Increasing canopy mortality challenges the future of Europe's forests

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Abstract: Pulses of tree mortality have been reported for many ecosystems across the globe. Yet, large-scale trends in tree mortality remain poorly quantified. Manually analyzing more than 680,000 satellite image chips at 19,896 plot locations, we here show that forest canopy mortality in Europe has continuously increased since 1985 (+1.5 ± 0.28 % yr^{-1}), with the highest canopy mortality rate of the past 34 years observed in 2018 (1.14 ± 0.16 %). Using simulation modeling we further demonstrate that a continued increase in canopy mortality will largely alter forest demography, with the median forest age falling below 30 years in nearly half of Europe's countries by 2050. These demographic changes will have substantial cascading effects on the regeneration, biodiversity, and carbon storage. The current trend of increasing canopy mortality reported herein thus challenges the future of Europe's forests, and should be a key priority of forest policy and management.

Keywords: Tree mortality, disturbances, resilience, forest demography, Landsat

Introduction

Tree mortality is a key demographic process in forest ecosystems. It drives natural ecosystem dynamics and occurs at different spatial scales, from the level of individual trees (Franklin *et al.* 2002; Lutz and Halpern 2006) to large-scale pulses of mortality, referred to as disturbances (Turner 2010). In addition to natural causes of tree death (e.g., through resource limitation, wildfire or insect outbreaks), also human land-use and demand for biomass are globally important drivers of tree mortality (Curtis *et al.* 2018). Because trees are long-lived and regenerate slowly, tree mortality can shape the structure and functioning of forest ecosystems for decades to centuries (Anderegg *et al.* 2012). As such, it is important to understand rates and patterns of tree mortality from the individual to the global scale.

There is accumulating evidence that rates and patterns of tree mortality are changing in forest ecosystems around the globe, partly as a result of climate change, but also as a result of changes in human land-use (van Mantgem *et al.* 2009; Allen *et al.* 2010; Seidl *et al.* 2017). Large-scale changes in tree mortality can substantially alter forest ecosystems ecosystem services (Thom and Seidl 2016), forest ecosystems functions (Anderegg *et al.* 2012), and forest regeneration potential (Anderson-Teixeira *et al.* 2013), and ultimately shift the population structure towards younger trees (McDowell *et al.* 2020). As old forests are particularly important for biodiversity (Bengtsson *et al.* 2000) and carbon storage (Luyssaert *et al.* 2008), such a shift could have detrimental impacts on global forest ecosystems.

In Central Europe the proportion of forest canopy experiencing mortality has doubled over the last three decades (Senf *et al.* 2018), potentially impacting Europe's forests as described above. Yet, how representative such drastic regional changes are for continental-scale forest dynamics remains unclear, as consistent quantifications of forest mortality over large spatial and temporal extents remain missing. This limited quantitative understanding makes assessments of future forest development in Europe highly uncertain. We here address this knowledge gap by (1)

manually interpreting 680,000 satellite image chips at 19,896 plot locations covering 210 Mill. ha of forest area and a 34 years period from 1985 to 2018 to robustly quantify rates of and trends in canopy mortality for continental Europe; and by (2) applying simulation modeling to determine how trends in canopy mortality could affect the forest demography of Europe's forests.

Materials and Methods

Estimating canopy mortality rates

We used a stratified random sampling design to select plots for satellite image interpretation across continental Europe. Continental Europe here includes 35 countries (Table S1 and Figure S1) with a minimum land area of 10,000 km^2 (excluding Lichtenstein, Luxembourg, Monte Carlo and Malta). A plot was defined as a 30 * 30 m square corresponding to a Landsat satellite pixel. We used an equalized stratified sampling design, randomly placing 500 plots within forest areas of each country. We preferred an equalized stratified sampling design over a proportional sampling design as sampling proportional to forest area would have led to sampling sizes too large for manual interpretation in some countries (e.g., Finland), whereas only few samples would have been placed into others (e.g., Denmark). Forest areas were determined using an existing Landsat-based forest cover map that identifies all areas which have been forested at some point in time during the study period 1985 to 2018. Using a forest cover map for stratifying our sampling greatly improved sampling efficiency, but also led to selecting plots falsely identified as being forested. We excluded these plots during satellite image interpretation, leading to varying realized sample sizes per country (Table S1). Data for six countries (Austria, Czechia, Germany, Poland, Slovakia and Switzerland) were taken from a previous study (Senf *et al.* 2018), which used a similar sampling design but larger sample sizes. To avoid loss of information from down-sampling, we used the full sample sizes for those countries, but tested whether our results were consistent with smaller sample sizes (see Figure S10).

For each plot we manually interpreted temporal-spectral profiles of satellite imagery from the full Landsat satellite archive to assess whether a canopy mortality event occurred at this specific plot location at any given year of the study period. A canopy mortality event was defined as any loss of canopy (e.g., biotic natural disturbance, abiotic natural disturbance, regular timber harvest) that resulted in an identifiable change in the canopy's spectral reflectance properties. The interpreter thus makes an informed decision whether the spectral change was caused by a disturbance or mortality event, or is a result of clouds, noise, vegetation phenology or other ephemeral changes not related to structural changes of the forest canopy. Hence, the final measurement recorded for each plot and year is the presence or absence of a canopy mortality event. The interpretation closely follows a previously established response design (Senf *et al.* 2018), and more detailed information are given therein.

We estimated annual canopy turnover rates from the number of plots experiencing canopy mortality over the total number of plots sampled within each country. For doing so, we used a Bayesian partially pooled binomial model with a logit link function (Senf *et al.* 2018) implemented in Stan (Carpenter *et al.* 2017). The model includes a linear regression term with year as predictor, explicitly modeling fractional changes in mean canopy turnover rate over time (i.e., the temporal trend in canopy turnover). We first modeled annual canopy turnover rates and trends at the country level, subsequently aggregating to regions (Central-, Eastern-, Northern-, South-Eastern, Southern-, and Western-Europe; Fig. S1) and the continental level using forest cover as weight (Table S1).

Simulating future forest demography

We used neutral landscape models (NLM) to assess the impact of different future mortality trajectories on forest demography. We built NLM of random and clumped forests for each country using the NLRM package (Sciaini *et al.* 2018). The grain of the simulation was set to 1 ha (i.e., 100 times 100 meter), being close to the median patch size of natural mortality in temperate

Europe (Senf and Seidl 2018). The extent of the simulations was fixed at 100 km^2 (i.e., 10 * 10 km), resulting in 10,000 forest cells (hereafter called 'stand') being simulated per country. The proportion of forested stands was set to the average forest proportion of each country. We mapped forest age classes for the year 2015 to stands using reconstructed age class distributions from Vilén *et al.* 2012. For six countries, age class data were not available (Bosnia and Herzegovina, Greece, Serbia, Montenegro, Northern Macedonia, and Moldova), which restricted our analysis to 29 countries.

After initializing the landscape, we iteratively updated the age of each stand on a yearly basis (i.e., aging them by one year) over the period 2019-2050. The annual proportion of pixels experiencing mortality was drawn each year from the Bayesian partially pooled binomial model described above. To allocate mortality in space, we ranked each stands likelihood of being affected by mortality based on four alternative age-based mortality functions (Figure S2). Individual tree mortality is U-shaped over stand age, with high mortality risk in young trees (competition for resources, self-thinning) and old trees (hydraulic limitations, disturbances like wind and insects, timber harvesting). As individual tree mortality from competition between individual trees does not leave a strong signature in the forest canopy, we here only capture the latter causes of mortality, which is why we assumed monotonically increasing canopy mortality probability with age in our simulations. We assumed no recovery failure in our NLM, that is all stands regrew after a mortality event.

We used NLMs to study three scenarios (Figure S3): First, a stabilization of canopy mortality rates at the mean value observed for the period 1985 to 2018; Second, a stabilization of canopy mortality rates at values observed for 2018; And third, a further increase in canopy mortality at the country-specific trends observed for the past 34 years. In total we ran eight alternative NLM configurations per country (clumped/random landscape initialization times four alternative mortality functions) for three scenarios, which were replicated 15 times for each of the

29 countries, resulting in the analysis of 10,440 NLMs in total. From those NLMs, we derived the median age of forests within each country for the year 2050 and for the three scenarios as indicator of changes in forest demography.

Results and discussion

Trends in canopy mortality rates

Canopy mortality increased by 1.50 ± 0.28 % per year across Europe (Figure 1). The average canopy mortality rate in the late 20th century (1985 to 1999) was 0.79 ± 0.04 % yr^{-1} (i.e., a forest area of 1.7 Mill. ha affected by canopy mortality each year) and increased to 0.99 ± 0.04 % yr^{-1} (i.e., 2.1 Mill. ha) in the early 21st century (2000 to 2018). Mortality increased at an accelerating pace throughout the observation period, with the highest canopy mortality rate of the past 34 years observed for 2018 (1.14 ± 0.16 % yr^{-1}).

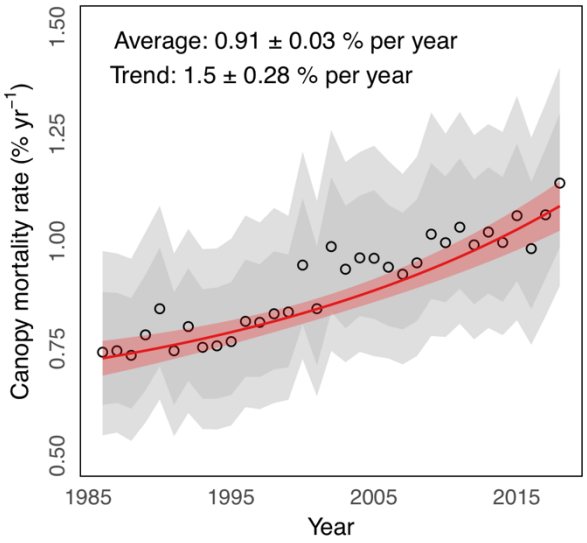

Fig. 1 Canopy mortality rates and trends for Europe's forests. Black circles indicate the mean continental-scale canopy mortality, with grey ribbons indicating the uncertainty range (darker hue = standard deviation; lighter hue = 90 % credible interval). The red line gives the mean temporal trend and its standard deviation.

Changes in canopy mortality varied substantially between countries and regions (Figure 2). Out of the 35 countries analyzed, 28 had a positive trend in canopy mortality (Figure 2; Table S2 and Figure S4). Trends were strongest in Central and Eastern Europe, where canopy mortality increased on average by 55 % and 78 % from the late 20th to the early 21st century. Weaker but nonetheless positive trends were found for Western and Northern Europe, where canopy mortality increased on average by 39 % and 19 % over the same period. No evidence for changes in canopy mortality could be found for South-West Europe, and evidence for increasing canopy mortality in South-East Europe was weak (Figure 2).

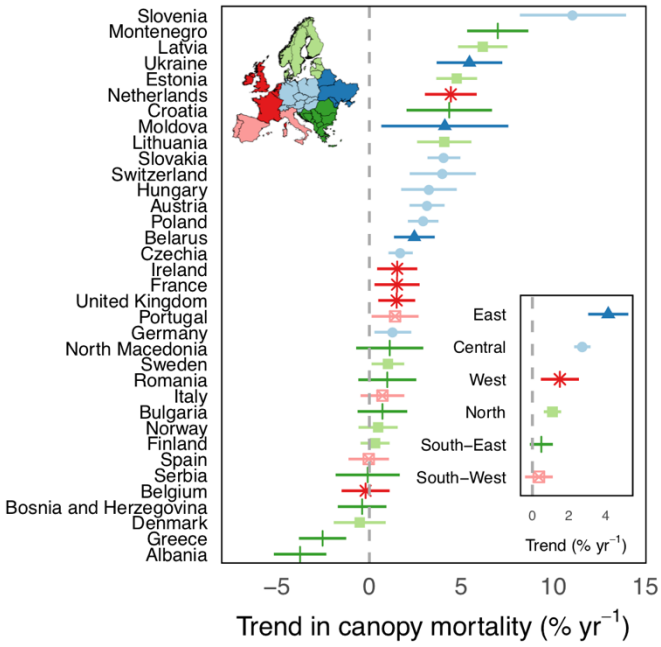

Fig. 2 Trends in canopy mortality at the country and regional level. Dots indicate the mean trend in canopy mortality, error-bars give the standard deviation. Colors indicate the assignment of countries to different regions (see inserts).

Drivers of increasing canopy mortality are manifold, interactive, and vary locally. While an in-depth analyses of these local drivers is beyond the scope of this study, we here discuss several coinciding continental-scale developments that are likely to contribute to the overall

increase in canopy mortality in Europe: First, large parts of Europe's forests have accumulated biomass in recent decades (Ciais *et al.* 2008), and many countries have started utilizing their growing timber resources more actively by increasing annual fellings (European Environmental Agency 2016). The notion that timber harvest is an important factor contributing to increasing canopy mortality is also supported by a high correlation with harvesting statistics (Figure S5 and S6). Human resource use is thus a major driver of current trends in canopy mortality identified for Europe's forests. Second, the collapse of the Soviet Union has led to large-scale transformations of economic and political systems in parts of Europe, resulting in a pronounced increase in both regular harvests and illegal logging (Kuemmerle *et al.* 2007). The particularly strong increase in canopy mortality rates observed for European countries of the former Soviet Union (Figure S4) can in part be explained by those historical legacies. Third, many forests across Europe have seen episodes of large-scale storm events and severe bark beetle outbreaks in recent decades (Seidl *et al.* 2014), which likely contribute to the particularly strong trends observed for Central and Eastern Europe. Hence, increased natural disturbances – a result of both structural legacies and climate change (Seidl *et al.* 2011) – can thus be considered an additional important driver of increasing canopy mortality trends. Increased tree mortality caused by drought has further been reported for Europe recently (Allen *et al.* 2010; Carnicer *et al.* 2011), and the particular high mortality rates observed for 2018 might be a consequence of drought. In this context it is interesting to note, however, that we did not find strong evidence for increasing canopy mortality in Southern Europe, despite the notion that warm and dry areas are particularly prone to drought induced forest diebacks (Allen *et al.* 2010) and increasing forest fires (Moriondo *et al.* 2006). Yet, drought induced forest dieback might be too dispersed to trigger substantial changes in canopy mortality measurable from satellite imagery (Hartmann *et al.* 2018), and while the number of fires in the Mediterranean has increased, the annual area burned has decreased in recent decades (see Figure S7). Finally, we like to note that only 2.6 % of the mortality events led to a change of land

use from forest to non-forest. That is, land use change is of relatively minor importance for canopy mortality in Europe.

Impacts of increasing forest canopy mortality on forest demography

We find widely varying demographic development trajectories with the three scenarios developed herein (Figure S8). A stabilization of canopy mortality at the level observed in the recent past (1985-2018) would not result in drastic demographic changes (Figure 3). This scenario in fact results in an increasing proportion of countries with large old forests (i.e., median forest age of 60 years or older) compared to the current situation. The aging trend found for Europe's forests thus overcompensates tree mortality effects on demography in this first scenario. Stabilizing canopy mortality rates at values observed for 2018, however, stops the aging trend of Europe's forests (Figure 3), leading to a stagnation of the current situation and an increase of countries with young forests (median age younger than 30 years). A continued increase in canopy mortality at rates as observed for the past 34 years would lead to considerably shifts in the age structure of Europe's forests (Figure 3). For instance, while the forests of only 14 % of European countries have a median age younger than 30 years today, this number increases to 48 % in 2050 if observed canopy mortality trends will continue. A continued increase in canopy mortality would thus inverse the current aging trend of Europe's forests.

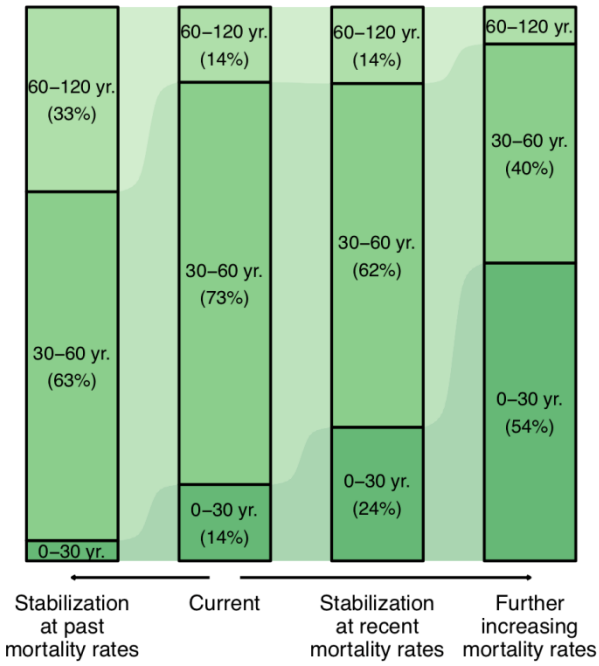

Fig. 3 Effects of changing canopy mortality rates on the median age of Europe's forests in 2050. The distribution of median ages of the forests of 29 European countries was simulated for the year 2050 under three scenarios (Figure S3): (1) Stabilization at canopy mortality rates observed between 1985 and 2018 (*Stabilization at past rates*); (2) Stabilization at canopy mortality rates observed for the year 2018 (*Stabilization at recent rates*); (3) Increasing canopy mortality rates extrapolating trends observed between 1985 and 2018 for each country (see Figure 2; *Further increasing canopy mortality rates*). The current condition shows the distribution of median ages in 2015. See Figure S9 for a sensitivity analysis of all combinations of landscape configuration types and mortality functions. See Figure S8 for a detailed representation of individual runs of the NLMs.

Changes in forest demography resulting from increasing canopy mortality have the potential to challenge the integrity of Europe's forests in three important ways. First, a shift towards young forests could result in considerable bottlenecks for the regeneration potential of forests due to decreasing seed availability and increased distance to seed sources (Anderson-Teixeira *et al.* 2013). Second, the prevalence of old forests will be substantially reduced under a

continued increase in canopy mortality. The shift towards younger forests will simultaneously reduce the diversity in age classes on the landscape, resulting in a biological homogenization of forest habitats (van der Plas *et al.* 2016). As both the prevalence of old forests and the diversity in developmental stages are important indicators of biodiversity (Bengtsson *et al.* 2000), a future increase in canopy mortality can have widespread negative consequences for forest biodiversity. Third, increasing canopy mortality reduces the residence time of carbon in forest ecosystems (Yu *et al.* 2019; Pugh *et al.* 2019), with negative impacts on the total carbon stored in forests (Körner 2017). Likewise, as old forests are hotspots of forest carbon storage and act as long-term carbon sinks (Zhou *et al.* 2006; Luyssaert *et al.* 2008), the loss of old forests under increasing canopy mortality rates further signifies a dampening of the carbon storage potential of Europe's forests. A continued increase in canopy mortality might hence offset potential C gains from accelerated tree growth under climate change (Yu *et al.* 2019).

Conclusion and management implications

Here we show that canopy mortality rates have increased consistently throughout the past 34 years in Europe, and that a further increase has the potential to substantially alter Europe's forest demography. It is of paramount importance for forest policy and management to counteract the ongoing trends in forest mortality and implement strategies to safeguard the integrity of Europe's forest ecosystems. This could be achieved via: (i) increasing the resistance and resilience of Europe's forests to natural disturbances by, e.g., counteracting biotic homogenization; (ii) conserve existing and creating future old-growth forests by establishing areas that are exempt from timber extraction, especially in places where the risk of natural disturbances is low; (iii) accounting for natural disturbances in long-term forest planning ; and (iv) considering constraints of age structure in managing forests for a bio-based economy. Developing strategies to address the increasing canopy mortality should be a key priority of forest policy and management in Europe.

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Author contributions

C. Senf and R. Seidl acquired the funding for the research project. C. Senf and R. Seidl conceptualized the research project. C. Senf and J. Sebald administrated the research project and curated the data acquisition. C. Senf conducted the formal data analysis. C. Senf wrote the original draft, with review and editing from J. Sebald and R. Seidl.

Competing interests

Authors declare no competing interests.

Data availability

All data collected for this manuscript is available under http://doi.org/10.5281/zenodo.3561925.