LETTERS
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# Increasing forest disturbances in Europe and their impact on carbon storage

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**Disturbances from wind, bark beetles and wildfires have increased in Europe's forests throughout the twentieth century[1]. Climatic changes were identified as a key driver behind this increase[2], yet how the expected continuation of climate change will affect Europe's forest disturbance regime remains unresolved. Increasing disturbances could strongly impact the forest carbon budget[3,4], and are suggested to contribute to the recently observed carbon sink saturation in Europe's forests[5]. Here we show that forest disturbance damage in Europe has continued to increase in the first decade of the twenty-first century. On the basis of an ensemble of climate change scenarios we find that damage from wind, bark beetles and forest fires is likely to increase further in coming decades, and estimate the rate of increase to be +0.91 x $10^6$ $m^3$ of timber per year until 2030. We show that this intensification can offset the effect of management strategies aiming to increase the forest carbon sink, and calculate the disturbance-related reduction of the carbon storage potential in Europe's forests to be 503.4 Tg C in 2021–2030. Our results highlight the considerable carbon cycle feedbacks of changing disturbance regimes, and underline that future forest policy and management will require a stronger focus on disturbance risk and resilience.**

Natural disturbances, that is, large pulses of tree mortality from agents such as wildfire, insect outbreaks or strong winds, are integral drivers of forest dynamics[6] and contribute to the diversity and adaptive capacity of ecosystems[7]. Yet, forest disturbance regimes have changed considerably in recent years. The frequency and severity of large wildfires, for instance, has increased around the globe in past decades[1,8,9]. In addition, recent bark beetle outbreaks, for example, in North America and Central Europe[10,11], have reached unprecedented levels. A continuation of this trend towards more frequent and severe disturbances is also presumed for the coming decades. Bark beetles are, for instance, expected to colonize previously unsuitable habitats in higher latitudes and mountain forests[12], and large wildfires occurring only rarely in the past are predicted to return with higher frequency under climate change[13].

Intensifying disturbance regimes are thus expected to be among the most severe impacts of climate change on forest ecosystems, raising concerns that disturbances might increasingly interfere with a continuous and sustainable provisioning of ecosystem services to society[14,15]. With regard to forest carbon (C) storage, which is an increasingly important ecosystem service in the context of climate change mitigation, forests are 'slow in, rapid out' systems[16], with disturbance being a major pathway of fast, large-scale ecosystem C loss[3]. Forest-related climate change mitigation policies are thus highly sensitive to disturbance regimes[4]. Intensifying disturbance regimes have already been associated with a weakening of the European forest C sink recently[5]. A further increase in disturbance damage in the future might thus pose a major risk for Europe's climate change mitigation efforts, as it could counteract the efforts to offset anthropogenic climate change through enhanced C storage in forest ecosystems[4]. Yet, consistent continental-scale assessments of potential changes in the forest disturbance regime under climate change are still missing so far. Furthermore, it is as of yet unclear how alternative European forest policies[17] will influence disturbance regimes, and to which degree increasing disturbances might offset the potential of these policies to enhance Europe's forest C storage capacity.

Using a new combination of Europe-wide disturbance observations (>29,000 records), scenario simulations of future forest development, and statistical disturbance modelling, we here report a continental-scale disturbance time series from 1971 to 2030 (Supplementary Information). Our analysis focused on an area of $131.6 \times 10^6$ hectares of forests available for wood supply in 2005, covering 29 European countries in eight different ecoregions. We address the three most detrimental forest disturbance agents in Europe, which are wind, bark beetles and forest fires. Future disturbance damage for 2011–2030 is projected under four alternative forest management strategies[17] for an ensemble of climate scenarios (continental-scale ensemble median warming of $+1.1\,°C$, precipitation increase of +2.8%, and an increase in maximum daily windspeed by +0.7% until 2030 compared with 1971–2001, see Supplementary Table 4). To investigate potential impacts of disturbance on climate change mitigation efforts we quantified the impact of future disturbance regimes on the C storage capacity of Europe's forests by means of an analytical C cycle model[18]. We evaluated how the effects of changing climate and disturbance regimes interact with alternative management strategies with regard to their implications on forest C storage.

We found that the disturbance intensification previously reported for the second half of the twentieth century[1,2] accelerated in the first decade of the twenty-first century. With damage of $32.3 \times 10^6\ m^3\ yr^{-1}$ (wind), $14.5 \times 10^6\ m^3\ yr^{-1}$ (bark beetles) and $9.4 \times 10^6\ m^3\ yr^{-1}$ (forest fires), the disturbance levels observed for the first decade of the twenty-first century were the highest of the past 40 years for all three disturbance agents (increasing by +139.6%, +601.9% and +231.1% relative to 1971–1980, respectively). The total disturbance damage from these three agents increased on average by $+1.06 \times 10^6\ m^3\ yr^{-1}$ between 1971 and 2001. This rate of increase rose to $+1.60 \times 10^6\ m^3\ yr^{-1}$ in 2002–2010.

Assuming a continuation of current forest management (reference strategy), projections under climate change resulted in a further increase in disturbance damage in all scenarios and for all agents (Fig. 1). The ensemble median (and interquartile range, IQR) wind damage for Europe was estimated to $44.5 \times 10^6\ m^3\ yr^{-1}$

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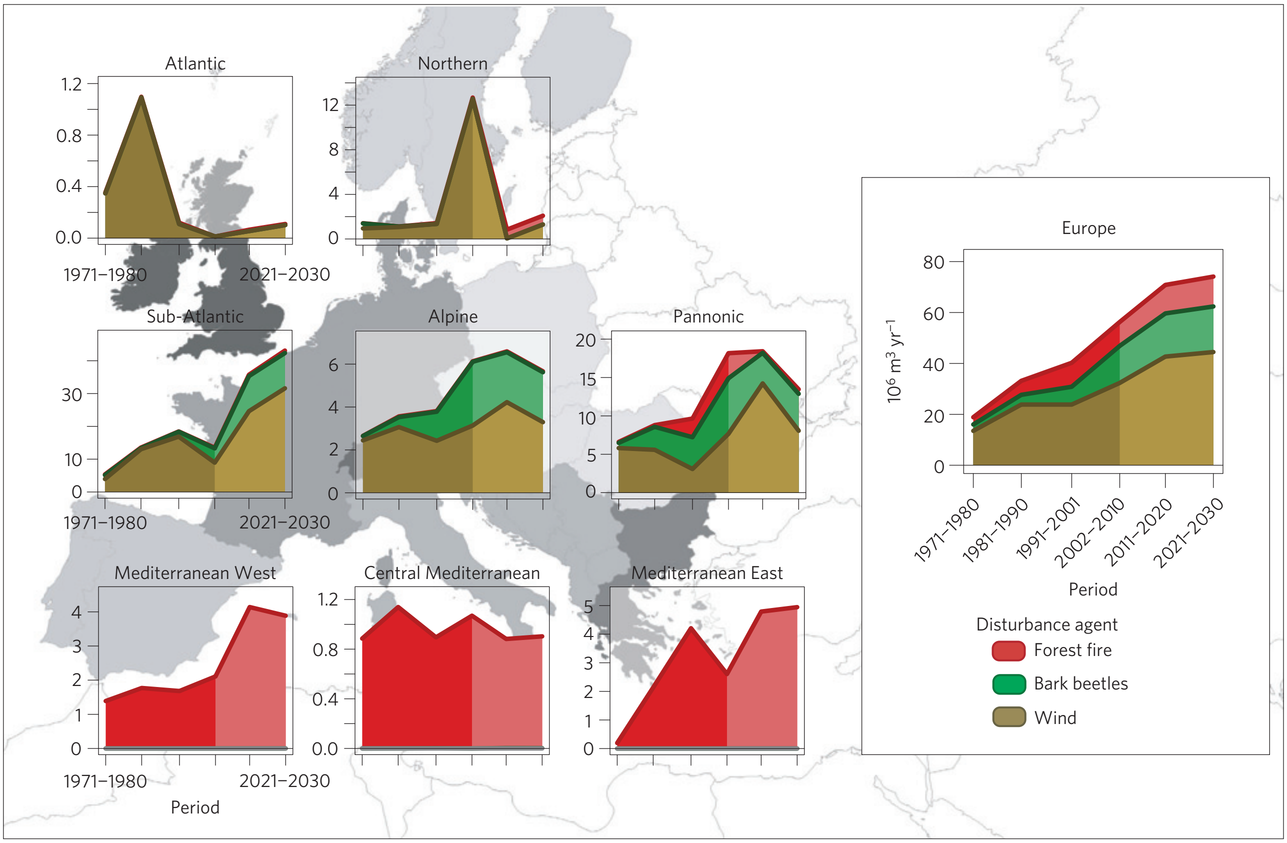


**Figure 1 | Forest disturbance damage in Europe 1971–2030.** Values are disturbance damage in millions of cubic metres of timber per year—note the different scales on the individual panels. Predictions (lighter hues) assume a continuation of business-as-usual forest management (reference strategy) and represent the median over an ensemble of scenarios of future climate and forest growth. Missing agents—such as bark beetles in the Northern and Atlantic ecoregions—indicate that they were not modelled in these particular ecoregions owing to a lack of historical data and/or relevance of the agent in these areas (Supplementary Table 5). The *x* axes are the same in all panels.

(IQR: $6.5 \times 10^6$ m$^3$ yr$^{-1}$) in 2021–2030 (+229.4% compared with 1971–1980). Bark beetle damage increased to $17.9 \times 10^6$ m$^3$ yr$^{-1}$ (IQR: $1.4 \times 10^6$ m$^3$ yr$^{-1}$) in 2021–2030 (+763.7% relative to 1971–1980). For the same period, the timber volume damaged from forest fires was predicted to increase to $11.7 \times 10^6$ m$^3$ yr$^{-1}$ (IQR: $0.6 \times 10^6$ m$^3$ yr$^{-1}$) (+313.9% relative to 1971–1980). Over all agents, the annual rate of increase in disturbance damage predicted for 2011–2030 was $+0.91 \times 10^6$ m$^3$ yr$^{-1}$ (median over the ensemble of climate change scenarios). If stable climatic conditions were assumed, however, disturbance damage remained constant or decreased moderately (Supplementary Fig. 9). This documents that climate change is the key driver of the disturbance changes projected for the coming decades (see also Supplementary Information).

Ecoregions across Europe were affected by the predicted intensification of disturbance regimes (Fig. 1). Forest fires, the dominant disturbance agent in the Mediterranean region, were projected to increase particularly on the Iberian Peninsula, whereas bark beetle damage increased most strongly in the Alps. Wind damage, being the disturbance most strongly driven by individual events of extreme weather, showed the highest variation over time, but was also projected to increase throughout the study period, particularly in mid-latitude ecoregions. In general, predicted increases in disturbance percentage (that is, the annual disturbance damage relative to growing stock, Fig. 2) were smaller than changes in absolute damage levels. Yet, also the continental-scale disturbance percentage over all three agents increased considerably, from 0.126% yr$^{-1}$ (1971–1980) to 0.264% yr$^{-1}$ in 2002–2010 and 0.311% yr$^{-1}$ in 2021–2030.

**Table 1 | The impact of climate change and natural disturbances on the carbon stored in Europe's forest ecosystems (in Tg C).**

| | | Disturbance | | |
|---|---|---|---|---|
| | | No | Yes | Effect size |
| Climate change | No | 22,295 | 21,975 | −319.8 |
| | Yes | 22,421 | 21,917 | −503.4 |
| | Effect size | +126.3 | −57.4 | −183.6 |

Results are for the period 2021–2030, and effect sizes relate to a 20-year analysis period. Projections are for a continuation of reference management, and the median over an ensemble of climate scenarios is reported for assessments under climate change.

The projected intensification of disturbance regimes has considerable impacts on the C storage capacity of Europe's forests. In 2021–2030, Europe's forest ecosystems could potentially store a total of 22,421 Tg C (ensemble median under reference management), with an annual C uptake (net ecosystem productivity) of 99.2 Tg C yr$^{-1}$ (Supplementary Table 6). This potential C stock (that is, the C stored when disregarding the effect of natural disturbances) is lowered by 503.4 Tg C (IQR: 36.7 Tg C) when damage by wind, bark beetles and forest fires is considered (Table 1). The continental-scale C effect of disturbance is thus of the same order of magnitude as the total amount of C stored in the forest ecosystems of the Atlantic ecoregion of Europe (Supplementary Table 9). More than one-third of this disturbance effect (183.6 Tg C) can be attributed to the changes in the climate and disturbance regimes predicted for 2011–2030. Disturbances lead to the reversal of an otherwise positive climate change effect on



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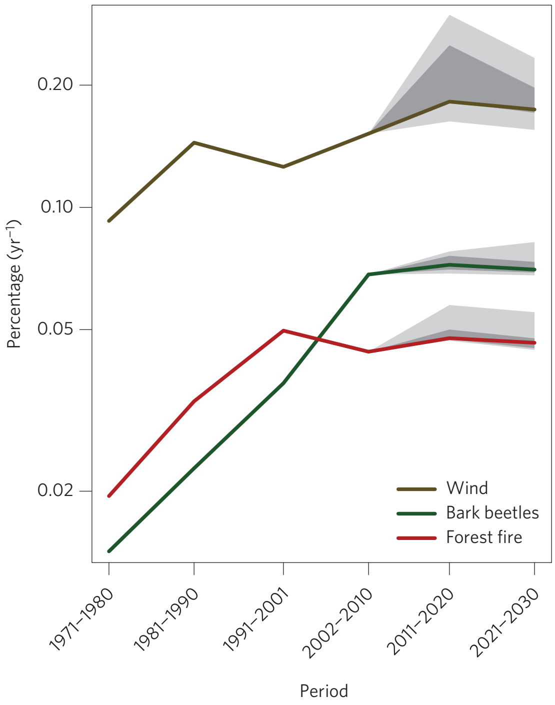


**Figure 2 | Disturbance percentage in Europe's forest ecosystems.** Average annual damage by wind, bark beetles, and forest fires relative to the growing stock in the respective periods. Predictions beyond 2010 assume a continuation of business-as-usual forest management (reference strategy). The median, interquartile range (dark grey) and minimum–maximum range (light grey) over an ensemble of scenarios of future climate and tree growth is indicated. Note that the *y* axis is logarithmically scaled.

the forest C balance: whereas climate change alone was projected to increase forest C stocks in Europe (+126.3 Tg C), the combined effect of changing climate and disturbance regimes resulted in a C loss of −57.4 Tg C in 2021–2030 compared with simulations under stable climate (Table 1).

Alternative management strategies can increase the forest C sink and enhance the climate change mitigation function of forests, for example, through increased rotation periods and optimized thinning regimes. Relative to the continuation of business-as-usual management (reference strategy), implementing a dedicated carbon management strategy would increase the C stored in Europe's forests by 562.7 Tg C in 2021–2030, and shifting towards biodiversity conservation would still increase C stocks by 153.4 Tg C (undisturbed simulations, ensemble median values, Table 2). However, these management strategies at the same time alter the susceptibility of forests to disturbance (for example, older forests have a higher predisposition to wind and bark beetle damage), which can lead to increased disturbance impact and disturbance-related C loss. In the carbon and biodiversity strategies the absolute level of timber volume damaged by disturbance increased by +12.4% and +7.6% relative to reference management (see also Supplementary Table 8). This increase in disturbance diminishes the C gain from management. In the biodiversity strategy, for instance, the total C gain relative to reference management is reduced to 72.6 Tg C (−52.7%) when the effect of disturbance is accounted for (Table 2).

We generally found the effect of disturbance on C stocks to be of the same order of magnitude as the C signal from alternative management strategies. This indicates that a changing disturbance regime has the potential to thwart desired management effects in Europe's forests. Our continental-scale findings of disturbance impacts on C storage are in congruence with previous studies on particular disturbance agents and events in Europe[19–21]. Also the considerable interactions between management strategies and disturbance impacts on C stocks found in our analysis are well in line with theory and previous assessments[4,22]. However, an in-depth evaluation of our methodology also revealed uncertainties regarding the future trajectories of Europe's disturbance regimes. Particularly for wind disturbance—which, at present, amounts to more than half of the total damage from the three agents addressed here—some regional disturbance models considerably underestimated damage in selected periods (Supplementary Fig. 4). This suggests that not all relevant processes might be captured in these models, and underlines the need for more process-oriented analyses in the future[23]. Moreover, regionally important disturbance agents not addressed here (for example, insect herbivores, pathogens) might also be sensitive to climatic changes. Furthermore, considering the extended time horizon of forest dynamics, future work should aim at going beyond the temporal horizon addressed here, as changes in forest structure and composition might become more important drivers of disturbance regimes than direct effects of climate change over longer timescales[24].

Generally, it is important to note that intensifying forest disturbance regimes will not only affect the forest C sink, but will also have implications for a wide variety of other ecosystem services. Besides devaluating timber through burning, breakage and post-disturbance fungal infections, the predicted rise in disturbance damage will increase management costs (for example, through salvage operations, fire suppression, and insect prevention measures) and fan the volatility of timber markets[25]. This will further amplify the negative effects of climate change on the timber-based forest economy in Europe[26]. Also the provisioning of drinking water could be negatively affected by intensifying disturbance regimes[27], as water filtering and retention strongly rely on the maintenance of a continuous forest canopy. However, not only provisioning services of forest ecosystems but also cultural, regulating and supporting services (for example, recreational value, protection against soil erosion, air quality and primary productivity) might be adversely affected by the continued increase in natural disturbances projected here. As intensifying disturbance regimes

**Table 2 | The effect of alternative forest management strategies on the C stored in Europe's forests (in Tg C) relative to reference management in 2021–2030 (that is, after a 20-year analysis period).**

| Climate change effect | Disturbance effect | Effect of alternative management strategies | | |
|---|---|---|---|---|
| | | Carbon | Biodiversity | Wood energy |
| No | No | +561.9 | +155.2 | −268.1 |
| No | Yes | +449.1 | +3.1 | −262.9 |
| Yes | No | +562.7 | +153.4 | −268.4 |
| Yes | Yes | +510.1 | +72.6 | −259.1 |

Management effects are reported for all four combinations of climate change and disturbance effects, and the median over an ensemble of climate scenarios is reported for assessments under climate change.



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have the potential to strongly interfere with management objectives, considerations of disturbance risk and resilience will require a more central role in Europe's forest policy and management to sustain ecosystem functions and services in the future.

## Methods

**Assessment tools.** To project trajectories of future forest development under different management strategies and future climates we used the European Forest Information SCENario model EFISCEN. EFISCEN is a large-scale forest simulation model that projects forest resource development at regional to European scale[28]. In EFISCEN, the state of the forest is described as an area distribution over age- and volume-classes in matrices, based on national forest inventory data. Transitions of area between matrix cells represent different natural processes in the simulation (for example, growth, mortality), and are influenced by management regimes and scenario changes. The effects of climatic changes are implemented in EFISCEN through deriving response functions for key processes such as forest growth from detailed process-based models.

We used empirically parameterized disturbance models to project the future damage by wind, bark beetles and wildfires in Europe's forest ecosystems. The empirical relationships were developed using country-scale disturbance data for the period 1958–2001[1], and are based on a compilation of >29,000 disturbance records across Europe[29]. The disturbance agents wind, bark beetles and forest fire were represented by individual models at country scale. Using unsupervised machine learning, indicators of climate as well as forest extent, structure and composition were selected as predictor variables[2]. Their influence strength on disturbance damage was determined through structural equation modelling[2]. For prediction, we used climate scenario data in combination with the respective forest structure and composition projections of EFISCEN.

To estimate the impact of disturbance on the forest C budget we used the REGIME model[18], which provides a general framework to quantitatively assess disturbance effects on ecosystem carbon storage capacity at large spatial scales. The main constituents of the C cycle in REGIME are net primary production, the size of the ecosystem C pools, and their residence times. The disturbance regime is characterized by the fraction of live biomass C removed per unit of time. We used simulation results of undisturbed EFISCEN runs to parameterize the REGIME model, and estimated disturbance levels by means of empirical disturbance models. The overall C effect of disturbance in Europe's forests was calculated by additively combining the three disturbance agents studied. Details and evaluations of the applied approaches can be found in the Supplementary Information.

**Scenario analysis.** For the period 2011–2030 we studied 14 different scenarios of future climate change and tree growth (Supplementary Table 4). These scenarios cover three different storylines of future global development as outlined by the Intergovernmental Panel on Climate Change (A1B, B1 and B2). The corresponding changes in the climate system were derived from runs with three different sets of global circulation models and regional climate models, and climate change signals were calculated by standardizing the prediction period to a past baseline period. For each of these scenarios (with the exception of the B2 storyline) two alternative assumptions with regard to the fertilizing effect of $CO_2$ on tree growth were studied, ranging from full acclimation (no fertilizing effect) to a persistent growth enhancement through elevated atmospheric $CO_2$ levels[30]. For the ensemble analysis of future trajectories we focused on the nine unique (non-replicated) scenarios of future climate change and tree growth, and report the ensemble median except where stated otherwise. A scenario of stable climate (assuming the climate conditions of 1971–2001) was used to isolate the role of climate change in our projections.

For all climate scenarios, four different management strategies were simulated with EFISCEN (ref. 17). The reference strategy describes the future trajectory of Europe's forests under a continuation of current forest policies (business-as-usual management). Both forest area and growing stock increase distinctly under this strategy, whereas the proportion of conifers on growing stock increases only slightly and the median forest age decreases. The three alternative management strategies represent a shift in forest policy towards carbon management, biodiversity conservation, and wood energy production, respectively[17]. By the end of the study period in 2030 these alternative strategies considerably alter the forest extent, structure and composition relative to reference management (Supplementary Table 7). The strategies with the most profound changes in forest structure, composition and extent are the biodiversity and carbon strategies. The former assumes that priority is given to the protection of biological diversity, resulting in less wood removals, longer rotation periods and increasing growing stock. In addition, a sizeable percentage of the forest area is taken out of management. As the focus of this study is on forests available for wood supply[17], the forest area is decreasing under the biodiversity strategy in our analysis. In the carbon strategy, rotation periods were increased and thinning regimes were optimized for increased C storage. The fourth strategy, promoting wood energy, showed comparatively little contrast to reference management with regard to indicators relevant in the context of disturbance damage, as many of its assumptions relate to increased removal of harvest residues as well as market changes and policy responses.

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## Author contributions

R.S. initiated the research and designed the study, conducted the analysis, and wrote the paper. M-J.S. contributed to study design, compiled the observational disturbance data, conducted the analysis of forest scenarios, and contributed to writing the paper. W.R. conducted the analysis of carbon effects and contributed to writing the paper. P.J.V. conducted the analysis of forest policy scenarios and contributed to writing the paper.

## Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.S.

## Competing financial interests

The authors declare no competing financial interests.



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ERRATUM

# Increasing forest disturbances in Europe and their impact on carbon storage

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In the version of this Letter originally published, the received date was incorrect and should have read 14 October 2013. This error has now been corrected in all versions of the Letter.

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CORRIGENDUM

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In the version of this Letter previously published, the value given for net ecosystem productivity was incorrect, and should have read 99.2 Tg C $yr^{-1}$; this has no impact on the reported results. These corrections have been made in the online versions of the Letter.

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