Title: Tropical cyclone migration mitigates the impact of climate change on cool-temperate and boreal forests

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Author contributions

All authors conceived this viewpoint and contributed to the writing and editing of the manuscript.

Data accessibility statement

No data associated with this study.

Number of words in the abstract =*100*; main text = *1177*, number of cited references = *22*, number of tables & figures = *1.*

Abstract

The poleward migration of tropical cyclones (TCs) inevitably triggers unprecedented ecological consequences for cool-temperate and boreal forests, including shifts in species distribution, global carbon dynamics, or forest policies. However, our current understanding of the impact of TCs' expansion into new regions is limited and lacks attention by both, the media and research community, compared to TCs' impact on (sub-)tropical forests. We suggest that TCs should not only be perceived as destructive weather phenomena but also as vehicle mitigating the impact of climate change on forest ecosystems via enabling the forest transition and reducing the negative impact of prolonged drought periods.

Introduction

Tropical cyclones (TCs) induce destructive impacts, such as wind damage, floods, or landslides, causing considerable socioeconomic losses annually, particularly in the broader coastal zones of the North Atlantic and Western Pacific (Peduzzi *et al.*, 2012; Patrick *et al.*, 2022). High media attention is devoted especially to TCs affecting densely populated areas, regardless of their intensity. In general, TCs are known to play a key role as disturbance agents in (sub-)tropical forests (Ibanez *et al.*, 2019). Recently recognised poleward (Studholme *et al.*, 2021) and inland (Zhu & Quiring, 2022) migrations in TC activity, however, pose a novel disturbance agent to cool-temperate and boreal coniferous-dominated forests (Fig.1a-c) (Fibich *et al.*, 2023; Korznikov *et al.*, 2023). Nevertheless, due to low population density, TCs do not induce substantial economic damage across the territories bordering cool-temperate and boreal forests in Northeast America and Asia. As a result, the unprecedented impact of TCs on northern forests receives only a little attention from both the media and research community, despite the possible far-reaching consequences.

However, what does the increase in TC activity mean for the cool-temperate and boreal forests? Here we aim to convey the idea that TCs are a significant factor in forest dynamics across extensive coastal regions of temperate-boreal forest transition (Altman *et al.*, 2018). Hence, the poleward migration of TCs inevitably triggers unprecedented ecological consequences in those forest ecosystems (Fig. 1d). Yet, our current understanding of the impact of TCs' expansion into new regions is limited, despite the fact that it has the potential to play a crucial role in the ecosystem processes that influence species distribution, greenhouse gas dynamics, global carbon dynamics, or forest policies.

Framing impact of TCs on northern forests

As TCs extend their reach into more north and inland regions not used to this type of disturbance and thus lacking resistance to it, they induce unprecedented large-scale mortality of canopy trees over thousands of hectares (Korznikov *et al.*, 2023). The forests in the coastal regions of Northeast America and Asia are humid due to the influence of the wet oceanic air masses from the Atlantic and Pacific oceans, respectively, resulting in a relatively low natural risk of forest fires compared to more inland areas. Hence, the process of natural forest dynamics in these cool-temperate and boreal forests have relied on small-scale disturbances until now (Thom & Seidl, 2016). Such intermediate disturbance dynamics allowed these forests to maintain high species diversity and to provide a stable carbon sink function compared to areas under the regular influence of wildfires (Walker *et al.*, 2019). Consequently, the ecological impact of TCs shifting the disturbance regime across these newly affected regions (Fig. 1a, b) should not be underestimated.

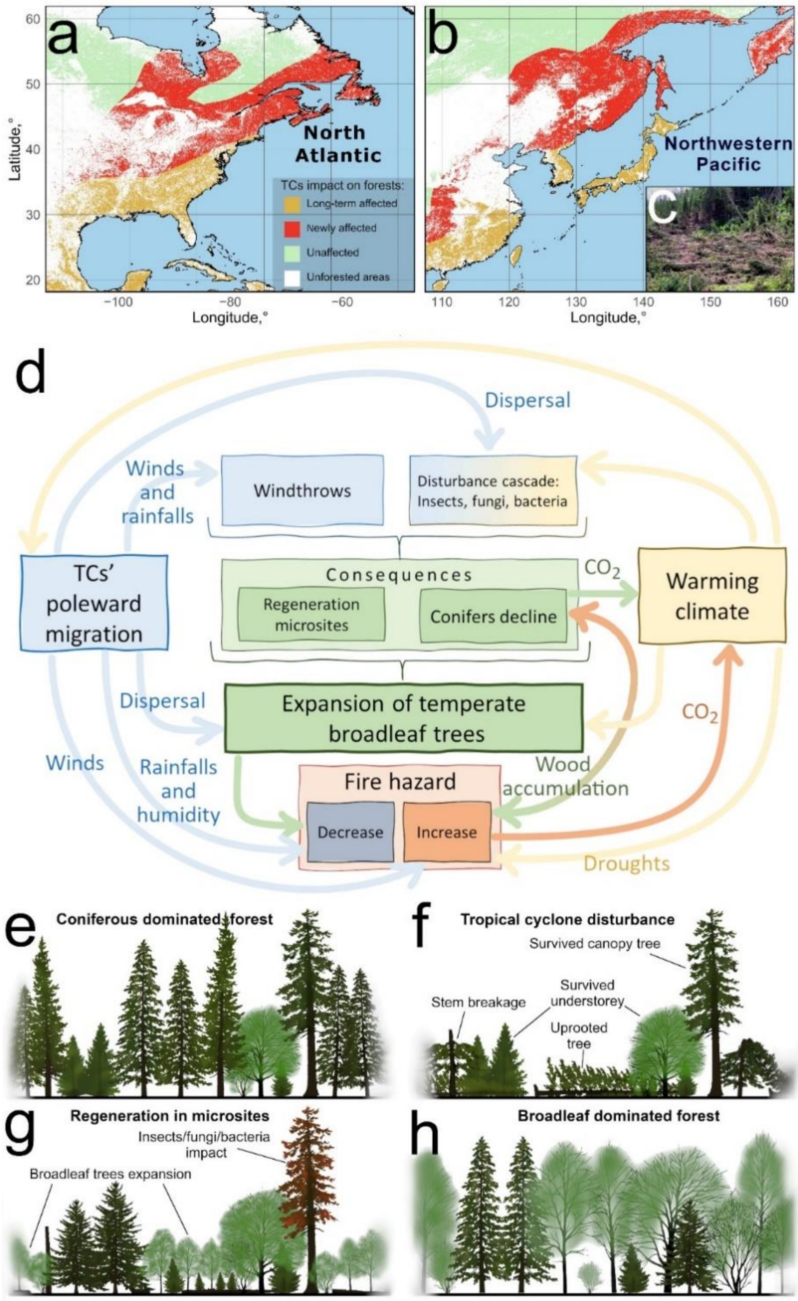

Fig. 1. Overview of influence of migrating TCs on northern forest ecosystems. Regions affect by TCs across the Northeast America (**a**) and Asia (**b**) with example of TC disturbance on coniferous forest (**c**). Schematic diagram illustrating key processes and their interaction related to impact of TCs on forest ecosystems under warming climate (**d**). Illustration of TC facilitated transition of cool-temperate-boreal forests dominated by coniferous trees to mixed wood forests dominated by broadleaf taxa (**e-h**). For **a** and **b**: forests distribution taken from GLCNMO v. 3; TC impact based on two-dimensional Kernel density estimation of 3-h resolution TCs' point data provided by IBTrACS (Knapp *et al.*, 2010) and comparing the densities of TCs' points occurred in 1980-1990 (long-term affected) and 2010-2020 (newly affected).

TC disturbances trigger a cascade process with far-reaching ecological consequences (Seidl *et al.*, 2017), leading to the progressive suppression of coniferous trees and providing an opportunity for the spreading of cool-temperate broadleaf tree species (Fig. 1e-h), as a part of the thermophilization process (Reich *et al.*, 2022). In particular, the decline of coniferous trees is attributed to their higher vulnerability to stem breakage and uprooting under strong TC winds (Foster, 1988). Furthermore, the trees surviving the TC disturbance, often injured, face an increased risk of insect outbreaks or bacterial/fungal diseases, which also increase in the warming climate (Seidl *et al.*, 2017; Altman *et al.*, 2024). From this perspective, the migration of TCs directly contributes to the decline of boreal forests through complex environmental interactions (Fig. 1d). In general, it is projected that global warming will gradually lead to the mortality of boreal coniferous species and their replacement by temperate trees (Reich *et al.*, 2022; Rotbarth *et al.*, 2023). Nevertheless, limited dispersal capabilities and unfavourable regeneration microsites for temperate species may slow down this transformative process (Reich *et al.*, 2022). Thus, the trajectories of southern boreal forest replacement by temperate forest trees remain uncertain.

Novel environment from shifts in TC activity support forest transition dynamics

Here we suggest that altered disturbance regimes induced by the unprecedented influence of TCs will accelerate the transition of the replacement of boreal coniferous species by cool-temperate broadleaf taxa. In particular, the large-scale disturbances as well as frequent small-scale gaps induced by TCs provide a network of suitable microsites for broadleaf tree regeneration necessary for their northward migration from cool-temperate forests (Thom & Seidl, 2016; Brice *et al.*, 2020). In addition, TCs themselves may directly facilitate long-distance dispersal (Nathan *et al.*, 2008) and thus contribute to accelerating the spread of broadleaf species and increasing their density (Brice *et al.*, 2020), which is necessary for the sufficient pace of temperate trees migration to avoid regeneration failure of boreal forests (Reich *et al.*, 2022).

Accumulated dead wood during TC disturbance, in combination with warming and drier weather, can significantly increase the fire hazard (Seidl *et al.*, 2017; Ibanez *et al.*, 2022). TCs may also contribute to the uncontrolled spread of fires by powerful winds, as demonstrated in a tragic fire in Hawaii propelled by TC Dora this year (Marris, 2023). On the contrary, the rapid regeneration of broadleaf trees can increase resilience to the fire risk (Hart *et al.*, 2019). Regarding the relationship between TCs and forest fires, several possible scenarios exist, and it still remains unclear which disturbance-succession pathways will develop in individual regions (Ibanez *et al.*, 2022; Altman *et al.*, 2024). In addition, TCs' rainfalls may facilitate the recovery of forest areas from dry spells (Chen & Luyssaert, 2023), which are becoming more frequent under climate warming.

Conclusion

We suggest that TCs should not only be perceived as one of the most destructive weather phenomena but also as a vehicle mitigating the impact of climate change on forest ecosystems via enabling the forest transition and reducing the negative impact of prolonged drought periods. Understanding the mechanisms of ecosystem rearrangements in the cool-temperate and boreal forests affected by TCs is crucial for forest growth, diversity, forest management, and assessing potential risks for carbon sequestration. We call for increasing research activity and interdisciplinary projects investigating the influence of TCs on new areas in the time of ongoing climate change. Further research is necessary to overcome the currently limited understanding of the mechanisms underlying changes in forest dynamics induced by TCs.

Acknowledgements

The study was funded by research grant 23-05272S of the Czech Science Foundation and the long-term research development project No. RVO 67985939 of the Czech Academy of Sciences.

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