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

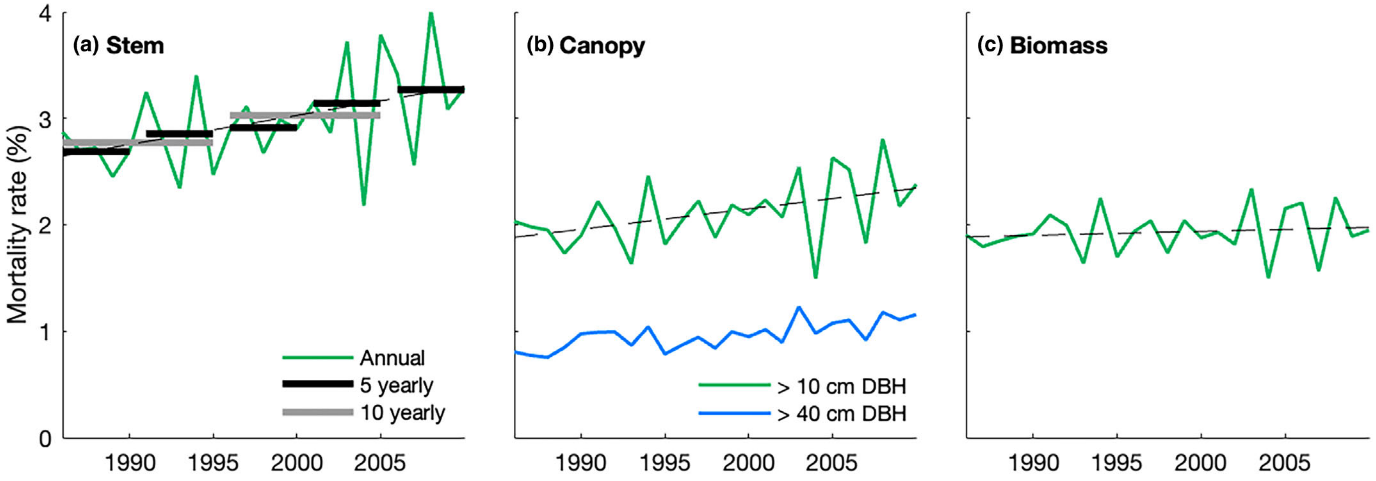


Fig. 1 Different indicators and aggregations of mortality rates can give very different impressions of the dynamics they describe. (a) Stem mortality rates can vary substantially from year to year, information which is lost in the 5- or 10-yr aggregations typically used in ground-based inventories. Shown 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^{-1}, 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).

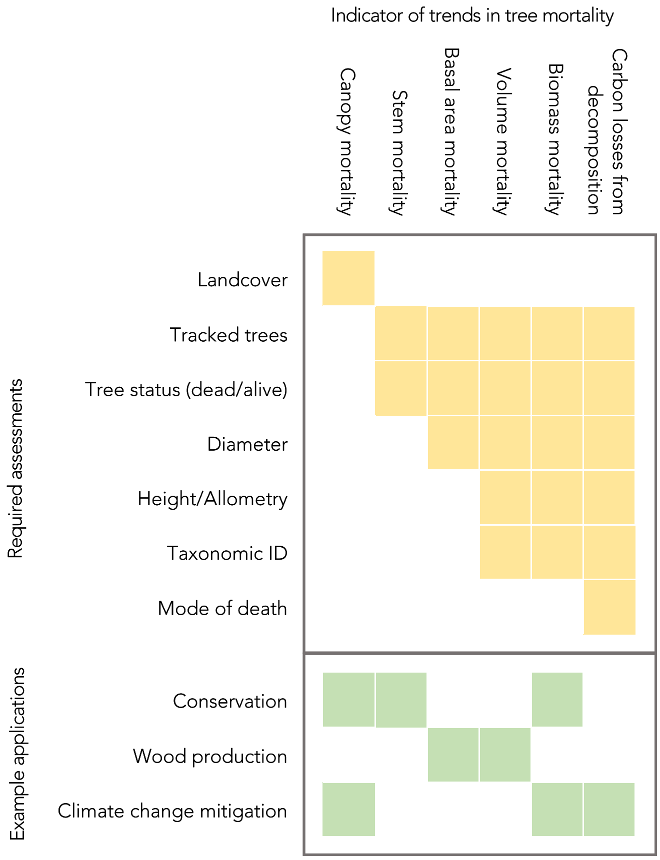
forest structure, composition or mortality, as well as in relating the observed changes to ground-based monitoring (Fig. 1). Bringing together diverse efforts and protocols across platforms, alongside filling geographical gaps in monitoring efforts, remains a large, yet resolvable, challenge (Zweifel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



Indicator of trends in tree mortality

		Canopy mortality	Stem mortality	Basal area mortality	Volume mortality	Biomass mortality	Carbon losses from decomposition
Required assessments	Landcover	🟨					
	Tracked trees		🟨	🟨	🟨	🟨	🟨
	Tree status (dead/alive)		🟨	🟨	🟨	🟨	🟨
	Diameter			🟨	🟨	🟨	🟨
	Height/Allometry				🟨	🟨	🟨
	Taxonomic ID				🟨	🟨	🟨
	Mode of death						🟨
Example applications	Conservation	🟩	🟩			🟩	
	Wood production			🟩	🟩		
	Climate change mitigation	🟩				🟩	🟩

Fig. 2 Minimum requirements for assessing different indicators of trends in tree mortality and applications of each indicator. Coloured squares represent the requirement of these measurements for the trend of interest. Decomposition is included because of its carbon cycle implications, where mode of death (e.g. standing, fallen and harvested) is key.

Monitoring of defoliation, insect and pathogen occurrence and management actions provide insights into drivers of trends, as does association with high-quality meteorological observations. All this information needs to be brought together at a spatial scale that is fine enough to have tree-scale relevance, but coarse enough to allow assessments at a global scale. An idealised monitoring scheme that can both assess trends in tree mortality and facilitate attribution of causes and drivers must comprise:

(**1**) A continuous time series with at least 5-yearly resolution of status of individual trees (alive/dead) paired with more frequent complementary observations at annual resolution. Annual resolution allows to link mortality to climatic events with much greater certainty than 5–10-yr intervals, greatly improving attribution. It also improves the quality of assessments in point number 5 below and crucially allows timely identification of changes in mortality rates.

(**2**) Representativeness across both geographical and environmental gradients (e.g. topography) to enable characterisation at the landscape scale and up.

(**3**) Identification of species and structural characteristics (diameter and biomass) of surviving and dead individuals. This information is crucial to calculate indicators beyond stem mortality (point number 4) and to diagnose which types and sizes of trees are most being affected.

(**4**) Multiple indicators of mortality to support different applications (Fig. 2).

(**5**) Information on the mode of death. At its most basic level, this should cover whether a tree died standing, broken, uprooted or was harvested. This information in combination with assessment of the presence of charcoal may allow for the attribution of potential causes of death, such as droughts, fires and storms.

(**6**) Standardising the above points 1 through 5 across the globe and making the observations rapidly accessible to scientists and the wider public.

Whilst annual field surveys clearly bring benefits in terms of attributing mortality to drivers (Das *et al*., 2016; Arellano *et al*., 2021), the labour-intensiveness of such surveys makes them unpractical at scale in the real world. We assess that a 5-yr time resolution is not unrealistically intensive, being already applied in many national surveys (Fridman *et al*., 2014; Talarczyk, 2014); but it allows for reasonably timely identification of death. Complementary approaches to provide annual information paired to the full assessment include: (1) annual mortality and disturbance agents assessments on a subset of plots, for example as applied by ICP Forests across Europe (Ferretti, 2013), or targeting a subset of trees, as applied by ForestGEO (Arellano *et al*., 2021); (2) remote sensing assessments of the individual plots, possibly linked to targeted sampling following periods of stress; or (3) scheduling of re-censuses such that 20% of plots, broadly distributed across the monitored region, are revisited each year (Fridman *et al*., 2014; Talarczyk, 2014). An effective global dissemination system for results, such as that now available for deforestation (www.globalforestwatch.org), is also required, such that the latest knowledge from science can quickly be disseminated to society and to inform national and international policy decision-makers governing the future of the world's forests.

Currently available global ground-based monitoring

A comprehensive assessment of the current state of long-term forest monitoring data is the first step towards contextualising the currently available global understanding of trends in tree mortality. This includes assessing the potential, and limitations, of existing *in situ* forest monitoring initiatives to quantify changes in tree mortality over time. To achieve this goal, we conducted an online survey among foresters and researchers, distributed through the International Tree Mortality Network (https://www.tree-mortality.net) and social media. The survey provided us with methodological information and metadata on where and how tree mortality has been monitored across the globe. We also actively searched for plot networks and approached people individually to respond to the questionnaire, as well as adding information on NFIs where they are available online.

After filtering for duplicates and entries with missing information on the number of plots or plot size, our survey had a total of 316 entries from 89 countries on all forested continents. The total number of sampling sites was 466 865, and the total sampling site area covered by all monitoring networks together was > 40 500 ha

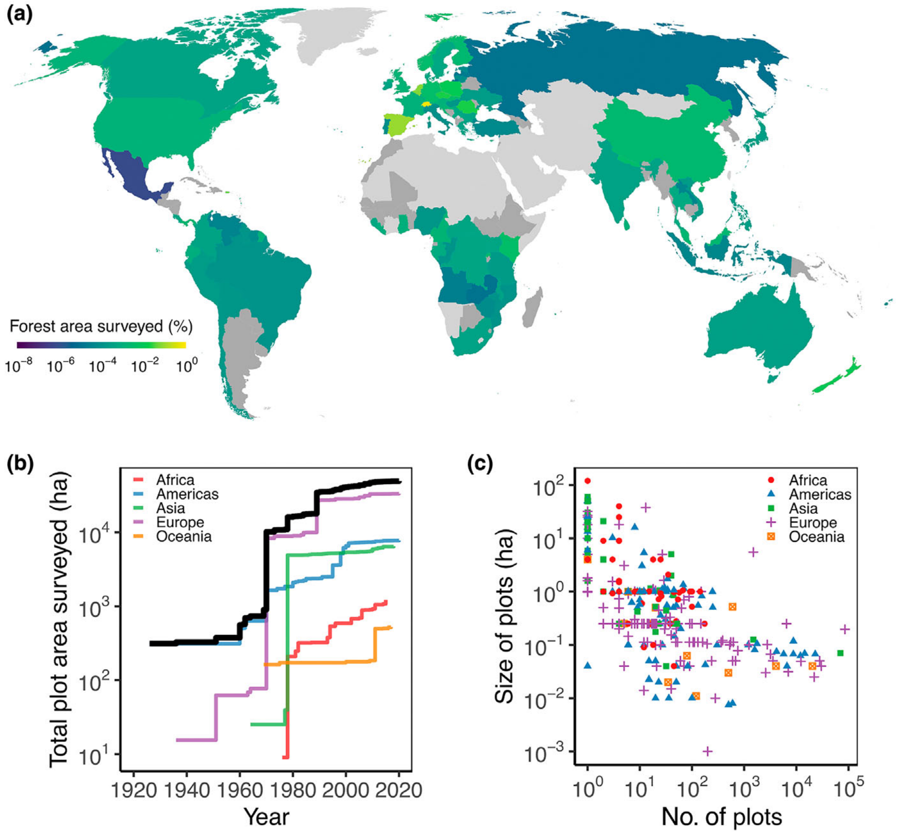


Fig. 3 Summary of the spatial and temporal coverage of forest plots according to our survey of global mortality monitoring plots: (a) percent of the total forest area surveyed per country, (b) plot area surveyed over time for different continents and globally (black line), and (c) the distribution of 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 drivers/causes of mortality. For instance, assessing additional plot-level variables, such as signs of management or biotic damage, would be quicker than collecting detailed tree-level variables, whilst still providing important information on trends in forest condition (Hartmann *et al.*, 2018b). Such methods are already well documented in protocols employed by some agencies (Pollard, 2006).

In regions without regular national forest assessment programmes, our survey often identified substantial numbers of research plots. Developing cooperation between researchers who manage these plots, who often study distinct topics, can provide powerful information, even if their research does not address systematic sampling in space. Initiatives, such as ForestPlots.net (ForestPlots.net *et al.*, 2021), the Tropical managed Forests Observatory (TmFO) (Sist *et al.*, 2015) and ForestGEO (Anderson-Teixeira *et al.*, 2015) that connect researchers to facilitate standardising protocols and metadata and to curate data, provide examples of how to fill major data gaps in mortality trends (Hubau *et al.*, 2020). Many such plots exist with one or two censuses as a basis for mortality estimations. Where plot locations have been recorded accurately, prioritising remeasurement of these plots, with protocols appropriate for capturing mortality, could dramatically increase the area under observation for mortality trends. In some regions, new plots must be established. The costs of establishing new intensive monitoring campaigns could be offset by integration with remote sensing or targeted sampling approaches to reduce the required intensity of ground sampling, particularly in tropical regions where fieldwork is more challenging (see the 'Bringing it all together – data integration across scales' section). Even where new NFIs are currently being established, research plots remain crucial because of their long-term record, often stretching back decades (Phillips & Gentry, 1994; ForestPlots.net *et al.*, 2021), which provide necessary context for the rates that are observed in the present day. However, relying on these research plots raises questions of research equity and the fair share of research rewards (see the 'A comprehensive and fair global network' section).

The role of remote sensing

Remote sensing is often seen as a promising tool for filling gaps in monitoring tree mortality (Hartmann *et al.*, 2018a). This applies especially to satellite remote sensing systems, which can provide consistent and spatially explicit information on land cover (including trees) from anywhere around the world. Yet, there are often misconceptions around what most remote sensing systems actually measure with respect to tree mortality. First and foremost, most satellite remote sensing systems provide a bird's-eye view on trees. That is, they only give information on changes in canopy trees and – with some exceptions explained below – not on the full cohort of trees within a stand. Second, most satellite remote sensing systems record changes in spectral reflectance over time. Whilst this can serve as a proxy for tree vitality (Buras *et al.*, 2020), they do not directly measure tree mortality, and models translating the changes in spectral reflectance properties into measures of tree mortality are needed. However, those models require proper calibration and validation (Senf *et al.*, 2017; Cotrozzi, 2022). Third, most satellite remote sensing systems provide an aggregated signal at a spatial grain coarser than individual trees (typically 10–100 m), which makes it challenging to relate the state of individual trees to the signal recorded by the sensor. Due to those limitations, trends derived from satellite remote sensing represent total canopy cover loss rather than trends in mortality of individual trees (Fig. 1). This can challenge communication between remote sensing scientists and users of remote sensing products. Nevertheless, thanks to the outstandingly long and free-to-access archives of national space agencies (Wulder *et al.*, 2022), mapping trends in tree cover loss is operational globally (Hansen *et al.*, 2013). Many ongoing changes in forest, such as increased natural disturbances or illegal logging, would thus remain undetected without the broad-scale view provided by satellite remote sensing. This applies especially to spatial patterns of tree canopy change (e.g. patch-size distributions; Jucker, 2022), which cannot be characterised well with plot-based inventories.

Novel remote sensing data and technologies enable increasingly detailed analyses that might become operational in the future. For example, commercial satellite data providers operate a series of satellites with passive optical sensors of high (< 5 m) and very high (< 1 m) spatial resolution, which have potential for detecting individual tree loss (Guo *et al.*, 2007; Meddens *et al.*, 2011; Brodrick & Asner, 2017). The most prominent example of this kind of data comes from the Planet missions, from which mosaics for the entire tropics were recently made available through Norway's International Climate and Forest Initiative (https://www.nicfi.no). Yet, despite a finer spatial resolution, those systems suffer from the same drawbacks as coarser sensor systems relying on reflectance in the optical wavelength region: they only provide information on trees in the forest canopy and models are required to map spectral changes to actual tree mortality. Remote sensing systems and technologies like Light Detection And Ranging (LiDAR) can overcome some of those challenges, enabling assessment of changes in canopy structure following tree death directly (Dalagnol *et al.*, 2021; Cushman *et al.*, 2022; Huertas *et al.*, 2022). However, repeated LiDAR surveys are costly and limited in their spatial extent due to the need for aircrafts or uncrewed aerial vehicles (UAVs). An operational global monitoring of tree mortality at the individual tree or biomass level would thus require major investment into data acquisition (e.g. global repeated aerial LiDAR campaigns), which might be complemented by novel spaceborne systems, such as from the Global Ecosystem Dynamics Investigation (GEDI) mission.

Bringing it all together – data integration across scales

The development of a monitoring system for tree mortality will depend on whether we can successfully integrate the existing wealth of data from different sources and scales, both temporal and spatial. This includes harmonising different sources of ground data, and integrating ground and remote sensing data. Process-based forest models may help this integration take place.

A consistent meta-network Sampling designs and field measurement protocols for monitoring tree mortality differ among networks and monitoring programmes (e.g. ForestGEO and 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 (Beloiu *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; Dokoohaki *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; Báldi & 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.

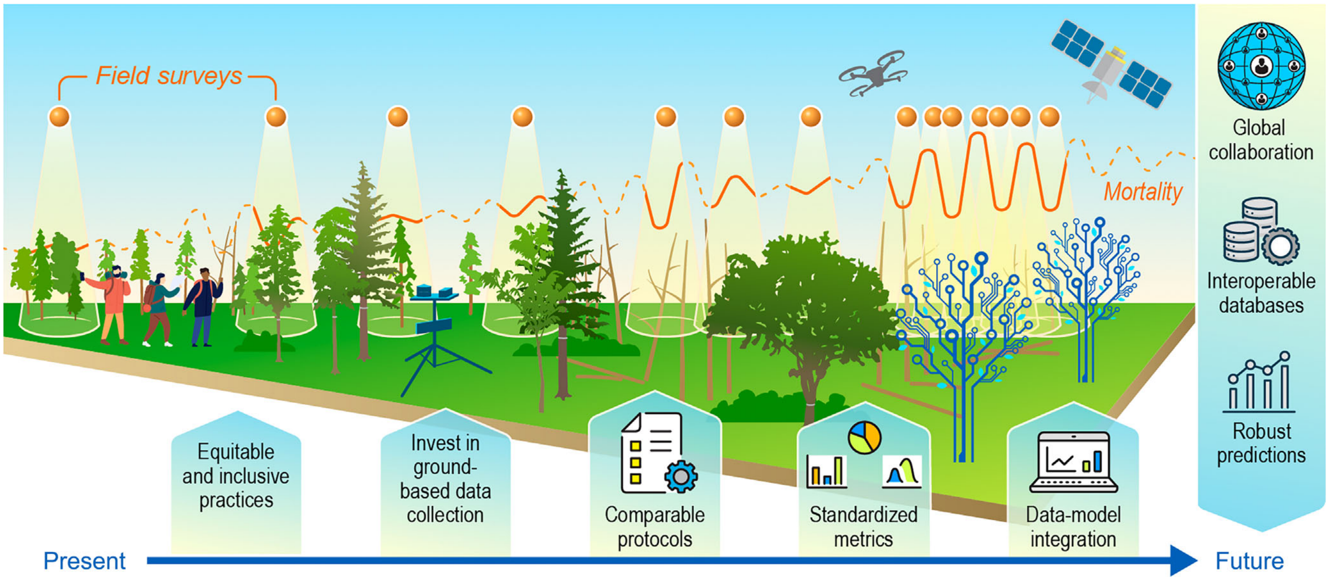


Fig. 4 Roadmap towards a global understanding of tree mortality. The five major steps integrate long-term field data with remote sensing and modelling techniques to build a fair, diverse and equitable system to monitor tree mortality at global scales. At its core, this system is built in a progressive 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 (Bruelheide *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.

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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.

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