbance agents and their dynamics as well. Examples could include studies of the lifecycle and spread of particular insects, or fire behavior under varying forest fuel and climate conditions (Koch et al. 2014; Parks et al. 2015).

In the face of climate change and other anthropomorphic stressors, broadscale changes in forest disturbance regimes have long been anticipated and are meanwhile apparent to varying degrees (Patacca et al. 2023). In this respect, disturbance monitoring can indicate broader changes in Earth systems and expected future forest conditions, including the frequency and severity of specific types of disturbance events and processes. Furthermore, in many forest types, increased disturbance activity is the likely pathway for forest ecosystem transition to different structure and species composition or towards forest degradation, especially in drier, hotter regions (Kleinman et al. 2019; Lindner et al. 2010). These changes can be far-reaching and will take place on regional to global scales.

In response to global change in forest extent and conditions, a number of international processes now require country reporting in relation to stipulated goals and accounting frameworks (number 4). In several cases, these goals are part of a larger framework extending beyond the consideration of just forests — the UN Sustainable Development Goals are one such example and the greenhouse gas inventories associated with UNFCCC are another. In either case forest disturbance reporting is not explicitly required, but disturbance must be incorporated when deriving forest conditions and carbon accounts. In the global core set of forest-related indicators "Proportion of forest area disturbed" and "Area of degraded forest" are included as two of 21 indicators proposed for reported by all countries worldwide (FAO and CPF 2022; Linser and Prins 2022). At regional scales, reporting activities associated with efforts such as Forest Europe and the Montréal Process require forest disturbance and damage metrics (Ferretti et al. 2020; Köhl et al. 2020; Montreal Process 2023). Carbon or biodiversity accounting may be required at varying scales for regulatory or incentive schemes, this accounting may in turn require the explicit incorporation of disturbance and damage data (Kaarakka et al. 2023; Nabuurs et al. 2024).

FOREST DISTURBANCE AND DAMAGE MEASUREMENTS

The foregoing section presents a top-down approach, considering the values and objectives driving our disturbance and damage reporting activities. It must be stressed, however, that aggregate reporting will be shaped as much, or more so, by bottom-up considerations associated with data collection protocols, available resources, and available technologies. In terms of national level reporting that can be aggregated at international scales, the FAO FRA effort (FAO 2020b) has taken the lead in providing global statistics on forest disturbances on a country-by-country basis, but consistency and data gaps remain a significant challenge, even for countries with ample resources devoted to forest monitoring. These problems likewise persist at regional, national, and even subnational scales (Senf and Seidl 2020; Köhl et al. 2024). There is much room for improvement, and the techniques used, along with their limitations, will fundamentally determine capacity to measure disturbance, the specific indicators to be measured, and the ability to aggregate these measures over space and time.

While new methods of sampling forest ecosystems continue to be developed - for instance eDNA (Ladin et al. 2021) and further improved airborne and satellite remote sensing technologies (Borecki et al. 2015; Government of Canada 2021), the main methods in current use can be categorized based on two major breakpoints: (1) the mode of observation (generally land-based observation versus remote sensing); and (2) the statistical frame (random versus targeted sample). See Box 1 below with examples.

Box 1. Examples of different types of forest disturbance and damage measurement activities.

- **Plot-based, random sample inventory systems**
  - National Forest Inventories (NFIs) conducted in many European and North American countries
- **Remote sensing using satellite imagery**
  - World Resources institute (WRI) forest cover analysis
  - Landscape Change Monitoring System (LCMS)
- **Targeted one-time survey**
  - Rapid forest disturbance and damage assessments based on the EU EUFODOS project in various European countries.
  - After tempest damage forest assessment by French IFN (Inventaire Forestier National)
- **Targeted repeated survey using aircraft**
  - USA IDS (Insect and Disease survey)
- **Other**
  - ICP Forests (depositions, defoliation/crown assessment)
  - Other monitoring and sampling efforts, usually at sub-national to local scale (e.g., physical measurement of available salvage timber following localized disturbance event)

The mode of observation

Land-based observation and plot-based sampling

Land-based observation, in particular first-hand visual assessment, has been the primary means of gathering information about forests throughout history. It began with casual observations by explorers and foresters and has evolved into more and more complex and objective means of recording information. Today, plot-based sampling approaches are used extensively, notably in national forest inventories (NFIs). Land-based observation is by far the most flexible tool available for forest sampling, allowing for numerous detailed measurements at any given forest location. In addition to directly sampling evidence of disturbance by type (e.g. fire or insects), this multifactor sampling activity allows for the development of ancillary data that can be used for context and the analysis of associations between disturbance, damage and other forest characteristics - data that is often unobtainable from other sources. Owing to their breadth, flexibility, and relatively long history of use, NFIs and related plot-based forest sampling activities are the major source of information on forest conditions in general.

NFIs have a number of shortcomings. They are labor intensive and thus expensive. Not all countries can afford to develop plot-based sampling with sufficient density or number of sampled variables to adequately describe their forest resources. In Europe, Denmark is the first country to abandon its in-situ forest inventory and replace it by a monitoring approach solely based on advanced technologies such as satellite data and pattern recognition (Bisgaard Jensen, 2024). It is not yet clear if the continuation of monitoring and reporting can be maintained. Countries that do maintain NFIs must balance plot density, return intervals, and number of variables/indicators against scarce resources, with the result that forest inventory data often does not have the spatial or temporal granularity requested by domestic stakeholders. The regional level reporting of FAO or Forest Europe does not demand a high degree of spatial detail, but the long return intervals in many NFIs (the USA for example uses a ten-year plot return interval in its western states, as do many European countries) means that inventory results averaged over time will lag considerably behind current year disturbance activity and may serve to obscure relatively recent changes in disturbance regimes, especially if these changes are characterized by extreme events perceived as disasters by the general public. These types of events will require rapid assessment targeted to the affected area, including the use of NFI plot networks and methods for extraordinary inventories. For example, this approach has been used in France following devastating weather events such as Cyclone Klaus in 2009 (Bélouard et al. 2012). However, if an ad hoc inventory is done according to different protocols, the resulting data will not match the statistical frames used by NFIs and thus cannot be easily aggregated into national level results.

Also, NFIs and related inventories are generally quite complex, involving numerous measurement protocols for different forest elements, and requiring statistical techniques to ensure a representative sample that is free of bias across both time and space. This results in different standards and definitions applied in different NFIs, many of which have been developed and applied over many years. Harmonizing metrics over this diversity of approaches is a considerable challenge for regional and international reporting, particularly since this diversity is inherent in the initial data-generation process, and not just in the assumptions and analyses techniques used on a uniform database spanning all countries. This is in marked contrast to remote sensing approaches, especially those using satellite imagery.

Remote sensing

Remote sensing can be defined as the collection of data by instruments not in close or direct contact with the subject of observation. Typically, these instruments will be mounted on aerial or satellite platforms. Interpretation of aerial photographs comprised the major remote sensing application in forestry for most of the last century, but remote sensing capabilities have been vastly increased in recent decades owing to the advent and subsequent development of satellite imagery platforms such as Landsat and Sentinel. Aerial applications have likewise expanded along with the types of sensors that are available, and with the increasing use of drones to mitigate costs and risk to flight crews (Tang and Shao 2015).

In that they provide a relatively uniform, wall-to-wall data sampling at regional or even global scale, satellite platforms are particularly relevant to the harmonized regional disturbance and damage reporting (Hislop et al. 2020; Köhl et al. 2024). Where specific satellite images are used at global or regional scales, analysts can be certain that everyone is working off the same data foundation. Advanced sensors allow us to see beyond visible light into spectral bands where healthy vegetation is readily discernible. This, when coupled with frequent observations, can yield phenological observations that offer a different perspective on vegetation that otherwise would not be measured from a ground plot. Also, earth observation techniques such as satellite data, airborne LIDAR or UAV-based imagery often provide repeated observations on a much more frequent time schedule than the plot return intervals commonly used in NFIs, allowing for more timely data and the possibility of rapid assessments of particular damage events.

At the same time, however, satellites are quite limited to the objects they can and cannot "see," and they cannot replicate the flexibility and detail provided by the on-the-ground human observation supplied in NFIs and related inventory activities (Emmert et al. 2023; Ohmann et al. 2014). In particular, casual attribution and the identification of specific disturbance and damage agents are problematic in remote sensing, with many applications of satellite data being limited to structural attributes, notably forest cover or lack thereof, without identification of underlying causes (Senf and Seidl 2020). It is important to note, however, that satellite imagery can be integrated into NFIs to increase accuracy and efficiency (Lister et al. 2020).

Statistical frame

The second major breakpoint for categorizing sampling activities is between those that occur within a random sample frame and can thus be extrapolated to the statistical population as a whole, versus those using a targeted frame (e.g. sampling areas where known problems are occurring).

Random sample frames

In NFIs a variety of forest variables are measured, usually by direct observation, through random plot sampling and are then extrapolated to describe forest characteristics for a given geographical unit or aggregation of units. The precision of these extrapolations varies positively with the density of the plots and the area over which the measures are aggregated; the accuracy varies positively with the rigor of the statistical design and the absence of systematic bias (McRoberts et al. 2016; Kangas and Maltamo 2006). NFIs and similar inventories measure a wide variety of variables, many of which are not directly related to forest disturbance and damage, but they are flexible enough due to human sampling, to include measures of disturbance processes that are deemed important enough to justify the additional effort. It should be noted, however, that adding or adjusting variables in large NFIs is difficult in terms of institutional inertia and maintaining consistent time series. Another issue affecting the utility of NFIs is the extended time period between plot returns mentioned above - they are better at measuring long-term trends than specific extreme events.

Targeted sample frames

Targeted sample frames, on the other hand, can sample specific areas of interest but do not allow for statistically valid extrapolations. However, they are more flexible, cost-effective, and can be tailored to address timely issues and rapid damage assessments. Lower elevation remote sensing applications (airplanes and drones) are commonly used for targeted surveys, but the sampling frames, and their statistical implications, are often unclear, posing problems for widescale aggregation of results. There are examples of national aggregate reporting derived from targeted samples. For example, through its aerial insect and disease survey, the U.S. Forest Service provides annual estimates of insect and disease-induced tree mortality based on a targeted, though extensive, sample. These aggregate mortality numbers are used to characterize general trends and conditions of selected insects and diseases across multiple years (USDA Forest Service 2020), but these are not presented as statistically consistent results comparable to measurements developed by the U.S. NFI.

In general, the consistent sampling frame and wall-to-wall coverage provided by NFIs and satellite-based remote sensing platforms indicate that these two approaches are the most likely source candidate metrics for harmonization to allow for aggregate reporting across a larger region. At the same time, other forest-specific measures of disturbance and damage may be considered on a pragmatic basis to provide supporting information, even if this information cannot be fully integrated into regional aggregates.

FOREST DISTURBANCE AND DAMAGE VARIABLES MEASURED

Regarding the phenomena being measured as disturbance, the most common metrics include tree mortality, defoliation, and various direct measures of disturbance and damage, including evidence of fire or the physical presence of insects and other pathogens. These measures, in turn, can be transformed into different reporting units such as mortality per hectare, total area affected, number of trees affected, timber volume affected, and so forth. Depending upon the spatial resolution of the sampling method, results can then be mapped onto forest landscapes or aggregated for different ecological or jurisdictional units. As noted above, such mapping and aggregation may be quite difficult when performed across different sampling regimes, and, even under uniform regimes, spatial and temporal discontinuities in the sampled landscape may pose challenges. Also, for mortality and defoliation, the actual disturbance agent underlying the perceived impact must be inferred. This is a point that is particularly relevant in the case of remote sensing. So far numerous remote sensing applications for mapping and characterizing forest disturbance and damage have been completed. They provide a real-time, wall-to-wall overview of damage and disruptions, but have the disadvantage of a lack of attribution; affected areas can be recorded, but not the underlying causes. Therefore, combinations of earth observation and in-situ data are still indispensable for comprehensive status assessments and causal analyses (Köhl et al. 2024, Lausch et al. 2018).

In addition to the major sampling activities described above, various other metrics can be used to improve our understanding of forest disturbances and their impacts, ranging from environmental sampling (e.g., pollution deposition, climatic indicators), or wildlife population monitoring, to economic and social measures (lives and property lost to damaging events or funds expended to mitigate risk). Some of these will be of direct relevance to forest damages and of intense interest to the general public. Box 2 provides a partial list of indicators currently sampled or of potential interest.

Box 2: Damage-related indicators currently sampled or of potential interest (Köhl et al. 2024).

- **NFIs and plot-based sampling**
  - Tree mortality, defoliation, growth (also by ICP Forests, Michel et al. 2023)
  - Direct evidence of damage from fire, insects & diseases, game, cattle, rodents, weather, and other disturbance agents
  - Presence of insects and phytopathogens
  - Human induced damages (harvesting damages and damages by forest operations which cause severe economic losses and decrease of the ecosystems health and vitality, e.g. decrease in timber quality, rot, decay, destruction of natural regeneration, soil degradation)
  - Removals (salvage cutting)
  - Damaged area
- **Remote Sensing**
  - Mortality
  - Defoliation
  - Damage distribution in ha (particularly for large-scale events)
  - Damaged volumes via automated processing of satellite images
- **Other indicators**
  - Socio-economic indicators such as human health impacts, insurance and mitigation costs, damage to structures
  - Ecological indicators such as abundance of species, eDNA, etc.
  - Geophysical indicators such as soil moisture and temperature

CHALLENGES OF REPORTING FOREST DISTURBANCE AND DAMAGE

Complexity

Forest ecosystems are dynamic and complex, and forest disturbance processes are equally complex. They interact over time with changing forest stand characteristics and other disturbance processes. The vast number of disturbance processes, and the variety of lifecycles, interactions, and effects they possess, constitute a major challenge in comprehensive reporting, particularly at broad spatial scale. Forest insects provide a case in point. At any given time, numerous insects will be present in a given forest stand, many of them endemic (coevolved) to the specific forest type exemplified by that stand and thus playing both positive and negative roles in forest health (Campbell and Liegel 1996; Vacher et al. 2021). Disturbance impacts may be relatively low in this case but still substantial in terms of reduced growth and individual tree mortality. On the other hand, positive contributions to biodiversity and forest structure may likewise be substantial. Where is the border-line between “normal” and “destructive” levels of their impact and how should this form of disturbance and damage be reported, if at all? Of course, insects are noticed primarily when their populations and impacts increase dramatically, often when the specific insect is invasive, though native species can also result in substantial impacts, as infestations of the Mountain pine beetle (Dendroctonus ponderosae) in North America (Kunegel-Lion and Lewis 2020) or the European spruce bark beetle (Ips typographus) in Central Europe have demonstrated (Seidl et al. 2011; Seidl et al. 2016). Even in the case of severe infestation, the impacts to forests can be variable, ranging from patchy defoliation to extensive mortality, depending on the effects and life-cycle of the insect involved. As a result, broadscale reporting of insect impacts to forests is often restricted to mapping the extent of a specific infestation, or one-off studies estimating mortality and impacts to specific values. Aggregating impacts across different insect types is possible (USDA Forest Service 2020), but the results need to be interpreted carefully. Although seemingly more homogenous than insects, fire is another complex disturbance process characterized by endemism, variable impact, and positive effects in certain settings. While commonly reported in terms of total area burned, fire severity is increasingly recognized as an essential measure, with low severity (“good”) fire being contrasted with high severity (“bad”) fire (Keyser and Westerling 2009; Montealegre et al. 2014; Smith and Hoover 2024). Moreover, the spatial configuration of disturbance impacts varies considerably between various disturbance events in ways that are important to understanding process and impact but are not captured in simple measures of total area impacted. This, of course, adds another layer of complexity in disturbance reporting.

Casual attribution

The complex and interacting nature of many forest disturbance processes presents a significant challenge in attributing causality and distinguishing between proximate, intermediate and ultimate causes. A clear example of this is when trees weakened by drought (the ultimate cause) are subject to insect infestations (the intermediate cause), resulting in tree mortality, increased fuel loads and greater susceptibility to fire (the proximate cause). This is just one example, and there are many such interactions between disturbance agents operating in many forests (Rogers 1996; Köhl et al. 2024). From a direct measurement standpoint, this may not be all that problematic - the most recent proximate cause (e.g. fire in the example above) since the last plot measurement or other sampling iteration will likely be coded. However, from a management standpoint, the identification of the ultimate cause will be a central concern. The same is true for broadscale change detection.

Establishing reference values

One of the main reasons identified above for disturbance monitoring at large spatial scales is broadscale change detection, particularly as it relates to the climate and biodiversity emergencies, and this change detection proceeds through comparison with reference values or “baseline” conditions (The Montreal Process on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests, for example, explicitly mentions reference conditions in its two disturbance indicators, Montréal Process 2015). Many disturbance processes are characterized by high stochastic (i.e., random) variation across space and time. Large deviations in disturbance activity may signal substantial shifts in forest dynamics in the face of climate change. However, in other cases they may just be a string of extreme observations in a highly variable system. Furthermore, many forest stands have been significantly altered from their natural state, particularly those subject to substantial forest management activities (Muys et al. 2022). Despite this, they may still supply a full suite of ecosystem output and services. In fact, through active forest management, agricultural clearing followed by abandonment and forest regrowth, or fire suppression, a substantial proportion of temperate and boreal forests have been significantly affected by human intervention, even if they have not always been subject to active forest management (FAO 2020b; Köhl et al. 2020). Widescale fire suppression in some regions resulting in increased fuel loadings, a more homogenous spatial distribution of these fuels, and thereby increased susceptibility to catastrophic fire is a case in point (Moritz et al. 2018). Even in unmanaged forests, conditions are dynamic, meaning they evolve over time, and the identification of appropriate and relatively stable baselines for comparison becomes more challenging, as does the identification of the ultimate cause (Köhl et al. 2024). While they can still be used for reporting, reference values will entail an arbitrary component. The resulting measures based on these reference values will incorporate this arbitrary component and should be interpreted carefully.

Aggregation and consistent measurement protocols

In order to produce aggregate measures at regional scale, consistent measurement protocols are necessary. At the same time however, and particularly in the case of plot-based inventories where numerous sampling options are available, local or country-level sampling protocols may vary considerably in line with local concerns, practices, and institutional capacities. Traditional inventory reporting categories such as forest area or wood volume may be reconciled across different spatial reporting units through well-developed conversion factors and related adjustments, but forest disturbance is more challenging because of the complexities discussed above. For example, in aggregating measurements for insect infestations, for each country in the aggregation there is a need to consider the type of sampling activity (remote sensing or plot-based sample, random or directed sampling); what is actually being measured (defoliation or mortality or presence of insect); and the specific units of measurement being used. Further analysis will require identification of ultimate and proximate cause, and relation to temporal and spatial reference values, values which vary considerably among the countries in the Northern Hemisphere.

ENVISIONING A REGIONAL DISTURBANCE AND DAMAGE REPORTING SYSTEM

Ideally, a regional reporting system for forest disturbance and damage in Europe or in the Northern Hemisphere or any other larger region would provide consistent and comprehensive aggregate measures so that disturbance activity can be analyzed at multiple scales, ranging from localities to the region as a whole, using the same overall dataset. However, the numerous reporting challenges associated with disturbance and damage present a substantial barrier to fully consistent aggregate reporting at multiple, nested scales. Substantial compromises to specificity and statistical rigor will be necessary, and certain measures will be much easier to handle than others. These compromises and challenges are quite similar to those faced by the FAO Forest Resources Assessment (FRA) in its comprehensive global reporting on forest conditions. Like FRA, a sustained commitment to continual improvement is needed in aggregate reporting for the Northern Hemisphere and its two related criteria and indicator processes for sustainable forest management, Forest Europe and the Montreal Process (the latter of which extends to temperate and boreal forests in the Southern Hemisphere). A first step would be producing approximate aggregations of selected measures that can be refined over time with growing understanding of both specific measurement approaches and the underlying disturbance processes being measured. This gradual approach will require ongoing commitment to the development and adoption of best practices in terms of initial measurement and subsequent analysis, and it will entail balancing the need for local detail against the need for comparable aggregates at broader scales. Initial efforts will involve a compilation and analysis of existing country level data sets, as done by Köhl et al. (2024). To be successful in the long run, however, the regional reporting process of e.g. Forest Europe or the Montreal Process will have to pursue continual improvement in terms of data acquisition and development, harmonization, reporting, and interpretation with an eye to region-wide findings as well as those pertaining at the national level. This would be an ambitious undertaking, but even modest progress could yield substantial benefits in terms of national reporting capacity and regional reporting coverage for those forest disturbances and damages initially chosen for harmonization and reporting.

CONCLUSIONS

This paper has focuses on conceptual issues associated with the production of regional aggregate statistics describing forest disturbance processes. Beginning with a discussion of “disturbance” and “damage,” we have emphasized the importance of an increasingly diverse set of human expectations in determining what and how we measure these phenomena and the way we interpret them. Monitoring efforts are motivated by the overarching goals of (1) determining targeted management response, (2) increasing scientific understanding of forest ecosystems and their behavior, (3) detecting overall change in forest systems resulting from climate change or other anthropogenic factors, and (4) supporting regional or global environmental accounting frameworks. Each of these goals may suggest different specific measures and or temporal and spatial scales of analysis, with regional development of aggregate statistics being perhaps most relevant to goals (2) and (3). While goals (3) and (4) are perhaps the most important, it should be noted that adequate and comparable data on disturbance processes will support scientific communication and understanding, and this in turn will support the development and dissemination of effective policies and management responses at national to local scales. The tools we possess to gather data on forest disturbance and damage are numerous, flexible, and constantly expanding like machine learning for satellite imagery analysis or eDNA for pathogens detection which help rapidly improve the quality and consistency of data on disturbances across regions. They are, however, also imperfect, complex, and inconsistently applied in the various countries, a fact that becomes all the more apparent when trying to aggregate measures across space and time. Among these tools, the plot-based random sampling techniques common to NFIs are perhaps the most developed in terms of sampling infrastructure and understanding of statistical properties, but remote sensing applications, notably those using satellite imagery, are developing rapidly. In any case, aggregating data from different approaches, and even between different NFIs, can entail considerable challenges, particularly given the complexity and variability of many disturbance processes. This is not a new problem, however, and many different organizations have long provided aggregate statistics, data inconsistencies and gaps notwithstanding. And in doing so they have spurred scientific communication, understanding, and concrete improvements in data reporting. Aggregation of disturbance and damage data will face similar challenges but will entail similar benefits.

Damage and disturbances take on a particular significance when considering carbon sequestration by forests. Without forests, achieving net-zero targets is impossible. Recent reports provide initial evidence that climate change is threatening the CO2 sink of forests (Ke et al., 2024; BMEL, 2024). Reliable assessment and reporting of the forest area affected by damage and disturbances and the underlying causes is essential in order to take targeted measures to preserve the forest CO2 sink and to maintain and enhance the multiple functions of forests.

CONFLICTS OF INTEREST

The authors confirm there are no conflicts of interest.

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