Meetings

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'

International and interdisciplinary meeting on tree mortality, Herrenhausen castle, Hanover, Germany June 2017

From the 21st to the 23rd June 2017, the Herrenhausen castle in Hannover/Germany hosted a diverse and large crowd with more than 70 tree physiologists, forest ecologists, forest inventory experts, remote-sensing scientists, and vegetation modelers. Participants from six continents and from more than 20 countries gathered to discuss how to improve the scientific determination of global-scale patterns, drivers, and trends of a threatening phenomenon: the apparent emergence of recent widespread tree mortality events in diverse forests around the world.

Continuing the theme of a workshop held at the Max-Planck Institute for Biogeochemistry in Jena (Germany) in 2014 (Hartmann *et al.*, 2015), the Hanover meeting intended to develop approaches, tools and collaborative actions to accelerate progress in addressing regional patterns and trends of tree mortality (Williams *et al.*, 2013). Over the last decade climate change related tree mortality events have been increasingly reported around the globe (van Mantgem *et al.*, 2009; Carnicer *et al.*, 2011; Peng *et al.*, 2011; Brienen *et al.*, 2015), but to what degree this is a global trend, amplifying under increasing climate change, remains uncertain.

Why study global tree mortality patterns now?

Tree and forest mortality have been of interest to researchers for decades. Some work on forest decline reaches back to 1909, and in the 1980s the German phrase 'Waldsterben' became internationally acknowledged for reporting the decline and death of forests in Central Europe. By the 1970s and 1980s, forest decline research was being conducted in Europe, North America, Hawaii, New Zealand and Australia, including assessments of physical destruction and physiological decline caused by abiotic stress, biotic disease/pathogens and tree population demography (e.g. Mueller-Dombois, 1987). One of the pioneers of tree mortality research, Dieter Mueller-Dombois, was a guest of honour at the Hanover meeting and he provided guidance for the current initiative for global forest monitoring.

While global forest growth assessments have been carried out (Pan *et al.*, 2011), no study has attempted to generate spatially-explicit models of global tree mortality, which are necessary to generate a mechanistic understanding and to robustly quantify mortality at a global scale. The current initiative can build upon: (1) an increasing amount of data on forest ecosystems, including national forest inventories and monitoring, as well as an increasing number of research plot networks in all forested biomes; (2) a growing willingness of scientists and governmental agencies to openly share data; and (3) a greater availability of powerful tools for assessing and monitoring forests at broad spatial scales, such as remote-sensing products from satellites or airborne LIDAR. Despite this progress, current monitoring approaches are still incomplete in their spatial extent and data resolution is often inadequate for detecting scattered individual tree mortality and for identifying causal relationships between drivers of change in forest condition (McDowell *et al.*, 2015).

Tree mortality and forest health

Forest (ecosystem) health is a difficult concept. Although the term is widely used in environmental sciences (> 3600 articles listed in *Web of Science®* since 2000) for populations and communities, we propose that health in its strictest sense is defined at the scale of an individual as the absence of disease. Common definitions of forest or ecosystem health are usually utilitarian and describe management targets or reference conditions related to human needs or the persistence of forest types within a given landscape (Kolb *et al.*, 1995). Other definitions analogize ecosystem health to human health by setting thresholds for 'healthy' conditions based on 'ill' characteristics (Schaeffer *et al.*, 1988), i.e. health outcomes of a group of individuals measured as morbidity (loss of life quality due to disease) and mortality (frequency of death) (Kindig & Stoddart, 2003). As morbidity cannot be objectively assessed for trees, non-normal (i.e. increasing) mortality rates are likely to be the most robust indicator of forest health; however, identifying deviations from normal background mortality rates requires the long-term monitoring of forest ecosystems (Trumbore *et al.*, 2015).

Interdisciplinarity is the key to faster progress in global forest monitoring of tree mortality

Tree mortality is a complex process, involving a whole suite of interacting biotic and abiotic factors (Manion, 1991). Given the interdisciplinary nature of tree mortality and forest die-off, the workshop brought together scientists from four larger research areas covering different aspects of climate change-driven global tree mortality, namely physiological mechanisms of mortality, forest inventory, remote sensing and modelling (Fig. 1). A major goal was to encourage interdisciplinary thinking and to initiate concrete networking activities that might enable us to assess the conditions that lead to predictable global patterns of tree mortality. Keynote talks by Craig Allen, William Anderegg, Andreas Bolte, Matt Hanson and Belinda Medlyn highlighted major challenges in global tree and forest mortality assessments and in the attribution of causality. A keynote from these talks was that a more robust determination of patterns and trends in forest condition and tree mortality increasingly requires several disciplines to interact and willingly share data and knowledge.

Particular emphasis has been placed on the importance of real-time monitoring of forest condition. Global Forest Watch (GFW, http://www.globalforestwatch.org/map; Hansen *et al.*, 2013) uses global remote sensing data (Landsat) and powerful distributed computing approaches to determine annual changes in global forest cover, as well as near-real time monitoring in some deforestation hotspots. Attribution of causality is currently limited to spatially-aggregated direct causes of mortality, such as wildfires, land-use change, forest harvest, or broad-scale disease and insect damage (Fig. 2). The GFW method finds substantial amounts of spatially-diffuse, fine-scale tree cover loss (mortality) that is currently not attributed. This loss is likely to be, at least partially, tree mortality due to climatic changes (e.g. warming or drought) indicative of a major long-term threat to current forests (Allen *et al.*, 2015).

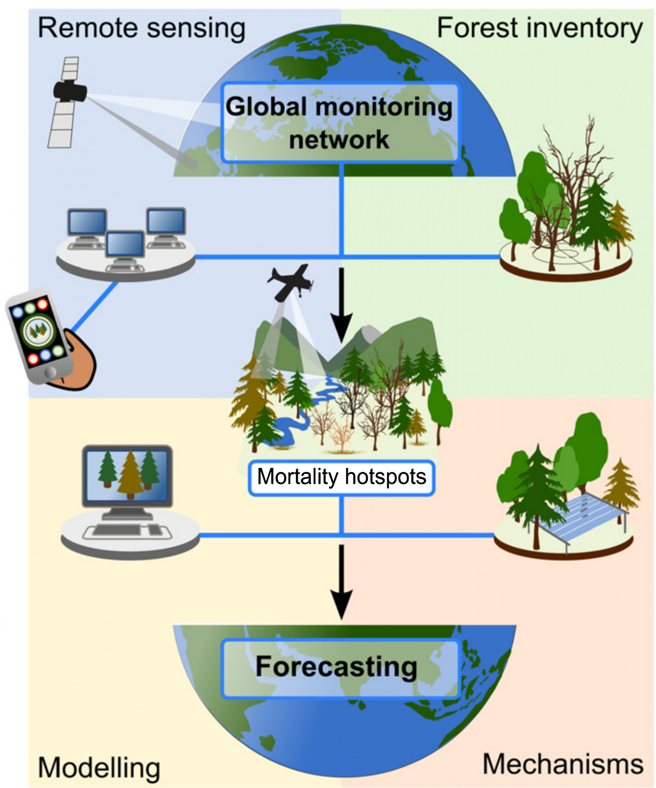

Fig. 1 Strategy for a global assessment of forest condition. An integrated multidisciplinary global monitoring network quantifies background tree mortality and identifies hotspots of intensive tree mortality, based on satellite data, LIDAR cruises, and merged data sources including forest inventories, research plots and citizen science. The mortality hotspots can guide the siting of intensive field observations and experiments to establish improved mechanistic relationships in vegetation models for more realistic projections of future forest conditions.

During a series of breakout sessions, workshop participants discussed research gaps and needs among and across disciplines, with the overarching goal of developing a joint strategy for a global monitoring network. This interdisciplinary strategy aims (Fig. 1) to: (1) quantify patterns and trends of both diffuse background tree mortality rates and also identify and attribute forest die-off (e.g. regionally-widespread mortality) hotspots that cannot be explained by wildfires, land-use change, forest harvest or epidemic insect outbreaks by using (1a) remote-sensing products like multi-spectral satellite data and LIDAR and (1b) merged data sources from forest inventories, research plot data and additional information from public sources ('citizen science'). In such die-off hotspots, (2) drivers of mortality can then be derived via combinations of empirical modelling of monitored broad-scale tree mortality patterns relative to landscape characteristics and climatic variability, as is done in intensive long-term field observations (e.g. International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests, ICP forests). Furthermore, mechanistic relationships between these drivers and tree mortality can be derived from field and glasshouse manipulations in affected ecosystems. Take together, these multidisciplinary approaches will provide improved knowledge of tree mortality mechanisms for refining current broad-scale vegetation-climate models (e.g. Dynamic Global Vegetation Models, DGVMs and Earth System Models, ESMs), with the ultimate goal of (3) achieving information about the demographic variability of forest mortality and more realistic projections of future forest condition under ongoing climate change.

A global monitoring network of tree mortality – laying the foundation

The idea of a global monitoring network of tree mortality is not new and has been proposed in several earlier publications (e.g. Allen *et al.*, 2010; Hartmann *et al.*, 2015; Trumbore *et al.*, 2015). But in contrast to previous efforts, this workshop has already led to several concrete actions toward the implementation of this idea as a formal global initiative. These include: (1) an on-line metadata collection (http://www.tree-mortality.net/) will provide information on small- and large-scale forest monitoring networks by bringing together multiple-plot networks like ICP Forests or ForestGEO that feature a large number of plots using standardized protocols. This data compilation will be used for ground-truthing of remote-sensing data and will provide a frequently updated global tree mortality event map fed by remote sensing and citizen science. Furthermore, the network (2) envisions a structural integration into existing organizations of global forest research networks, for example as a new section of the International Union of Forest Research Organizations (IUFRO). Several working groups created during the workshop will join efforts in (3) developing methods and protocols for monitoring mortality that acknowledge the current limitations of uneven *in situ* monitoring networks and of

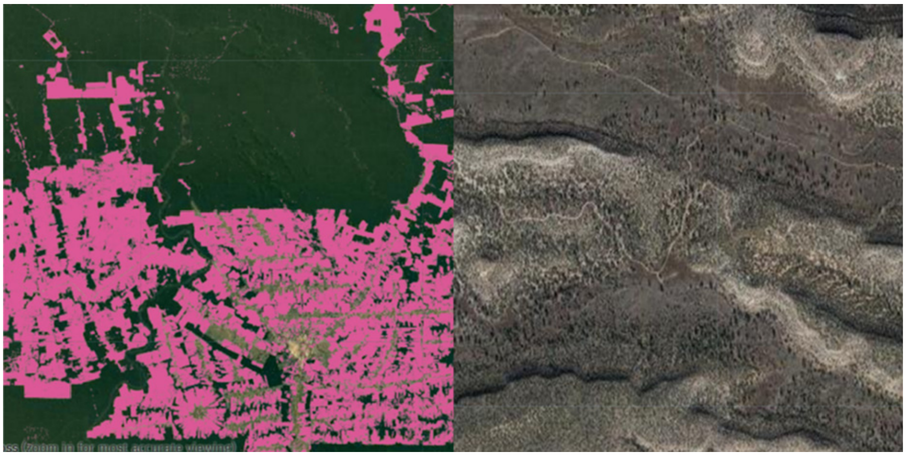

Fig. 2 Change in forest cover (pink areas) as shown on the Global Forest Watch (GFW) interactive map (left panel); patchy deforestation with land-use change in Brazil is easily detected by algorithms analyzing Landsat images with 30 × 30 m pixel resolution. However, a high level of more diffuse 'hazy' mortality (> 90% of the co-dominant tree species) at a semi-arid woodland site near Los Alamos, New Mexico, USA, due to a global change-type hotter drought (Breshears *et al.*, 2005) was not detected by the GFW algorithms (right panel), likely to due in part to resolution-related challenges (Garrity *et al.*, 2013). Additional data sources may be required to identify such mortality hotspots.

current remote sensing-based techniques of the attribution of tree cover loss and detection of individual mortality events. Presented in (4) a multidisciplinary strategy paper this agenda will help drafting and securing funding for activities like the hosting of merged data from multiple national forest inventories, international forest monitoring networks and research plot data. In addition, (5) several promising collaborative efforts to share data on forest condition at the global scale have been initiated (e.g. the Global Forest Biodiversity Initiative (GFBI), http://www.gfbinitiative.org/) and have been further consolidated during the inaugural GFBI conference that was held in Beijing, China, on 6–9 September 2017. With the data from 1.2 million forest inventory plots now compiled and online (cf. Crowther *et al.*, 2015; Liang *et al.*, 2016), including information about tree density, size and species composition across multiple years, we will be able to examine current global patterns in tree mortality. Understanding the mechanisms underlying these global mortality patterns will then require them to be linked directly to climate and biophysical characteristics across the global forest landscape.

The future of the network depends on motivated scientists with a strong vision

Establishing a global monitoring network of tree mortality is a challenging task requiring long-term commitment. Obstacles will have to be overcome, ranging from scientific (e.g. designing of common protocols, integration of different data sources) and organizational (e.g. securing funding, long-term maintenance of database) to methodological (e.g. implementation and development) challenges. Although efforts to initiate such a network have now begun, its complete implementation may require years of devotion and endurance. However, workshop participants were well prepared for the task, as a quote from the workshop boldly underscored: 'With ongoing missions to study the moon and Mars, we may soon understand these astronomical bodies better than the most important ecosystem of our planet – forests. It's about time to change that!'

Please join us at: http://www.tree-mortality.net/. The website will allow you to sign up for upcoming activities and to contribute to the network.

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References

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, Vennetier 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.

Breshears DD, Cobb NS, Rich PM, Price KP, Allen CD, Balice RG, Romme WH, Kastens JH, Floyd ML, Belnap J *et al.* 2005. Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences, USA* **102**: 15144–15148.

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.

Carnicer J, Coll M, Ninyerola M, Pons X, Sanchez G, Penuelas J. 2011. Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. *Proceedings of the National Academy of Sciences, USA* **108**: 1474–1478.

Crowther TW, Glick HB, Covey KR, Bettigole C, Maynard DS, Thomas SM, Smith JR, Hintler G, Duguid MC, Amatulli G *et al.* 2015. Mapping tree density at a global scale. *Nature* **525**: 201–205.

Garrity SR, Allen CD, Brumby SP, Gangodagamage C, McDowell NG, Cai DM. 2013. Quantifying tree mortality in a mixed species woodland using multitemporal high spatial resolution satellite imagery. *Remote Sensing of Environment* **129**: 54–65.

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 21st-century forest cover change. *Science* **342**: 850–853.

Hartmann H, Adams HD, Anderegg WRL, Jansen S, Zeppel MJB. 2015. Research frontiers in drought-induced tree mortality: crossing scales and disciplines. *New Phytologist* **205**: 965–969.

Kindig D, Stoddart G. 2003. What is population health? *American Journal of Public Health* **93**: 380–383.

Kolb T, Wagner M, Covington W. 1995. *Forest health from different perspectives.* United States Department of Agriculture Forest Service general technical report RM: 5–13.

Liang J, Crowther TW, Picard N, Wiser S, Zhou M, Alberti G, Schulze E-D, McGuire AD, Bozzato F, Pretzsch H *et al.* 2016. Positive biodiversity-productivity relationship predominant in global forests. *Science* **354**: aaf8957.

Manion PD. 1991. *Tree disease concepts.* Engelwood Cliffs, NJ, USA: Prentice Hall.

van Mantgem PJ, Stephenson NL, Byrne JC, Daniels LD, Franklin JF, Fulé PZ, Harmon ME, Larson AJ, Smith JM, Taylor AH *et al.* 2009. Widespread increase of tree mortality rates in the Western United States. *Science* **323**: 521–524.

McDowell NG, Coops NC, Beck PSA, Chambers JQ, Gangodagamage C, Hicke JA, Huang CY, Kennedy R, Krofcheck DJ, Litvak M *et al.* 2015. Global satellite monitoring of climate-induced vegetation disturbances. *Trends in Plant Science* **20**: 114–123.

Mueller-Dombois D. 1987. Natural dieback in forests. *BioScience* **37**: 575–583.

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.

Peng C, Ma Z, Lei X, Zhu Q, Chen H, Wang W, Liu S, Li W, Fang X, Zhou X. 2011. A drought-induced pervasive increase in tree mortality across Canada's boreal forests. *Nature Climate Change* **1**: 467–471.

Schaeffer DJ, Herricks EE, Kerster HW. 1988. Ecosystem health: I. Measuring ecosystem health. *Environmental Management* **12**: 445–455.

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

Williams AP, Allen CD, Macalady AK, Griffin D, Woodhouse CA, Meko DM, Swetnam TW, Rauscher SA, Seager R, Grissino-Mayer HD. 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change* **3**: 292–297.

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