

## Viewpoint

# Towards a global understanding of tree mortality

### Summary

Rates of tree mortality are increasing globally, with implications for forests and climate. Yet, how and why these trends vary globally remain unknown. Developing a comprehensive assessment of global tree mortality will require systematically integrating data from ground-based long-term forest monitoring with large-scale remote sensing. We surveyed the metadata from 466 865 forest monitoring plots across 89 countries and five continents using questionnaires and discuss the potential to use these to estimate tree mortality trends globally. Our survey shows that the area monitored has increased steadily since 1960, but we also identify many regions with limited ground-based information on tree mortality. The integration of existing ground-based forest inventories with remote sensing and modelling can potentially fill those gaps, but this requires development of technical solutions and agreements that enable seamless flows of information from the field to global assessments of tree mortality. A truly global monitoring effort should promote fair and equitable collaborations, transferring funding to and empowering scientists from less wealthy regions. Increasing interest in forests as a natural climate solution, the advancement of new technologies and world-wide connectivity means that now a global monitoring system of tree mortality is not just urgently needed but also possible.

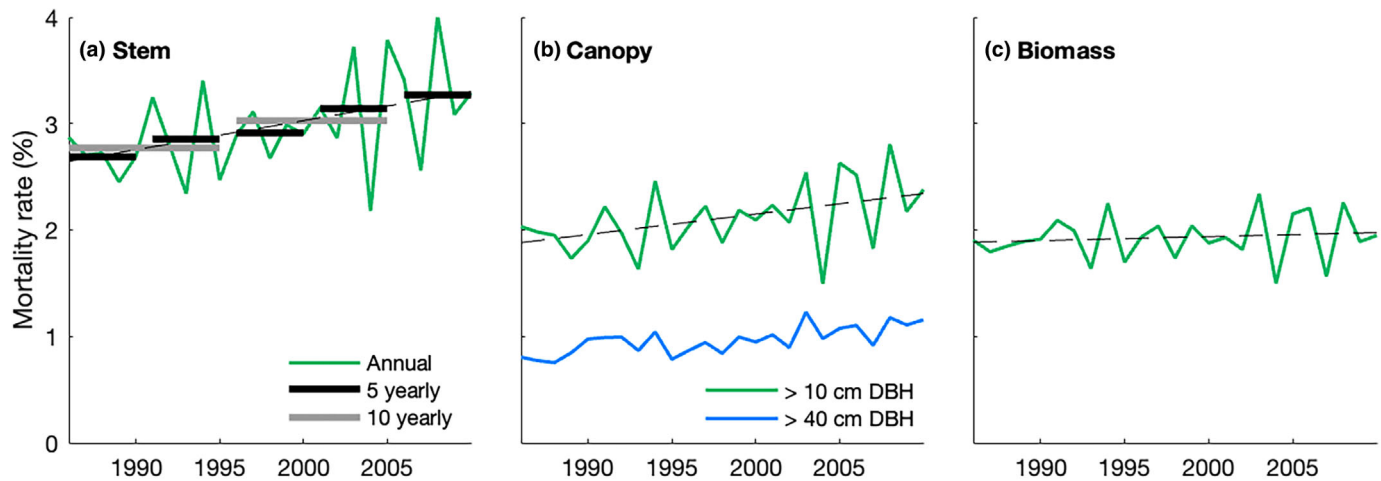
### Introduction

Increases in tree mortality over time have been detected in forest ecosystems around the globe (Brienen *et al.*, 2015; McDowell *et al.*, 2018, 2020; Senf *et al.*, 2021; Hammond *et al.*, 2022). The reported increases in tree mortality have been associated with anthropogenic climate change via increasing climate extremes, such as heat (Breshears *et al.*, 2009), atmospheric aridity (Allen *et al.*, 2015; Grossiord *et al.*, 2020), soil drought (Allen *et al.*, 2010; Senf *et al.*, 2020), fire severity (Abatzoglou & Williams, 2016; Ward *et al.*, 2020; van Wees *et al.*, 2021), storms (Uriarte *et al.*, 2019; Senf & Seidl, 2021b), insect outbreaks (Kurz *et al.*, 2008; Weed *et al.*, 2013; Seidl *et al.*, 2017), and spread of invasive insects and pathogens (Anderson-Teixeira *et al.*, 2021). Widespread increases in tree mortality will have pervasive and long-term impacts on global forest ecosystems, their biodiversity

and the ecosystem services they provide (Hartmann *et al.*, 2018b; McDowell *et al.*, 2020).

Understanding trends in, and causes of, tree mortality globally is crucial for climate change mitigation efforts, because forests have for decades been responsible for a net annual uptake of *c.* 20% of the carbon dioxide released by human activities (Pan *et al.*, 2011; Pugh *et al.*, 2019; Harris *et al.*, 2021). Yet, projections of the future of this sink diverge dramatically, with tree mortality rates emerging as one of the key uncertainties (Friend *et al.*, 2014; Wu *et al.*, 2018; Hubau *et al.*, 2020; Pugh *et al.*, 2020). With only very tight carbon budgets of *c.* 100 Pg C remaining to hold global temperatures within 1.5° of pre-industrial levels (Friedlingstein *et al.*, 2022), changes in forest regions can have substantial implications for national commitments required to reach this temperature target. For instance, the 2010 Amazon drought is estimated to have led to a regional reduction in carbon uptake of 0.5 Pg C (Potter *et al.*, 2011). Uncertainties in tree mortality rates also hang over the long-term efficacy of restoration programmes, widely touted as a key natural climate solution (Cook-Patton *et al.*, 2021). But forests are of interest for much more than climate change mitigation services. Understanding tree mortality trends is also fundamental to developing policies that can effectively support or enhance biodiversity, as it is for developing management plans that effectively deliver required wood supplies. Reducing the uncertainties in forest futures requires substantial increases in the accuracy of tree mortality representations in modelling tools. Understanding the present is a prerequisite to building robust predictions about the future, and regions being affected by increased mortality today can provide early warnings for their neighbours. Currently, however, monitoring of tree mortality globally is fragmented and inconsistent. Scientists and society thus lack a clear, accurate, and consistent assessment of rates and trends of tree mortality across the globe. This urgently needs to be resolved.

Monitoring changes in tree mortality is a challenging task. For over a century, foresters, scientists and government bodies have been monitoring forests by ground-based surveys of attributes, such as tree size, species identity, crown condition and whether trees are alive (Breidenbach *et al.*, 2020). Yet, traditional forest surveys were rarely designed specifically to monitor mortality: with few exceptions, they have long remeasurement intervals (typically > 4 yr) (Ståhl *et al.*, 2012), which – combined with the stochastic nature of tree mortality – makes tracking changes in tree mortality over time and attribution of causality difficult (Fig. 1). Furthermore, many forested regions lack standardised forest monitoring systems that assess the fate of individual trees due to logistical, financial, social or political reasons. Novel technologies from remote sensing can add insight over large scales, but challenges remain in monitoring the internal dynamics, such as changes in



**Fig. 1** Different indicators and aggregations of mortality rates can give very different impressions of the dynamics they describe. (a) Stem mortality rates can vary substantially from year to year, information which is lost in the 5- or 10-yr aggregations typically used in ground-based inventories. Shown here for stems > 10 cm diameter at breast height (DBH). (b) Mortality rates based on canopy area, as typically assessed from satellites, can differ substantially from stem mortality rates. When only trees large enough to be picked up by long-running satellite sensors like Landsat are considered (> 40 cm DBH; Scheel *et al.*, 2022), such differences can be even larger (blue line). (c) Biomass mortality rates are dominated by big trees, whilst stem mortality rates are dominated by small trees (Piponiot *et al.*, 2022). This means that trends can differ dramatically between the different metrics. The linear trend for trees > 10 cm DBH for stem, canopy and biomass mortality rate (dashed line) is 0.03, 0.02 and 0.00% yr<sup>-1</sup>, respectively. Example rates shown here are self-consistent and calculated based on simulations with the LPJ-GUESS vegetation model for forests in Central Europe by Scheel *et al.* (2022).

forest structure, composition or mortality, as well as in relating the observed changes to ground-based monitoring (Fig. 1). Bringing together diverse efforts and protocols across platforms, alongside filling geographical gaps in monitoring efforts, remains a large, yet resolvable, challenge (Zweifel *et al.*, 2023).

Here, we provide a framework to systematically and continuously monitor trends in tree mortality by synthesising existing data, analogous to concepts adopted by the climate science community (Harris *et al.*, 2020), providing information to inform national, regional and global policy. Specifically, we: (1) define the minimum requirements of ground-based forest monitoring data to identify trends in tree mortality; (2) review existing ground-based monitoring networks covering 89 countries across all forested continents; (3) discuss ways to close data gaps and improve data integration; and (4) highlight approaches to promote fair collaborations to overcome the underrepresentation of scientific knowledge from particular regions. Our framework provides a base to generate long-term monitoring of trends in tree mortality and to make robust predictions about future changes in tree mortality globally.

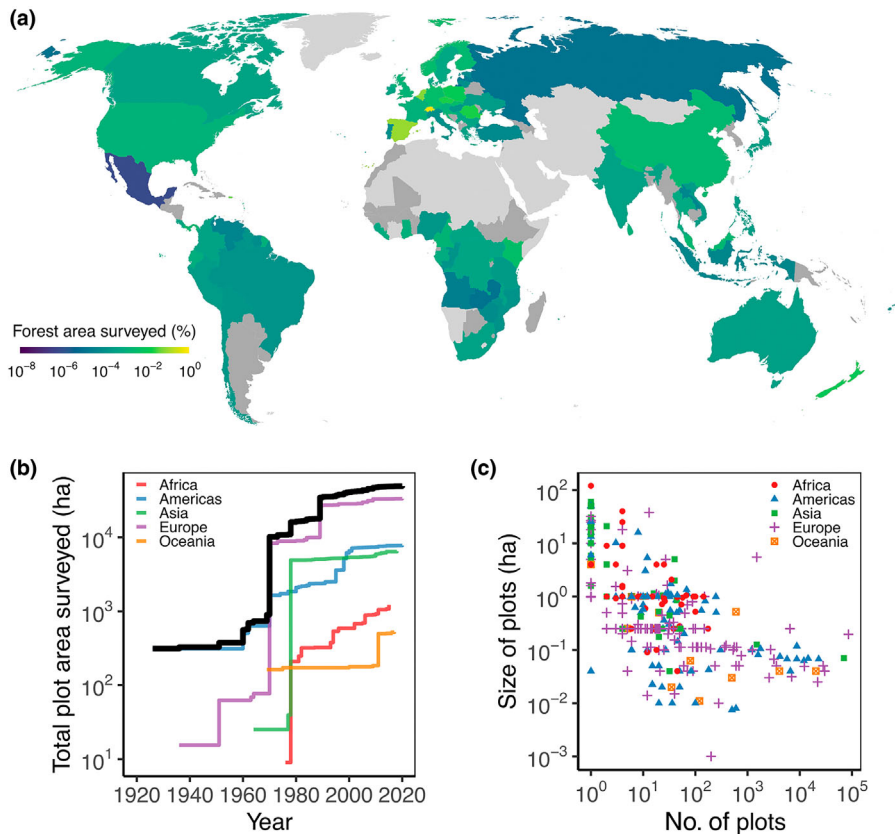
### Minimum data requirements to capture trends in tree mortality

Quantifying trends in forest dynamics, including tree mortality, requires linking repeated observations in time and space. At coarse scales, trends in canopy openings are now available from continental and global-scale satellite products (Hansen *et al.*, 2013; White *et al.*, 2017; Senf & Seidl, 2021a). These products provide an overview of areas of temporary tree cover loss due to large disturbance events. Whilst valuable, they do not resolve

individual trees and lack information on sub-canopy tree mortality and thus provide only limited, and indirect, insights into how increasing tree mortality is affecting wood production, conservation or climate change mitigation efforts. At finer scales, stem mortality rates measured from assessments of tree status in cyclic forest inventories give an indication of the probability of survival of individuals of a given tree species at a given location (Esquivel-Muelbert *et al.*, 2019). Combining this status information with tree size and allometric relationships enables the calculation of basal area or wood volume loss rates, which are key indicators for monitoring tree mortality in forestry (Yu *et al.*, 2019). Biomass and carbon losses can be calculated in a similar manner and are vital to understanding whether the carbon sink in the forest is changing (Hubau *et al.*, 2020). Each of these indicators provides key parameters for different areas of science and policymaking and has different minimum required measurements (Fig. 2).

Beyond quantifying trends to understanding causes and drivers, it is also crucial to inform those responsible for managing forests, yet this presents a range of challenges. For instance, attributing observed tree mortality to specific disturbance events requires frequent observations (e.g. annual or even intra-annual compared with the 5–10 yr typical of National Forest Inventories (NFIs)) or retrospective approaches, such as tree-ring data (Schurman *et al.*, 2018). Detailed information on local environmental conditions, such as topography and soil type, is also crucial for understanding causal relationships between tree mortality and environmental changes (Brun *et al.*, 2020; Stereńczak *et al.*, 2020; Costa *et al.*, 2023). Assessing the relative fitness of different tree species or functional strategies, key for informing climate change adaptation efforts, requires species- (and/or trait) specific data.





**Fig. 3** Summary of the spatial and temporal coverage of forest plots according to our survey of global mortality monitoring plots: (a) percent of the total forest area surveyed per country, (b) plot area surveyed over time for different continents and globally (black line), and (c) the distribution of size and number of plots. For countries coloured dark grey in (a), we did not receive any responses in our survey. Countries coloured light grey are countries with < 10% of their terrestrial land area covered by forests.

(c. 0.001% of the global forest area), but sampling area varied greatly among countries and over time (Fig. 3). The forest area monitored grew rapidly and steadily after 1960 (Fig. 2b). Russia, West Africa and Central America stand out as having the poorest coverage in terms of area surveyed (Fig. 3a). Sampling in Africa was further concentrated in only relatively few large plots, with poorer areal coverage (Fig. 3c). However, we note that these lower-recorded areas may also reflect less fluid communications with researchers in those countries. In general, there was a negative relationship between plot size and number of plots, with countries having few plots tending to have larger (research) plots, whereas countries with many plots tend to have smaller plots (likely inventory plots).

From those monitoring initiatives where metadata was available (36%, 114 out of 316 entries), the overwhelming majority track trees (94%) and all of those except one record tree status at every census (dead/alive), thus fulfilling the minimum requirement to calculate stem-based mortality (see Fig. 2). Two-thirds of the entries that track trees (66%) record plots at least every 5 yr and 86% revisit the plots at least every 10 yr, but only 11% of plots are annually surveyed as required to support a process-based understanding of tree mortality. Filtering for initiatives that track trees and tree status at least every 5 yr we found that this requirement was present in only 62% of the monitoring initiatives (71 out of 114 where full information was available). Except for two cases, all initiatives tracking trees also record tree diameter, thus allowing for estimation of (at least) basal area mortality (Fig. 2). Some of the

forest monitoring initiatives in our survey also collect information on tree condition (e.g. defoliation and discoloration; 38%), the potential causes of death (e.g. biotic, fire and wind throw; 68%) or whether the plot is subject to harvest (64%).

## Improving monitoring of tree mortality – a perspective

### How to fill ground-based monitoring gaps?

There are several potential routes to narrow the existing gaps in ground-based monitoring on spatial and temporal levels, as well as the types of indicators available (Fig. 1). National monitoring networks, such as NFIs are often relatively well funded for the long term. Protocols for these networks have typically been developed for capturing timber stocks, rather than assessing mortality rates. Ensuring that a subset of plots track individual trees across repeated censuses would fill several monitoring gaps. Decreasing the interval between NFIs from c. 5–10 yr to 1–2 yr would be ideal, but likely prohibitively expensive for most agencies. A realistic approach could, for instance, include a few frequently monitored but spatially representative plots (Ferretti, 2013), rapid censuses, which focus only on assessing mortality (Arellano *et al.*, 2021) (potentially including standardised protocols to identify major proximate mortality causes; Das *et al.*, 2016) or rolling assessment designs with a representative subset of plots being recensused each year. Furthermore, development of low-effort protocol modifications to collect targeted ancillary variables can help to attribute





national inventories), for example in plot size, recensus frequency, sampling density across the landscape and classifications of mortality cause. Such differences emerge from the diversity of focal research questions or applications (e.g. description of stand composition vs dynamics). Whilst fully standardising designs and protocols across all networks is unrealistic, and probably also undesirable because of the different motivations underlying surveys, much could be done to reduce unnecessary differences, for example in definitions and classifications. This would greatly reduce the challenges in comparing information from different networks. Intergovernmental organisations like Forest Europe and the European Forest Institute, which deliver advice to forest ministries across many European countries, or international forest monitoring (e.g. the UN ECE ICP Forests) and forestry steward organisations like FAO or IUFRO, may foster such initiatives for harmonising protocols and even sampling designs.

Yet, much can also be done to improve harmonisation of data *post hoc*. Such harmonisation spans from what definition of forest is used as a basis for aggregation, through to diameter thresholds for sampling and the allometric equations applied. Given an appreciation of the differences in protocols, commonalities of data from different sources should be identified and, if true conformity across datasets is not possible, crosswalks should be established by looking for the 'lowest common denominator'. Achieving this will require empirical studies that evaluate comparability of data collected by different protocols. Overall, the size of the task to harmonise data will depend on the application, differing, for instance, if the aim is to understand implications of tree mortality for stand-level biomass or to compare mortality rates between different species or functional groups. Key to facilitating all these efforts is reporting of adequate metadata of sampling designs, field protocols and the data workflows used to create aggregated products.

**Efficient gap filling** Remote sensing can help in filling spatial gaps in tree mortality monitoring and/or to increase the temporal density of existing inventories. To make remote sensing truly useful for filling gaps in ground-based monitoring of tree mortality, there needs to be improved integration of remote sensing and field-based data. This will facilitate both remote sensing model calibration/validation and the complementing of field-based measurements with the high temporal frequency and spatial view of remote sensing data. However, integrating remote sensing and field data is challenging. Issues arise from, among others, difficulties in matching plots to pixels due to missing spatial coordinates or low geolocation accuracies (e.g. many NFIs will only provide approximate coordinates due to data privacy issues or low accuracy georeferencing), complex terrain (area seen from space differs from area on the ground), often much smaller plot than pixel sizes, missing information on whether the tree occupies the canopy or is confined to the understory (i.e. whether the tree will be exposed to air- and spaceborne remote sensing), or a temporal mismatch between field and remote sensing data acquisition (especially for historical data). There thus is a need for adapting field protocols to allow better integration of field and remote sensing data. Whilst changing some aspects of field protocols is difficult without losing

backwards compatibility, minor adjustments will cause large improvements, for example exactly defining plot areas and precisely geolocating plots.

Besides challenges in combining data, methods for scaling tree mortality measures from the individual tree to the scale captured by satellites are also underdeveloped. Whilst freely available remote sensing data provide insights into long-term forest cover changes (as discussed above), it is hard to relate those trends to trends measured at the plot scale (Fig. 1). High spatial resolution data from various sources (e.g. UAV) can serve as a missing link between tree-based measures of tree mortality and the broader view offered by spaceborne remote sensing systems (Schiefer *et al.*, 2023). However, many high spatial resolution remote sensing data are commercially operated and not freely available to date; and flying targeted airborne or UAV campaigns repeatably over several years is costly and logistically challenging, especially in remote areas where this data would mostly be needed. Those challenges yet limit the usefulness of high spatial resolution data for operationally monitoring tree mortality at large scales. Existing approaches for scaling from trees to satellites are moreover often tailored to specific case studies and lack generalisability. To overcome those existing limitations, a global network of remote sensing super sites (i.e. sites where measurements of tree mortality and ancillary data are made at variable scales simultaneously) might allow for robust and generalisable scaling relationships to be developed. These could, for instance, build on the new GEO-TREES initiative for assessing biomass (Chave *et al.*, 2019; Labrière *et al.*, 2023). Finally, remote sensing can also serve as a complementary information stream for enhancing field-based data analyses of tree mortality trends, such as delivering information on the timing of mortality events between two census dates, on the spatial extent of a mortality event recorded by a plot network, or to target additional ground-based monitoring.

**Integrating knowledge** Although monitoring coverage is imperfect, in many regions sufficient data exist to accurately assess the rate of tree mortality. The key is to be able to harness in unison the disparate sources of data available relating to different aspects of tree mortality, forest state, dynamics and health. One step here is to combine measurements of different parts of the system made from different platforms (Beloïu *et al.*, 2022). However, true integration of disparate measurement systems is often challenging because of differences in exactly what is being measured (Fig. 1). Process-based modelling approaches can provide a route to bring together these aspects. Such models are designed to coherently link up equations describing individual processes within forests, based on our best understanding of how they work. The set of processes involved depends on the model, but typically include aspects such as photosynthesis, carbon allocation, growth, competition and disturbances, with resulting rates that differ by type of tree and the environment in which it is located. Constraining the result of one process within these models also imposes a constraint on the rest of the system, allowing information at different scales and on different aspects of the system to be linked together into one coherent picture. Such data integration techniques are increasingly being used with satellite observations for both water and carbon dynamics at various levels of process complexity (Bloom

*et al.*, 2016; Exbrayat *et al.*, 2018; Baatz *et al.*, 2021), as well as to initialise tree sizes (Rödig *et al.*, 2019). Large-scale integration of forest inventory observations is less well developed, but some studies exist (Lichstein *et al.*, 2014), and the latest vegetation dynamic models with detailed representations of stand structure and forest demography (Smith *et al.*, 2014; Argles *et al.*, 2020; Koven *et al.*, 2020) provide a strong basis for further progress. Method development will be required to solve computational challenges, to appropriately weight different observations in the integration according to spatial representativeness and sampling intensity, and to propagate uncertainty from them (Fer *et al.*, 2018; Dokoochaki *et al.*, 2022). Relationships from regions constrained by multiple data sources could be applied to better estimate mortality trends in regions where only limited observations (such as optical satellite data) are available. A well-developed model data integration system could be placed at the centre of a global forest observation system, providing aggregate information on multiple metrics that is analogous to the reanalysis approaches used in meteorology (Hersbach *et al.*, 2020).

### A comprehensive and fair global network

Any effort of data integration towards a global assessment of tree mortality will be ultimately limited by spatial and temporal gaps in ground-based, long-term forest monitoring. These gaps tend to be larger in low-income regions of the world and can be largely attributed to the lack of investment in long-term monitoring and to the challenges of working in remote areas devoid of basic infrastructure, are politically unstable or subject to criminal activities (Nuñez *et al.*, 2019; Baldi & Palotás, 2021; Maas *et al.*, 2021; Seidler *et al.*, 2021). In the tropics, there is also the additional challenge of working in systems of high species diversity, which requires highly qualified professionals in species identification. Different initiatives have tried to fill these gaps by implementing long-term monitoring sites in tropical regions (e.g. ForestGEO, LTER Brasil, PPBio), as well as integrating and supporting existing local monitoring initiatives (ForestPlots.net *et al.*, 2021). Although these efforts have led to invaluable advancement in our understanding of these forests, data gaps remain, and the lack of investment in long-term monitoring efforts and integration of monitoring into government policies, especially in less wealthy countries, remains a shortcoming.

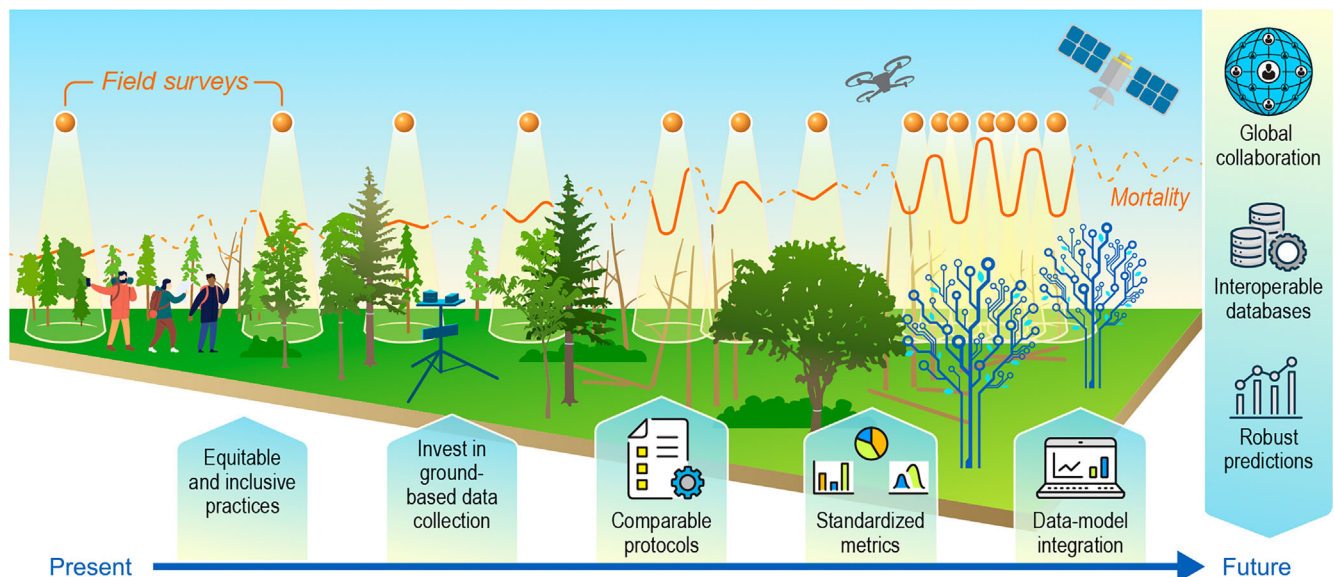
Forest monitoring in dense, species-rich and remote tropical systems can be extremely challenging. The identification of species alone can take up to twice the amount of time of recording and measuring the trees. For instance, the establishing of a new monitoring site of 1 ha takes up to 20 person-days in Central Amazonia, but identifying species, including collecting vouchers by climbers and *ex situ* identification by specialists, can take up to 40 person-days. Filling spatial gaps may include hiking for up to 5 d or hiring small aircrafts or boats to reach remote regions of continuous forests in Amazonia, the Upper Guinea Forest and the Congo Basin. Being remote can also mean being at risk, not just from potential accidents and diseases but also from potentially violent encounters with poachers, illegal loggers and miners, and armed militia. For these reasons, a whole region with 70 ha of permanent

plots was abandoned in 2019 in the English part of Cameroon, of which 58 ha are now in conflict areas and 12 ha have been converted to timber concession. Similarly, c. 20 ha of permanent plots in Southern Amazonia cannot be visited since 2018 because of illegal logging and land-grabbing. This, unfortunately, is not an uncommon situation across tropical regions.

Also problematic is the fact that the capability to locally employ more complex tools like remote sensing (see 'The role of remote sensing' section) and process-based modelling (see the 'Bringing it all together – data integration across scales' section) is often limited to wealthier countries. Part of the problem is that the efforts to understand forest functioning across large spatial scales are generally led by scientists whose national context gives greater opportunity to obtain funding for such analyses (Brearley *et al.*, 2019; North *et al.*, 2020; Asase *et al.*, 2022). This creates a power asymmetry in the collaboration between those who collect the data and those who lead the research analysis and papers (Boshoff, 2009). Moreover, this *modus operandi* often discourages scientists from less wealthy countries from sharing the data they collect. One step towards changing this situation is the adoption of co-design and co-production practices by those leading the analyses, that is, investing time and resources in discussing plans for analyses and in involving data originators in the analyses, with the necessary capacity building (Mahajan *et al.*, 2023).

Global data on forest dynamics will not be comprehensive until the issues around fair scientific collaborations between wealthy and poor countries are acknowledged, addressed and solved. Funding bodies and research institutions unfortunately reinforce and maintain these cultural standards through funding structures and evaluation systems that value individuals over groups, look for fast return on investments and favour short-term projects. This structure is incompatible with large global collaborations, which are becoming a common way of organising science. A shift in the way global collaborations take place demands large efforts and time commitments that are unlikely to be achieved if they are not appropriately funded (de Lima *et al.*, 2022) and evaluated in terms of their collective benefit. An ideal global network should place groups of people at the centre of the collaborative effort and spend a similar (or greater) amount of energy and resources as to what is spent on data analyses on capacity building, particularly of early-career researchers (Seidler *et al.*, 2021). Global initiatives should provide opportunities for all participants to be involved in decision-making and in the intellectual scientific process. To be truly inclusive, we should revise the current paradigm that focuses on individual scientific leaders, and instead global initiatives should consider adopting a collective mindset mirroring the strategy of science panels. For instance, the IPCC and the Science Panel for the Amazon, which value community effort over that of small teams or individuals, provide models, although it is necessary to ensure that different groups are appropriately represented (Mori, 2022). Governmental efforts, such as the NFIs, have the stability and the long-term vision needed to provide a platform for the integration of people and data across the globe. Regional efforts to harmonise NFIs across key data gaps are already taking place and similar efforts to integrate NFI and academic communities would be a major step towards closing data gaps.





**Fig. 4** Roadmap towards a global understanding of tree mortality. The five major steps integrate long-term field data with remote sensing and modelling techniques to build a fair, diverse and equitable system to monitor tree mortality at global scales. At its core, this system is built in a progressive fashion that over time (left to right in the figure) allows for expanding current monitoring frameworks, both spatially and temporarily, to enhance scientific and social collaborations via interoperable databases that ultimately will help develop stronger predictions on tree mortality, its trends and main drivers.

Different networks have developed strategies to improve fairness in collaboration. For instance, it is now increasingly common to invite all data contributors to participate in the writing processes as authors of manuscripts (e.g. [ForestPlots.net](#)) and to list the group as the first author (e.g. [ForestPlots.net](#) (ForestPlots.net *et al.*, 2021) and [DryFlor](#) (DRYFLOR *et al.*, 2016)). Although participation in manuscripts is an important step, deeper change will only happen by exchanging knowledge with and transferring resources to less wealthy regions. A fair global network should aim for those in less wealthy regions to lead local to global-scale analyses and to secure the continuity of field measurements and of their own research agendas. Indeed, a few networks are investing in capacity building by promoting workshops for data contributors (e.g. [ForestGEO](#) (Anderson-Teixeira *et al.*, 2015); [International Long Term Ecological Research](#), [ILTER](#)). It is also key to have the mode of collaboration and data sharing well defined, with roles written and agreed by all members ([sPlots](#) (Bruehlheide *et al.*, 2019), [ForestPlots.net](#) (ForestPlots.net *et al.*, 2021)). These first steps are extremely important, but they are only the beginning if we are to advance global science in an equitable manner. The steps towards fair, truly inclusive collaborations need to be encouraged and recognised by the scientific community and funding agencies. Only then, will we be able to achieve a comprehensive global understanding of tree mortality trends.

### Vision – what we need to do as a community

A global monitoring system of tree mortality requires the harmonisation of existing global long-term field data and their integration with remote sensing and modelling techniques to gap-fill these data across time and space (Fig. 4). This requires development of methods and agreements enabling seamless flows of information

from the field to global assessments. Whilst there is a wealth of established plots that could form the backbone of a global tree mortality monitoring system if funding continues (Fig. 3), some data networks might require adjustments to their protocols to substantially improve monitoring of tree death. This includes increasing the temporal resolution of data collection and shifting towards protocols that track individual trees and characterise the condition of both live and dead trees (i.e. standing, falling, uprooted or logged). The spatial and temporal gaps in forest inventory plots remain a major limitation to an operational tree mortality monitoring system. Not only hypothesis-driven research, but also data collection, needs to be a priority with funding bodies to better support the implementation and continuity of long-term ecological monitoring programmes (e.g. [Programa de Pesquisas Ecológicas de Longa Duração](#), [PELD](#)). Remote sensing techniques should be used to detect areas where forest canopy is changing, helping to target future ground-based work and fill in temporal and spatial gaps.

As a global effort, this must be used as an opportunity to advance towards an equitable scientific community. Funding agencies must invest in forest monitoring in data-gap areas, mostly located in less wealthy countries, whilst promoting fair collaborations and capacity building that empower local scientists. The format of science panels (i.e. the [IPCC](#) and [IPBES](#)) should allow more inclusive practices when compared to research papers led by a few individuals and for results to feed quickly into policy making. We call for a global tree mortality monitoring system to be supported by multilateral organisations, such as the [UN](#) and the [FAO](#), providing for the long-term maintenance of this global effort. Our current understanding of forests, the advancement of new technologies and world-wide connectivity means that now a global monitoring system of tree mortality is not just urgently needed but also feasible. In summary, we propose the following roadmap towards a global



understanding of tree mortality, building on our minimum requirements (Fig. 4):

- (1) Promote equitable practices across the community that empower those collecting the data.
- (2) Invest in ground-based data collection, sustaining long-term efforts and expanding to data-poor regions.
- (3) Adjust protocols to facilitate comparability and improve quantification of rates and causes of tree mortality.
- (4) Generate standardised tree mortality metrics from ground-based data that can be widely used by the scientific community and facilitate comparability across studies.
- (5) Integrate ground-based data with remote sensing data and process-based models to expand current observations temporally and spatially and understand their underlying drivers.

Following this roadmap will allow us to create interoperable datasets on tree mortality globally through fair collaboration and ultimately lead to robust predictions of tree mortality trends.

## Acknowledgements

The International Tree Mortality Network acknowledges funding from the Volkswagen Foundation for the symposium ‘Crossing scales and disciplines to identify global trends in tree mortality as indicator of forest health’ (A122411–AZ 92813), which initiated this collaboration. TP, AE-M and OLP acknowledge funding from European Research Council under the European Union’s Horizon 2020 research and innovation program (grant agreement no.: 758873, TreeMort); TP and CS were also funded by the European Forest Institute Network Fund. This paper is a contribution to the Swedish Research Council’s strategic research areas BECC and MERGE and the Nature-Based Future Solutions profile area at Lund University. AE-M was further funded by the Royal Society Standard (grant no.: RGS/R1\221115; ‘MegaFlora’), the UKRI/NERC TreeScapes NE/V021346/1 ‘MEMBRA’, the FRB/CESAB ‘Syn-treesys’ and the NERC/NSF consortium ‘Gigante’. OLP was supported by FORAMA (Royal Society project to OLP, award ref.: ICA/R1\180100). RM acknowledges funding from the Swedish Research Council (grant no.: 2019-03758). PR-B and MAZ acknowledge funding from Science and Innovation Ministry (IB-ForRes, subproject LARGE, no.: PID2021-123675OB-C41) and Stimulus to Excellence for Permanent University Professors (no.: EPU-INV/2020/010). GP was funded by the Royal Society of New Zealand’s Marsden Fund. AR acknowledge funding from Projects: BioClimpact (nos.: 7/23020401 and SPECTRAVEG-PN-III-P2-2.1-PED-2019-4924). CS-E acknowledges funding from the Chilean National Agency for Science (grant FONDECYT no.: 1231458). TJ acknowledges funding from NERC Independent Research Fellowship (grant code: NE/S01537X/1). NM was funded by the National Science Foundation; Department of Energy COMPASS-FME and NGEE-Tropics projects. GG received funding from the National Science Foundation DEB-1655896. CH acknowledges funding from the National Science and Technology Council (NSTC 111-2121-M-002-001). ES acknowledges the Kone Foundation (project: 202 005 775 RETROFOR – RETention forestry as a tool to secure Resilience and sustainability in

Operational FOREst management). KK was supported by the Institutional Support of VUKOZ-00027073. AV acknowledges INERTIA project PID2019-111332RB-C22. JM-V was supported by Grant PID2021-127452NB-I00 funded by MCIN/AEI/10.13039/501100011033 and the European Union NextGenerationEU/PRTR; grant 2021 SGR 00849 funded by AGAUR; and ICREA Academia. TK acknowledges funding from the German Aerospace Centre (DLR) and Federal Ministry for Economic Affairs and Climate Action (BMWK) (grant code: 50EE1909A). AG acknowledges funding from the FORWARDS project (EU project no.: 101084481) funded by the European Union and the Swiss State Secretariat for Education, Research and Innovation (SERI). AGG was support by Fondecyt 11150835, Fondecyt 1200468 and Grant ANID PIA/BASAL FB210006. MS-P acknowledges funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie (grant agreement no.: 891477). RS was supported by the European Research Council under the European Union’s Horizon 2020 research and innovation programme (grant agreement no.: 101001905). ALG acknowledges CNPq for the productivity (grant no.: 307861/2023-6). ACV was supported by CNPq for research grants (305199/2022-6; 408242/2021-3). BB-L was supported by COMPASS-FME, a multi-institutional project supported by the US Department of Energy, Office of Science, Biological and Environmental Research as part of the Environmental System Science Program. JF was supported by ARC LP160100996; MO acknowledges funding from Agencia Estatal de Investigación de España (Ramon y Cajal, RYC2021-032049-I). SJ acknowledges funding from the Academy of Finland (grant nos.: 330422, 337127). JP acknowledges TED2021-132627B-I00 grant, funded by MCIN and the European Union NextGeneration EU/PRTR. AJ acknowledges funding from the Natural Environment Research Council (grant nos.: NE/V00929X/1, NE/S010041/1 and NE/Y004205/1). BB-L and NM were supported by COMPASS-FME, a multi-institutional project funded by the US Department of Energy, Office of Science, Biological and Environmental Research, as part of the Environmental System Science Program. NM was also supported by the Department of Energy’s Next Generation Ecosystem Experiment-Tropics and by the US National Science Foundation. RRR acknowledges funding from Fundação de Amparo à pesquisa do estado de São Paulo-FAPESP (grant codes: 2018/18416-2, 2013/50718-5 and 1999/09635-0). NLP acknowledges funding from the Italian FEM projects grant no.: P1611006I. GXR was supported by FAPEMA (grant nos.: APP 01045/10 and APP 00262/12) and CAPES (grant no.: 3281/13). HJB acknowledges funding from the German Research Foundation (DFG) (grant no.: BO 1768). RAFL and SS acknowledge funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie (grant agreement nos.: 795114 and 895158). LTW acknowledges funding from the Swiss NFI, a cooperative effort between the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) and the Swiss Federal Office for the Environment (FOEN). MMT acknowledges the funding provided by Comisión Nacional de Áreas Naturales Protegidas and CONAHACYT – INECOL Chair (Project no.: 673; ‘Etnobiología, interacciones biológicas y restauración

ecológica en el Centro – Occidente de México). EGC was supported by CAPES (grant no.: 3281/13). KS acknowledges funding from Project LIFE+ ForBioSensing (contract no.: LIFE13ENV/PL/000048) and Poland's National Fund for Environmental Protection and Water Management (contract no.: 485/2014/WN10/OPNMLF/D). This study draws on and contributes to ideas and initiatives of the International Union of Forest Research Organizations (IUFRO) Task Force on monitoring global tree mortality trends and patterns. GA acknowledges funding from the US National Science Foundation award no.: 2020424: 'AccelNet: International Tropical Forest Science Alliance (ITFSA): A multi-network science and training initiative to accelerate understanding of the role of tropical forests in the Earth System'. Open Access funding enabled and organized by Projekt DEAL.

### Competing interests

None declared.

### Author contributions

CS, AE-M and TAMP initiated the publication with help of BS, HH, NR and RS. CS, AE-M and TAMP wrote the manuscript. WRLA, KJA-T, GA, MBS, BJB, HJB, BB-L, KMB, FQB, FB, MC, JJC, GC, FRC, RD, HD, SJD, SD, BPD, RAFdL, MF, JBF, MG, ALdG, AG, GSG, JLG, FMPG, LG, AGG, EGC, WMH, HH, MLH, AH, JH, MJH, C-yH, BH, T Jackson, T Jucker, ASJ, SJ, TK, JK, MMK, KK, NLP, L-TL, RLC, EEM, JMD, EHM, JM-V, NM, PWM, ASM, MAM, Jan-Peter Mund, RM, MM-T, SCM, TAN, SN, CAN, MNS, MJO, JP, GLWP, OLP, JMP, RRR, AR, GXR, NKR, PR-B, KXR, CS-E, TGM Sanders, RSB, T Scharnweber, M-JS, BS, S Schwarz, RS, ES, ACS, GS, J Socha, KS, J Stillhard, DBS, S Suvanto, MS, MS-P, AJT, ART, FTF, GV, ACV, AV, EV, LTW, SKW, KY, MAZ, LZO, DZ, ABdC-F, EvdM and MvdM contributed to several workshops discussing the individual subsections of the manuscript and they all revised the manuscript.

### Data availability

All data and code are available under: <https://zenodo.org/records/13221241>.

### International Tree Mortality Network\*<sup>†</sup>

(\*Authors for correspondence: email [cornelius.senf@tum.de](mailto:cornelius.senf@tum.de) (CS); [a.esquivelmuelbert@bham.ac.uk](mailto:a.esquivelmuelbert@bham.ac.uk) (AE-M); [thomas.pugh@nateko.lu.se](mailto:thomas.pugh@nateko.lu.se) (TAMP))

<sup>†</sup>A full list of collaborators and their affiliations appears in Appendix A1.

[Correction added on 8 February 2025, after first online publication: Tanja G. M. Sanders' name has been presented correctly and the ORCID number added. The Author contributions statement has been updated accordingly].

### References

- Abatzoglou JT, Williams AP. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences, USA* 113: 11770–11775.
- Allen CD, Breshears DD, McDowell NG. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere* 6: art129.
- Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Venetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH *et al.* 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259: 660–684.
- Anderson-Teixeira KJ, Davies SJ, Bennett AC, Gonzalez-Akre EB, Muller-Landau HC, Joseph Wright S, Abu Salim K, Almeyda Zambrano AM, Alonso A, Baltzer JL *et al.* 2015. CTFS-ForestGEO: a worldwide network monitoring forests in an era of global change. *Global Change Biology* 21: 528–549.
- Anderson-Teixeira KJ, Herrmann V, Cass WB, Williams AB, Paull SJ, Gonzalez-Akre EB, Helcoski R, Tepley AJ, Bourg NA, Cosma CT *et al.* 2021. Long-term impacts of invasive insects and pathogens on composition, biomass, and diversity of forests in Virginia's Blue Ridge Mountains. *Ecosystems* 24: 89–105.
- Arellano G, Zuleta D, Davies SJ. 2021. Tree death and damage: a standardized protocol for frequent surveys in tropical forests. *Journal of Vegetation Science* 32: e12981.
- Argles APK, Moore JR, Huntingford C, Wiltshire AJ, Harper AB, Jones CD, Cox PM. 2020. Robust ecosystem demography (RED v.1.0): a parsimonious approach to modelling vegetation dynamics in Earth system models. *Geoscientific Model Development* 13: 4067–4089.
- Asase A, Mzumara-Gawa TI, Owino JO, Peterson AT, Saupé E. 2022. Replacing 'parachute science' with 'global science' in ecology and conservation biology. *Conservation Science and Practice* 4: e517.
- Baatz R, Hendricks Franssen HJ, Euskirchen E, Sihi D, Dietze M, Ciavatta S, Fennel K, Beck H, De Lannoy G, Pauwels VRN *et al.* 2021. Reanalysis in earth system science: toward terrestrial ecosystem reanalysis. *Reviews of Geophysics* 59: e2020RG000715.
- Báldi A, Palotás B. 2021. How to diminish the geographical bias in IPBES and related science? *Conservation Letters* 14: e12786.
- Beloïu M, Stahlmann R, Beierkuhnlein C. 2022. Drought impacts in forest canopy and deciduous tree saplings in Central European forests. *Forest Ecology and Management* 509: 120075.
- Bloom AA, Exbrayat J-F, van der Velde IR, Feng L, Williams M. 2016. The decadal state of the terrestrial carbon cycle: Global retrievals of terrestrial carbon allocation, pools, and residence times. *Proceedings of the National Academy of Sciences, USA* 113: 1285–1290.
- Boshoff N. 2009. Neo-colonialism and research collaboration in Central Africa. *Scientometrics* 81: 413–434.
- Brearely FQ, Adinugroho WC, Cámara-Leret R, Krisnawati H, Ledo A, Qie L, Smith TEL, Aini F, Garnier F, Lestari NS *et al.* 2019. Opportunities and challenges for an Indonesian forest monitoring network. *Annals of Forest Science* 76: 1–12.
- Breidenbach J, Granhus A, Hysten G, Eriksen R, Astrup R. 2020. A century of national forest inventory in Norway – informing past, present, and future decisions. *Forest Ecosystems* 7: 46.
- Breshears DD, Myers OB, Meyer CW, Barnes FJ, Zou CB, Allen CD, McDowell NG, Pockman WT. 2009. Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements. *Frontiers in Ecology and the Environment* 7: 185–189.
- Brienen RJW, Phillips OL, Feldpausch TR, Gloor E, Baker TR, Lloyd J, Lopez-Gonzalez G, Monteagudo-Mendoza A, Malhi Y, Lewis SL *et al.* 2015. Long-term decline of the Amazon carbon sink. *Nature* 519: 344–348.
- Brodrick PG, Asner GP. 2017. Remotely sensed predictors of conifer tree mortality during severe drought. *Environmental Research Letters* 12: 115013.
- Bruelheide H, Dengler J, Jiménez-Alfaro B, Purschke O, Hennekens SM, Chytrý M, Pillar VD, Jansen F, Kattge J, Sandel B *et al.* 2019. sPlot – a new tool for global vegetation analyses. *Journal of Vegetation Science* 30: 161–186.

- Brun P, Psomas A, Ginzler C, Thuiller W, Zappa M, Zimmermann NE. 2020. Large-scale early-wilting response of Central European forests to the 2018 extreme drought. *Global Change Biology* 26: 7021–7035.
- Buras A, Rammig A, Zang CS. 2020. Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. *Biogeosciences* 17: 1655–1672.
- Chave J, Davies SJ, Phillips OL, Lewis SL, Sist P, Schepaschenko D, Armston J, Baker TR, Coomes D, Disney M *et al.* 2019. Ground data are essential for biomass remote sensing missions. *Surveys in Geophysics* 40: 863–880.
- Cook-Patton SC, Drever CR, Griscom BW, Hamrick K, Hardman H, Kroeger T, Pacheco P, Raghav S, Stevenson M, Webb C *et al.* 2021. Protect, manage and then restore lands for climate mitigation. *Nature Climate Change* 11: 1027–1034.
- Costa FRC, Schiatti J, Stark SC, Smith MN. 2023. The other side of tropical forest drought: do shallow water table regions of Amazonia act as large-scale hydrological refugia from drought? *New Phytologist* 237: 714–733.
- Cotrozzi L. 2022. Spectroscopic detection of forest diseases: a review (1970–2020). *Journal of Forestry Research* 33: 21–38.
- Cushman K c, Detto M, García M, Muller-Landau HC. 2022. Soils and topography control natural disturbance rates and thereby forest structure in a lowland tropical landscape. *Ecology Letters* 25: 1126–1138.
- Dalagnol R, Wagner FH, Galvão LS, Streher AS, Phillips OL, Gloor E, Pugh TAM, Ometto JPHB, Aragão LEOC. 2021. Large-scale variations in the dynamics of Amazon forest canopy gaps from airborne lidar data and opportunities for tree mortality estimates. *Scientific Reports* 11: 1388.
- Das AJ, Stephenson NL, Davis KP. 2016. Why do trees die? Characterizing the drivers of background tree mortality. *Ecology* 97: 2616–2627.
- Dokoochaki H, Morrison BD, Raiho A, Serbin SP, Zarada K, Dramko L, Dietze M. 2022. Development of an open-source regional data assimilation system in PECOAN v. 1.7.2: application to carbon cycle reanalysis across the contiguous US using SIPNET. *Geoscientific Model Development* 15: 3233–3252.
- DRYFLOR, Banda-R K, Delgado-Salinas A, Dexter KG, Linares-Palomino R, Oliveira-Filho A, Prado D, Pullan M, Quintana C, Riina R *et al.* 2016. Plant diversity patterns in neotropical dry forests and their conservation implications. *Science* 353: 1383–1387.
- Esquivel-Muelbert A, Baker TR, Dexter KG, Lewis SL, Brien R, Feldpausch TR, Lloyd J, Monteagudo-Mendoza A, Arroyo L, Álvarez-Dávila E *et al.* 2019. Compositional response of Amazon forests to climate change. *Global Change Biology* 25: 39–56.
- Exbrayat J-F, Smallman TL, Bloom AA, Hutley LB, Williams M. 2018. Inverse determination of the influence of fire on vegetation carbon turnover in the pantropics. *Global Biogeochemical Cycles* 32: 1776–1789.
- Fer I, Kelly R, Moorcroft PR, Richardson AD, Cowdery EM, Dietze MC. 2018. Linking big models to big data: efficient ecosystem model calibration through Bayesian model emulation. *Biogeosciences* 15: 5801–5830.
- Ferretti M. 2013. Chapter 6 – concepts and design principles adopted in the international cooperative program on the assessment and monitoring of air pollution effects on forests (ICP Forests). In: Ferretti M, Fischer R, eds. *Forest monitoring. Developments in environmental science*. Amsterdam, the Netherlands: Elsevier, 91–104.
- ForestPlots.net, Blundo C, Carilla J, Grau R, Malizia A, Malizia L, Osinaga-Acosta O, Bird M, Bradford M, Catchpole D *et al.* 2021. Taking the pulse of Earth's tropical forests using networks of highly distributed plots. *Biological Conservation* 260: 108849.
- Fridman J, Holm S, Nilsson M, Nilsson P, Ringvall AH, Ståhl G. 2014. Adapting National Forest Inventories to changing requirements – the case of the Swedish National Forest Inventory at the turn of the 20<sup>th</sup> century. *Silva Fennica* 48: 2120.
- Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Gregor L, Hauck J, Le Quéré C, Luijckx IT, Olsen A, Peters GP *et al.* 2022. Global carbon budget 2022. *Earth System Science Data* 14: 4811–4900.
- Friend AD, Lucht W, Rademacher TT, Keribin R, Betts R, Cadule P, Ciais P, Clark DB, Dankers R, Falloon PD *et al.* 2014. Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO<sub>2</sub>. *Proceedings of the National Academy of Sciences, USA* 111: 3280–3285.
- Grossiord C, Buckley TN, Cernusak LA, Novick KA, Poulter B, Siegwolf RTW, Sperry JS, McDowell NG. 2020. Plant responses to rising vapor pressure deficit. *New Phytologist* 226: 1550–1566.
- Guo Q, Kelly M, Gong P, Liu D. 2007. An object-based classification approach in mapping tree mortality using high spatial resolution imagery. *GIScience & Remote Sensing* 44: 24–47.
- Hammond WM, Williams AP, Abatzoglou JT, Adams HD, Klein T, López R, Sáenz-Romero C, Hartmann H, Breshears DD, Allen CD. 2022. Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. *Nature Communications* 13: 1761.
- Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR *et al.* 2013. High-resolution global maps of 21<sup>st</sup>-century forest cover change. *Science* 342: 850–853.
- Harris I, Osborn TJ, Jones P, Lister D. 2020. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data* 7: 109.
- Harris NL, Gibbs DA, Baccini A, Birdsey RA, de Bruin S, Farina M, Fatoyinbo L, Hansen MC, Herold M, Houghton RA *et al.* 2021. Global maps of twenty-first century forest carbon fluxes. *Nature Climate Change* 11: 234–240.
- Hartmann H, Moura CF, Anderegg WRL, Ruehr NK, Salmon Y, Allen CD, Arndt SK, Breshears DD, Davi H, Galbraith D *et al.* 2018a. Research frontiers for improving our understanding of drought-induced tree and forest mortality. *New Phytologist* 218: 15–28.
- Hartmann H, Schuldt B, Sanders TGM, Macinnis-Ng C, Boehmer HJ, Allen CD, Bolte A, Crowther TW, Hansen MC, Medlyn BE *et al.* 2018b. Monitoring global tree mortality patterns and trends. Report from the VW symposium 'Crossing scales and disciplines to identify global trends of tree mortality as indicators of forest health'. *New Phytologist* 217: 984–987.
- Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, Nicolas J, Peubey C, Radu R, Schepers D *et al.* 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* 146: 1999–2049.
- Hubau W, Lewis SL, Phillips OL, Affum-Baffoe K, Beeckman H, Cuní-Sánchez A, Daniels AK, Ewango CEN, Fauset S, Mukinzi JM *et al.* 2020. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* 579: 80–87.
- Huertas C, Sabatier D, Derroire G, Ferry B, Jackson Toby D, Pélissier R, Vincent G. 2022. Mapping tree mortality rate in a tropical moist forest using multi-temporal LiDAR. *International Journal of Applied Earth Observation and Geoinformation* 109: 102780.
- Jucker T. 2022. Deciphering the fingerprint of disturbance on the three-dimensional structure of the world's forests. *New Phytologist* 233: 612–617.
- Koven CD, Knox RG, Fisher RA, Chambers JQ, Christoffersen BO, Davies SJ, Detto M, Dietze MC, Faybishenko B, Holm J *et al.* 2020. Benchmarking and parameter sensitivity of physiological and vegetation dynamics using the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) at Barro Colorado Island, Panama. *Biogeosciences* 17: 3017–3044.
- Kurz WA, Stinson G, Rampley GJ, Dymond CC, Neilson ET. 2008. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National Academy of Sciences, USA* 105: 1551–1555.
- Labrière N, Davies SJ, Disney MI, Duncanson LI, Herold M, Lewis SL, Phillips OL, Quegan S, Saatchi SS, Schepaschenko DG *et al.* 2023. Toward a forest biomass reference measurement system for remote sensing applications. *Global Change Biology* 29: 827–840.
- Lichstein JW, Golaz N-Z, Malyshev S, Shevliakova E, Zhang T, Sheffield J, Birdsey RA, Sarmiento JL, Pacala SW. 2014. Confronting terrestrial biosphere models with forest inventory data. *Ecological Applications* 24: 699–715.
- de Lima RAF, Phillips OL, Duque A, Tello JS, Davies SJ, de Oliveira AA, Muller S, Honorio Coronado EN, Vilanova E, Cuní-Sánchez A *et al.* 2022. Making forest data fair and open. *Nature Ecology & Evolution* 6: 656–658.
- Maas B, Pakeman RJ, Godet L, Smith L, Devictor V, Primack R. 2021. Women and Global South strikingly underrepresented among top-publishing ecologists. *Conservation Letters* 14: e12797.
- Mahajan SL, Estradivari R, Ojwang L, Ahmadi GN. 2023. The good, the bad, and the ugly: reflections on co-designing science for impact between the Global South and Global North. *ICES Journal of Marine Science* 80: 390–393.
- McDowell N, Allen CD, Anderson-Teixeira K, Brando P, Brien R, Chambers J, Christoffersen B, Davies S, Doughty C, Duque A *et al.* 2018. Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist* 219: 851–869.



- McDowell NG, Allen CD, Anderson-Teixeira K, Aukema BH, Bond-Lamberty B, Chini L, Clark JS, Dietze M, Grossiord C, Hanbury-Brown A *et al.* 2020. Pervasive shifts in forest dynamics in a changing world. *Science* 368: eaaz9463.
- Meddens AJH, Hicke JA, Vierling LA. 2011. Evaluating the potential of multispectral imagery to map multiple stages of tree mortality. *Remote Sensing of Environment* 115: 1632–1642.
- Mori AS. 2022. Diversity, equity, and inclusion in academia to guide society. *Trends in Ecology & Evolution* 37: 1–4.
- North MA, Hastie WW, Hoyer L. 2020. Out of Africa: the underrepresentation of African authors in high-impact geoscience literature. *Earth-Science Reviews* 208: 103262.
- Núñez MA, Barlow J, Cadotte M, Lucas K, Newton E, Pettorelli N, Stephens PA. 2019. Assessing the uneven global distribution of readership, submissions and publications in applied ecology: obvious problems without obvious solutions. *Journal of Applied Ecology* 56: 4–9.
- Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG *et al.* 2011. A large and persistent carbon sink in the world's forests. *Science* 333: 988–993.
- Phillips OL, Gentry AH. 1994. Increasing turnover through time in tropical forests. *Science* 263: 954–958.
- Piponiot C, Anderson-Teixeira KJ, Davies SJ, Allen D, Bourg NA, Burslem DFRP, Cárdenas D, Chang-Yang C-H, Chuyong G, Cordell S *et al.* 2022. Distribution of biomass dynamics in relation to tree size in forests across the world. *New Phytologist* 234: 1664–1677.
- Pollard JE. 2006. *Forest inventory and analysis national data quality assessment report for 2000 to 2003*. Fort Collins, CO, USA: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Potter C, Klooster S, Hiatt C, Genovese V, Castilla-Rubio JC. 2011. Changes in the carbon cycle of Amazon ecosystems during the 2010 drought. *Environmental Research Letters* 6: 034024.
- Pugh TAM, Lindeskog M, Smith B, Poulter B, Arneth A, Haverd V, Calle L. 2019. Role of forest regrowth in global carbon sink dynamics. *Proceedings of the National Academy of Sciences, USA* 116: 4382.
- Pugh TAM, Rademacher T, Shafer SL, Steinkamp J, Barichivich J, Beckage B, Haverd V, Harper A, Heinke J, Nishina K *et al.* 2020. Understanding the uncertainty in global forest carbon turnover. *Biogeosciences* 17: 3961–3989.
- Rödig E, Knapp N, Fischer R, Bohn FJ, Dubayah R, Tang H, Huth A. 2019. From small-scale forest structure to Amazon-wide carbon estimates. *Nature Communications* 10: 5088.
- Scheel M, Lindeskog M, Smith B, Suvanto S, Pugh TAM. 2022. Increased Central European forest mortality explained by higher harvest rates driven by enhanced productivity. *Environmental Research Letters* 17: 114007.
- Schiefer F, Schmidlein S, Frick A, Frey J, Klinke R, Zielewska-Büttner K, Junttila S, Uhl A, Kattenborn T. 2023. UAV-based reference data for the prediction of fractional cover of standing deadwood from Sentinel time series. *ISPRS Open Journal of Photogrammetry and Remote Sensing* 8: 100034.
- Schurman JS, Trotsiuk V, Bace R, Cada V, Fraver S, Janda P, Kulakowski D, Labusova J, Mikolas M, Nagel TA *et al.* 2018. Large-scale disturbance legacies and the climate sensitivity of primary *Picea abies* forests. *Global Change Biology* 24: 2169–2181.
- Seidl R, Thom D, Kautz M, Martin-Benito D, Peltoniemi M, Vacchiano G, Wild J, Ascoli D, Petr M, Honkaniemi J *et al.* 2017. Forest disturbances under climate change. *Nature Climate Change* 7: 395–402.
- Seidler R, Primack RB, Goswami VR, Khaling S, Devy MS, Corlett RT, Knott CD, Kane EE, Susanto TW, Otlai E *et al.* 2021. Confronting ethical challenges in long-term research programs in the tropics. *Biological Conservation* 255: 108933.
- Senf C, Buras A, Zang CS, Rammig A, Seidl R. 2020. Excess forest mortality is consistently linked to drought across Europe. *Nature Communications* 11: 6200.
- Senf C, Sebold J, Seidl R. 2021. Increasing canopy mortality impacts the future demographic structure of Europe's forests. *One Earth* 4: 1–7.
- Senf C, Seidl R. 2021a. Mapping the forest disturbance regimes of Europe. *Nature Sustainability* 4: 63–70.
- Senf C, Seidl R. 2021b. Storm and fire disturbances in Europe: distribution and trends. *Global Change Biology* 27: 3605–3619.
- Senf C, Seidl R, Hostert P. 2017. Remote sensing of forest insect disturbances: current state and future directions. *International Journal of Applied Earth Observation and Geoinformation* 60: 49–60.
- Sist P, Rutishauser E, Peña-Claros M, Shenkin A, Héroult B, Blanc L, Baraloto C, Baya F, Benedet F, da Silva KE *et al.* 2015. The Tropical managed Forests Observatory: a research network addressing the future of tropical logged forests. *Applied Vegetation Science* 18: 171–174.
- Smith B, Wärlind D, Arneth A, Hickler T, Leadley P, Siltberg J, Zaehle S. 2014. Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. *Biogeosciences* 11: 2027–2054.
- Stahl G, Cienciala E, Chirici G, Lanz A, Vidal C, Winter S, McRoberts RE, Rondeux J, Schadauer K, Tomppo E. 2012. Bridging national and reference definitions for harmonizing forest statistics. *Forest Science* 58: 214–223.
- Stereńczak K, Mielczarek M, Kamińska A, Kraszewski B, Piasecka Z, Miścicki S, Heurich M. 2020. Influence of selected habitat and stand factors on bark beetle *Ips typographus* (L.) outbreak in the Białowieża Forest. *Forest Ecology and Management* 459: 117826.
- Talarczyk A. 2014. National forest inventory in Poland. *Baltic Forestry* 20: 2260.
- Uriarte M, Thompson J, Zimmerman JK. 2019. Hurricane María tripled stem breaks and doubled tree mortality relative to other major storms. *Nature Communications* 10: 1362.
- Ward M, Tulloch AIT, Radford JQ, Williams BA, Reside AE, Macdonald SL, Mayfield HJ, Maron M, Possingham HP, Vine SJ *et al.* 2020. Impact of 2019–2020 mega-fires on Australian fauna habitat. *Nature Ecology & Evolution* 4: 1321–1326.
- Weed AS, Ayres MP, Hicke JA. 2013. Consequences of climate change for biotic disturbances in North American forests. *Ecological Monographs* 83: 441–470.
- van Wees D, van der Werf GR, Randerson JT, Andela N, Chen Y, Morton DC. 2021. The role of fire in global forest loss dynamics. *Global Change Biology* 27: 2377–2391.
- White JC, Wulder MA, Hermosilla T, Coops NC, Hobart GW. 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.
- Wu D, Piao S, Liu Y, Ciais P, Yao Y. 2018. Evaluation of CMIP5 earth system models for the spatial patterns of biomass and soil carbon turnover times and their linkage with climate. *Journal of Climate* 31: 5947–5960.
- Wulder MA, Roy DP, Radeloff VC, Loveland TR, Anderson MC, Johnson DM, Healey S, Zhu Z, Scambos TA, Pahlevan N *et al.* 2022. Fifty years of Landsat science and impacts. *Remote Sensing of Environment* 280: 113195.
- Yu K, Smith WK, Trugman AT, Condit R, Hubbell SP, Sardans J, Peng C, Zhu K, Peñuelas J, Cailleret M *et al.* 2019. Pervasive decreases in living vegetation carbon turnover time across forest climate zones. *National Academy of Sciences of the United States of America* 116: 24662–24667.
- Zweifel R, Pappas C, Peters RL, Babst F, Balanzategui D, Basler D, Bastos A, Beloiu M, Buchmann N, Bose AK *et al.* 2023. Networking the forest infrastructure towards near real-time monitoring – a white paper. *Science of the Total Environment* 872: 162167.

## Appendix A1

### International Tree Mortality Network

Cornelius Senf (0000-0002-2389-2158)<sup>1</sup>, Adriane Esquivel-Muelbert (0000-0001-5335-1259)<sup>2,3</sup>, Thomas A. M. Pugh (0000-0002-6242-7371)<sup>2,3,4</sup>, William R. L. Anderegg (0000-0001-6551-3331)<sup>5,6</sup>, Kristina J. Anderson-Teixeira (0000-0001-8461-9713)<sup>7,8</sup>, Gabriel Arellano (0000-0003-3990-5344)<sup>9,10</sup>, Mirela Beloiu Schwenke (0000-0002-3592-8170)<sup>11</sup>, Barbara J. Bentz (0000-0002-2741-1542)<sup>12</sup>, Hans Juergen Boehmer (0000-0002-9176-4836)<sup>13,14</sup>, Ben Bond-Lamberty (0000-0001-9525-4633)<sup>15</sup>, Kauane Maiara Bordin (0000-0003-3871-6293)<sup>16</sup>,



Francis Q. Brearley<sup>17</sup>, Filippo Bussotti (0000-0002-8353-4459)<sup>18</sup>, Maxime Cailleret (0000-0001-6561-1943)<sup>19</sup>, J. Julio Camarero (0000-0003-2436-2922)<sup>20</sup>, Gherardo Chirici (0000-0002-0669-5726)<sup>18,21</sup>, Flavia R. C. Costa<sup>22</sup>, Ricardo Dalagnol (0000-0002-7151-8697)<sup>23,24</sup>, Hendrik Davi (0000-0001-8828-3145)<sup>25</sup>, Stuart J. Davies (0000-0002-8596-7522)<sup>8</sup>, Sylvain Delzon (0000-0003-3442-1711)<sup>26</sup>, Bishnu Prasad Dhakal (0000-0002-8534-6558)<sup>27</sup>, Renato A. Ferreira de Lima (0000-0002-1048-0138)<sup>28</sup>, Marco Ferretti (0000-0002-8488-0804)<sup>29</sup>, Joseph B. Fontaine (0000-0002-6515-7864)<sup>30</sup>, Matteo Garbarino (0000-0002-9010-1731)<sup>31</sup>, André Luís de Gasper (0000-0002-1940-9581)<sup>32</sup>, Arthur Gessler (0000-0002-1910-9589)<sup>33,34</sup>, Gregory S. Gilbert (0000-0002-5195-9903)<sup>35</sup>, John L. Godlee (0000-0001-5595-255X)<sup>36</sup>, Francisco Maiato Pedro Gonçalves<sup>37,38</sup>, Leen Govaere<sup>39</sup>, Alvaro G. Gutiérrez (0000-0001-8928-3198)<sup>40,41</sup>, Ernesto Gómez Cardozo (0000-0002-6846-4106)<sup>42</sup>, William M. Hammond (0000-0002-2904-810X)<sup>43</sup>, Henrik Hartmann (0000-0002-9926-5484)<sup>44,45</sup>, Martina L. Hobi (0000-0003-3537-9738)<sup>46</sup>, Andrés Holz (0000-0002-8587-2603)<sup>47</sup>, Jürgen Homeier (0000-0001-5676-3267)<sup>48,49</sup>, Mark Joseph Hovenden (0000-0001-7208-9700)<sup>50</sup>, Cho-ying Huang (0000-0002-9174-7542)<sup>51,52</sup>, Bruno Héroult (0000-0002-6950-7286)<sup>53,54</sup>, Toby Jackson (0000-0001-8143-6161)<sup>55</sup>, Tommaso Jucker (0000-0002-0751-6312)<sup>55</sup>, Alistair S. Jump (0000-0002-2167-6451)<sup>56</sup>, Samuli Junttila (0000-0001-8276-9259)<sup>57</sup>, Teja Kattenborn (0000-0001-7381-3828)<sup>58</sup>, Joice Klipel (0000-0003-3936-9692)<sup>16,59</sup>, Martyna M. Kotowska (0000-0002-2283-5979)<sup>49,60</sup>, Kamil Král (0000-0002-3848-2119)<sup>61</sup>, Nicola La Porta (0000-0002-7080-3349)<sup>62,63</sup>, Leonel Lopez-Toledo (0000-0003-3424-5746)<sup>64</sup>, René López-Camacho (0000-0003-2026-0371)<sup>65</sup>, Eduardo Eiji Maeda (0000-0001-7932-1824)<sup>66,67</sup>, Jesús Mallol Díaz<sup>68</sup>, Emanuel H. Martin (0000-0003-0432-6262)<sup>69</sup>, Jordi Martínez-Vilalta (0000-0002-2332-7298)<sup>70,71</sup>, Nate McDowell<sup>72,73</sup>, Peter W. Moonlight (0000-0003-4342-2089)<sup>74,75</sup>, Akira S. Mori (0000-0002-8422-1198)<sup>76</sup>, Mohd Afzanizam Muda (0000-0003-1374-2305)<sup>77</sup>, Jan-Peter Mund (0000-0002-4878-5519)<sup>78</sup>, Robert Muscarella (0000-0003-3039-1076)<sup>79</sup>, Moisés Méndez-Toribio (0000-0002-8568-8072)<sup>80,81</sup>, Sandra C. Müller (0000-0002-6316-2897)<sup>82</sup>, Thomas A. Nagel (0000-0002-4207-9218)<sup>83</sup>, Stefan Neagu (0000-0002-2399-3864)<sup>84,85</sup>, Charles Andrew Nock (0000-0002-3483-0390)<sup>86</sup>, Moses Nsanyi Sainge (0000-0003-1677-3043)<sup>87</sup>, Michael J. O'Brien<sup>88</sup>, Josep Peñuelas (0000-0002-7215-0150)<sup>70,89</sup>, George L. W. Perry (0000-0001-9672-9135)<sup>90</sup>, Oliver L. Phillips (0000-0002-8993-6168)<sup>91</sup>, Juan Manuel Posada<sup>92</sup>, Ricardo Ribeiro Rodrigues (0000-0003-4818-0736)<sup>93</sup>, Anamaria Roman (0000-0001-9674-6461)<sup>94</sup>, Guillaume Xavier Rousseau<sup>42,95</sup>, Nadine Katrin Ruehr (0000-0001-5989-7463)<sup>96,97</sup>, Paloma Ruiz-Benito (0000-0002-2781-5870)<sup>98,99</sup>, Katinka X. Ruthrof (0000-0003-2038-2264)<sup>30,100</sup>, Christian Salas-Eljatib (0000-0002-8468-0829)<sup>101,102</sup>, Tanja G. M. Sanders (0000-0002-4536-4540)<sup>103</sup>, Rodrigo Scarton Bergamin (0000-0002-2405-9977)<sup>2,104</sup>, Tobias Scharnweber (0000-0002-4933-5296)<sup>105,‡</sup>, Mart-Jan Schelhaas (0000-0003-4525-2677)<sup>106</sup>, Bernhard Schuldt (0000-0003-4738-5289)<sup>107</sup>, Selina Schwarz (0000-0001-6042-1649)<sup>108</sup>, Rupert Seidl (0000-0002-3338-3402)<sup>109,110</sup>, Ekaterina

Shorohova (0000-0002-8238-927X)<sup>111</sup>, Ana Carolina Silva<sup>112</sup>, Geert Sioen (0000-0001-5590-3512)<sup>113</sup>, Jarosław Socha (0000-0002-9568-5764)<sup>114</sup>, Krzysztof Stereńczak (0000-0002-9556-0144)<sup>115</sup>, Jonas Stillhard (0000-0001-8850-4817)<sup>29</sup>, Dejan B. Stojanovic<sup>116</sup>, Susanne Suvanto (0000-0002-0345-3596)<sup>2,104,111</sup>, Miroslav Svoboda (0000-0003-4050-3422)<sup>117</sup>, Martina Sánchez-Pinillos (0000-0002-1499-4507)<sup>118,119</sup>, Andrew J. Tanentzap<sup>120</sup>, Anthony R. Taylor (0000-0002-2122-6792)<sup>121</sup>, Fabiano Turini Farah (0000-0003-2406-8766)<sup>122</sup>, Giorgio Vacchiano (0000-0001-8100-0659)<sup>123</sup>, Alexander C. Vibrans (0000-0002-8789-5833)<sup>124</sup>, Alberto Vilagrosa (0000-0002-1432-1214)<sup>125,126</sup>, Emilio Vilanova (0000-0001-6289-5127)<sup>127</sup>, Lars T. Waser (0000-0002-2609-9147)<sup>29</sup>, Susan K. Wiser (0000-0002-8938-8181)<sup>128</sup>, Kailiang Yu<sup>129</sup>, Miguel A. Zavala (0000-0003-1456-0132)<sup>98</sup>, Laio Zimmermann Oliveira<sup>130</sup>, Daniel Zuleta (0000-0001-9832-6188)<sup>131,132</sup>, Alvaro Boson de Castro-Faria (0000-0001-6276-0898)<sup>133</sup>, Ernst van der Maaten (0000-0002-5218-6682)<sup>134</sup>, Marieke van der Maaten-Theunissen (0000-0002-2942-9180)<sup>134</sup>

‡Deceased.

- (1) Technical University of Munich, School of Life Sciences, Earth Observation for Ecosystem Management, Hans-Carl-von-Carlowitz-Platz 2, Freising, 85354, Germany
- (2) School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, B15 2TT, UK
- (3) Birmingham Institute of Forest Research (BIFoR), University of Birmingham, Birmingham, B15 2TT, UK
- (4) Department of Physical Geography and Ecosystem Science, Lund University, Box 117, Lund, 22100, Sweden
- (5) Wilkes Center for Climate Science and Policy, University of Utah, 1390 Presidents Circle, Salt Lake City, UT, 84103, USA
- (6) School of Biological Sciences, University of Utah, 257 South 1400 East, Salt Lake City, UT, 84103, USA
- (7) Conservation Ecology Center, Smithsonian's National Zoo & Conservation Biology Institute, Front Royal, VA, 22630, USA
- (8) ForestGEO, Smithsonian Tropical Research Institute, West Loading Dock MRC-166, 10th and Constitution Ave, Washington, DC, 20560, USA
- (9) Ecology and Evolutionary Biology, University of Michigan, 1105 N University Ave, Ann Arbor, MI, 48109, USA
- (10) Oikobit LLC, 2105 Vista Oeste St NW, Albuquerque, NM, 87120, USA
- (11) Department of Environmental Systems Science, ETH Zurich, Universitätstrasse 16, Zürich, 8092, Switzerland
- (12) USDA Forest Service, Rocky Mountain Research Station, 860 N 1200 E, Logan, UT, 84321, USA
- (13) Institute of Earth System Sciences – Geobotany Section, Leibniz University Hannover, Nienburger Straße 17, Hannover, 30167, Germany
- (14) School of Agriculture, Geography, Environment, Ocean and Natural Sciences, The University of the South Pacific, Laucala Bay, Suva, Fiji
- (15) Joint Global Change Research Institute, Pacific Northwest National Laboratory, 5825 University Research Ct. #3500, College Park, MD, 20740, USA

- (16) Plant Ecology Lab, Ecology Department, Universidade Federal do Rio Grande do Sul, Bento Gonçalves Ave, 9500, Porto Alegre, 90650-001, Brazil
- (17) Department of Natural Sciences, Manchester Metropolitan University, Chester Str., Manchester, M1 5GD, UK
- (18) Dipartimento di Scienze e Tecnologie Agrarie, Alimentari, Ambientali e Forestali, Università degli Studi di Firenze, Piazzale delle Cascine 18, Florence, 50144, Italy
- (19) Aix Marseille Univ, INRAE, UMR RECOVER, 3275 route de Cézanne, CS 40061, Aix-en-Provence, Cedex 5, France
- (20) Instituto Pirenaico de Ecología (IPE-CSIC), Avda. Montañana 1005, Zaragoza, 50059, Spain
- (21) Fondazione per il Futuro delle Città, Via di Novoli, 10, Florence, 50127, Italy
- (22) Instituto Nacional de Pesquisas da Amazônia, Coordenação de Pesquisas em Dinâmica Ambiental, Av André Araújo, 2936, Manaus, CEP 69067-375, Brazil
- (23) CTrees, 12S Raymond Ave, Pasadena, CA, 91105, USA
- (24) NASA-Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA
- (25) URFM, Ecologie des Forêts méditerranéennes, UR629, Agroparc, CS 40509, 84914, Avignon, Cedex 9, France
- (26) University of Bordeaux, INRAE, UMR BIOGECO, Pessac, 33615, France
- (27) Forest Research and Training Centre, Babarmahal, Kathmandu, 44600, Nepal
- (28) Departamento de Ciências Biológicas, ESALQ, Universidade de São Paulo, Avenida Pádua Dias, 11, Piracicaba, 13418-900, Brazil
- (29) Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zuercherstrasse 111, Birmensdorf, 8903, Switzerland
- (30) School of Environmental and Conservation Sciences, Murdoch University, 90 South St, Murdoch, WA, 6150, Australia
- (31) DISAFA Department, University of Torino, Largo P. Braccini 2, Grugliasco, TO, 10095, Italy
- (32) Departamento de Ciências Naturais, Universidade Regional de Blumenau, Blumenau, Santa Catarina, 89030-903, Brazil
- (33) Institute of Terrestrial Ecosystems, ETH Zurich, Universitätsstrasse 22, Zurich, 8092, Switzerland
- (34) Forest Dynamics, Swiss Federal Research Institute WSL, Zürcherstrasse 111, Birmensdorf, CH-8903, Switzerland
- (35) University of California, Santa Cruz, 1156 High St, Santa Cruz, CA, 95064, USA
- (36) School of GeoSciences, University of Edinburgh, Edinburgh, EH9 3FF, UK
- (37) Universidade Mandume Ya Ndemufayo, Av. Hoji Ya Henda, No. 30, Lubango, Angola
- (38) Herbário do Lubango, ISCED-Huíla, Rua Sarmiento Rodrigues S/N, Lubango, Angola
- (39) Agency for Nature and Forests, Havenlaan 88 bus 75, Brussel, 1000, Belgium
- (40) Departamento de Ciencias Ambientales y Recursos Naturales Renovables, Facultad de Ciencias Agronómicas, Universidad de Chile, Av. Santa Rosa 11315, La Pintana, Santiago, 8820808, Chile
- (41) Institute of Ecology and Biodiversity (IEB), Avenue Libertador Bernardo O'Higgins 340, Santiago, 8320165, Chile
- (42) Postgraduate Program in Agroecology, Maranhão State University (UEMA), Av. Lourenço Vieira da Silva 1000, Jardim São Cristovão, São Luís, MA, 65055-310, Brazil
- (43) Agronomy Department, Institute of Food and Agricultural Sciences, 1676 McCarty Drive, Gainesville, FL, 32611, USA
- (44) Institute for Forest Protection, Julius Kühn-Institute – Federal Research Centre for Cultivated Plants, Erwin-Baur Str. 27, Quedlinburg, 06484, Germany
- (45) Department of Biogeochemical Processes, Max Planck Institute for Biogeochemistry, Hans-Knoell-Str. 10, Jena, 07743, Germany
- (46) Forest Resources and Management, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, 8903, Switzerland
- (47) School of the Earth, Environment, and Society (Geography), 1721 SW Broadway, Portland, OR, 97201, USA
- (48) Faculty of Resource Management, HAWK University of Applied Sciences and Arts, Göttingen, 37077, Germany
- (49) Department of Plant Ecology and Ecosystems Research, University of Goettingen, Untere Karspüle 2, Göttingen, 37073, Germany
- (50) Biological Sciences, School of Natural Sciences, University of Tasmania, Locked Bag 55, Hobart, Tas., 7001, Australia
- (51) Department of Geography, National Taiwan University, 1 Sec. 4 Roosevelt Road, Taipei, 10617, Taiwan
- (52) Research Center for Future Earth, National Taiwan University, 1 Sec. 4 Roosevelt Road, Taipei, 10617, Taiwan
- (53) CIRAD, UPR Forêts et Sociétés, Montpellier, F-34398, France
- (54) Forêts et Sociétés, Univ Montpellier, CIRAD, Montpellier, F-34398, France
- (55) School of Biological Sciences, University of Bristol, Bristol, BS8 1TQ, UK
- (56) Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling, FK9 4LA, UK
- (57) School of Forest Sciences, University of Eastern Finland, Yliopistokatu 2, Joensuu, 80101, Finland
- (58) Sensor-based Geoinformatics (geosense), University of Freiburg, Tennenbacherstr. 4, Freiburg, 79106, Germany
- (59) Leuphana University of Lüneburg, Institute of Ecology, Universitätsallee 1, Lüneburg, 21335, Germany
- (60) School of Natural Sciences, Macquarie University, North Ryde, NSW, 2109, Australia
- (61) Department of Forest Ecology, Silva Tarouca Research Institute, Lidická 25/27, Brno, 60200, Czech Republic
- (62) Research and Innovation Centre, Fondazione Edmund Mach (FEM), Via Mach 1, Trento, San Michele all'Adige, 38010, Italy
- (63) MOUNTFOR Project Centre, European Forest Institute, Via E. Mach 1, Trento, San Michele all'Adige, 38010, Italy
- (64) Universidad Michoacana de San Nicolas de Hidalgo, Av. San Juanito Itzicuaros s/n, Morelia, 58195, Mexico
- (65) Universidad Distrital Francisco José de Caldas, Carrera 5 Este N° 15-82, Bogotá, 4000, Colombia
- (66) Department of Geosciences and Geography, University of Helsinki, Gustaf Hällströmin katu 2, Helsinki, 00014, Finland

- (67) Finnish Meteorological Institute, FMI, P.O. Box 503, Helsinki, FI-00101, Finland
- (68) Department of Physical Geography and Ecosystem Science, Lund University, Lund, 22362, Sweden
- (69) College of African Wildlife Management, Mweka, P. O. Box, Moshi, 3031, Tanzania
- (70) CREAM, Cerdanyola del Vallès, Barcelona, Catalonia, 08193, Spain
- (71) Universitat Autònoma de Barcelona, Bellaterra (Cerdanyola del Vallès), Catalonia, E08193, Spain
- (72) Atmospheric Sciences and Global Change Division, Pacific Northwest National Lab, PO Box 999, Richland, WA, 99352, USA
- (73) School of Biological Sciences, Washington State University, PO Box 644236, Pullman, WA, 99164-4236, USA
- (74) Botany, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland
- (75) Royal Botanic Garden Edinburgh, 20A Inverleith Row, Edinburgh, EH5 3RL, UK
- (76) Research Center for Advanced Science and Technology, University of Tokyo, 4-6-1 Komaba, Meguro, Tokyo, 153-8904, Japan
- (77) Forestry Department of Peninsular Malaysia (JPSM), State Project Management Office (SPMO) Selangor SMPEM Project, Pejabat Pembangunan Dan Latihan Perhutanan Sungai Buloh, KM21, Jalan Subang, Sungai Buloh, Selangor, 47000, Malaysia
- (78) Eberswalde University for Sustainable Development, Schicklerstrasse 5, Eberswalde, 16225, Germany
- (79) Department of Ecology and Genetics, Uppsala University, Kåbovägen 4 house 7, Uppsala, 75236, Sweden
- (80) Instituto de Ecología, A.C.-Centro Regional del Bajío, Red de Diversidad Biológica del Occidente Mexicano, Pátzcuaro, 61600, Mexico
- (81) Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT), Mexico City, 03940, Mexico
- (82) Departamento de Ecologia, Instituto de Biociências, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves, 9500, Porto Alegre, 90650-001, Brazil
- (83) Department of forestry and renewable forest resources, Biotechnical Faculty, University of Ljubljana, Jamnikarjeva 101, Ljubljana, 1000, Slovenia
- (84) National Forestry Research-Development Institute, Bd. Eroilor 128, Voluntari, 077190, Romania
- (85) University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Mărăști Boulevard, Bucharest, 011464, Romania
- (86) Department of Renewable Resources, College of Natural and Applied Sciences, University of Alberta, 116 St and 85 Ave, Edmonton, AB, T6G 2R3, Canada
- (87) Reptile and Amphibian Program Sierra Leone (RAP-SL), 7 McCauley Str. Murray Town, Freetown, Sierra Leone
- (88) Estación Experimental de Zonas Áridas, Consejo Superior de Investigaciones Científicas, Carretera de Sacramento s/n, La Cañada, Almería, 04120, Spain
- (89) CSIC, Global Ecology Unit CREAM-CSIC-UAB, Bellaterra, Barcelona, Catalonia, 08193, Spain
- (90) School of Environment, Private Bag 92019, Auckland, 1142, New Zealand
- (91) School of Geography, University of Leeds, Leeds, LS2 9JT, UK
- (92) Biology Department, Faculty of Natural Sciences, Universidad del Rosario, Carrera 24 No. 63C-69, Bogotá, 111221, Colombia
- (93) Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Laboratório de Ecologia e Restauração Florestal, Av. Pádua Dias n 11, LCB, Piracicaba, 13418-900, Brazil
- (94) Institute of Biological Research Cluj, Branch of NIRDDBS, 48 Republicii St., Cluj-Napoca 400015, Romania
- (95) Soil Biology Laboratory (LABS), UEMA, Av. Lourenço Vieira da Silva 1000, Jardim São Cristovão, São Luís, MA, 65055-310, Brazil
- (96) Karlsruhe Institute of Technology, KIT-Campus Alpin, Kreuzteckbahnstrasse 19, Garmisch-Partenkirchen, 82467, Germany
- (97) Karlsruhe Institute of Technology, Institute of Geography and Geocology, Kaiserstrasse 12, Garmisch-Partenkirchen, 82467, Germany
- (98) Departamento de Ciencias de la Vida, Universidad de Alcalá, Grupo de Ecología y Restauración Forestal (FORECO), Alcalá de Henares, Madrid, 28805, Spain
- (99) Departamento de Geología, Geografía y Medio Ambiente, Universidad de Alcalá, Grupo de Investigación en Teledetección Ambiental, Alcalá de Henares, Madrid, 28801, Spain
- (100) Department of Biodiversity, Conservation and Attractions, Biodiversity and Conservation Science, 17 Dick Perry Ave, Kensington, WA, 6151, Australia
- (101) Departamento de Gestión Forestal y su Medio Ambiente, Universidad de Chile, Santiago, 8330015, Chile
- (102) Vicerrectoría de Investigación y Postgrado, Universidad de La Frontera, Avenida Francisco Salazar, Temuco, 01145, Chile
- (103) Thünen-Institute of Forest Ecosystems, Alfred-Möller-Str. 1, Eberswalde, 16225, Germany
- (104) Birmingham Institute of Forest Research (BIFoR), University of Birmingham, Birmingham, B15 2TT, UK
- (105) Institute of Botany and Landscape Ecology, University of Greifswald, Soldmannstr.15, Greifswald, 17489, Germany
- (106) Wageningen Environmental Research (WENR), Wageningen University and Research, Droevendaalsesteeg 3, Wageningen, 6708PB, The Netherlands
- (107) Institute of Forest Botany and Forest Zoology, Chair of Forest Botany, Technical University of Dresden, Piennner Str. 7, Tharandt, 01737, Germany
- (108) Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research – Atmospheric Environmental Research (IMK-IFU), Kreuzteckbahnstraße 19, Garmisch-Partenkirchen, 82467, Germany
- (109) Technical University of Munich, School of Life Sciences, Ecosystem Dynamics and Forest Management Group, Hans-Carl-von-Carlowitz-Platz 2, Freising, 85354, Germany
- (110) Berchtesgaden National Park, Doktorberg 6, Berchtesgaden, 83471, Germany
- (111) Natural Resources Institute Finland (Luke), Latokartanonkaari 9, Helsinki, 00790, Finland

- (112) Universidade do Estado de Santa Catarina, Av. Luiz de Camões 2090, Lages, 88520-000, Brazil
- (113) Research Institute for Nature and Forest (INBO), Havenlaan 88/73, Brussels, 1000, Belgium
- (114) University of Agriculture in Krakow, Al. Mickiewicza 21, Krakow, 31-120, Poland
- (115) Department of Geomatics, Forest Research Institute, Braci Leśnej 3 St., Sękocin Stary, Raszyn, 05-090, Poland
- (116) Institute of Lowland Forestry and Environment, University of Novi Sad, Antona Cehova 13d, Novi Sad, 21102, Serbia
- (117) Faculty of Forestry and Wood Sciences, Czech University of Life Sciences, Kamycka 129, Praha 6, Suchbát, 16521, Czech Republic
- (118) ISEM CNRS Univ. Montpellier, Pl. E. Bataillon, Montpellier, 34090, France
- (119) CEF UQAM, Av. Président Kennedy 141, Montreal, QC, H2X 1Y4, Canada
- (120) Ecosystems and Global Change Group, School of the Environment, Trent University, 1600 West Bank Dr., Peterborough, ON, K9L 0G2, Canada
- (121) Faculty of Forestry and Environmental Management, University of New Brunswick, 28 Dineen Dr., Fredericton, E3B 5A3, Canada
- (122) Re.green, Juliano Bellini Road, Piracicaba, 13427-226, Brazil
- (123) DISAA - Università di Milano, via Celoria 2, Milan, 20133, Italy
- (124) Department of Forest Engineering, Universidade Regional de Blumenau, Rua São Paulo 3250, Blumenau, 89030-000, Brazil
- (125) Mediterranean Center for Environmental Studies (CEAM Foundation), Joint Research Unit University of Alicante-CEAM,

- University of Alicante, Sant Vicent del Raspeig, Alicante, 03690, Spain
- (126) Department of Ecology, University of Alicante, Sant Vicent del Raspeig, Alicante, 03690, Spain
- (127) Wildlife Conservation Society (WCS), 2300 Southern Boulevard, Bronx, NY, 10460, USA
- (128) Manaaki Whenua – Landcare Research, 74 Gerald St., Lincoln, 7608, New Zealand
- (129) High Meadows Environmental Institute, Princeton University, Princeton, NJ, 08544, USA
- (130) Universidade Regional de Blumenau, Rua São Paulo 3250, Blumenau, 89030-000, Brazil
- (131) Department of Biological and Environmental Sciences, University of Gothenburg, Gothenburg, Box 100, Gothenburg, 40530, Sweden
- (132) Forest Global Earth Observatory, Smithsonian Tropical Research Institute, West Loading Dock MRC-166, 10<sup>th</sup> and Constitution Ave, NW Washington, DC, 20560, USA
- (133) Universidade Tecnológica Federal do Paraná (UTFPR), Boa-Esperança Road, 4<sup>th</sup> Kilometer, Municipality of Dois Vizinhos, State of Paraná, 85660-000, Brazil
- (134) Chair of Forest Growth and Woody Biomass Production, TU Dresden, Dresden, 01062, Germany

**Key words:** disturbance, forest inventory, forest monitoring, remote sensing, tree dieback.

Received, 9 January 2024; accepted, 24 November 2024.

Disclaimer: The New Phytologist Foundation remains neutral with regard to jurisdictional claims in maps and in any institutional affiliations.