# How do windstorms cause damage to the Amazon forest?

**Tracking windthrow frequency using satellite images since 1985 reveals, on average, a two-fold increase in the number of windthrows and area damaged per year, providing evidence for increased atmospheric instability in the Amazon region over the last four decades.**

**Figure 1.** Aerial views of large-scale windthrow events in Central Amazon, Brazil. Picture: Adriana Simonetti, INVENTA/ATTO Project.

## Preface

The Amazon Basin covers roughly 7 million square kilometers and harbors nearly 25% of the world's terrestrial biomass and tree species. It plays a vital role in regulating the global climate by absorbing and storing large quantities of carbon dioxide in trees and soils. Amazon forests are dynamic and subject to natural disturbances that maintain diversity at the landscape scale by causing clustered tree mortality, opening gaps that are filled by new species.

Windthrow events (i.e., trees snapped and uprooted by wind) associated with convective storms are a major mechanism of tree mortality affecting Amazon forests (Fig. 1), especially in the west and central regions where they occur most frequently. Accurately monitoring and quantifying the occurrence of windthrows and associated tree mortality will contribute to understanding how this natural disturbance causes changes in forest structure, species composition, and carbon balance[1-5,10,11].

## Relevance of ATTO observations

Observations of tree damage caused by storms with destructive potential, recorded either directly on site or using aerial imagery, are the most important source of information on the effects of convective storms on tropical forests. However, this represents only part of the picture, as meteorological records for assessing wind patterns and their seasonal variation are available for only a few locations and are often produced with insufficient temporal resolution. The long-term, high-frequency meteorological data collected at ATTO are critical for assessing disturbance regimes at the local to regional scale that cannot be effectively captured by remote sensing.

## Increased frequency of windstorms since the 1980s

We have used satellite time histories to document the spatial distribution and temporal trends in large (≥ 30-hectare) windthrows across the entire Amazon basin. Between 1985 and 2020, the number of windthrows and total wind-damaged area approximately doubled. This indicates a rise in the frequency[1] (Fig. 2) and area affected by convective storms capable of producing the destructive winds and heavy rainfall that topple trees. The greatest wind speeds in the area close to Manaus occur during the wet season (14.96 m $s^{-1}$). This value is above the lower range of critical wind speed (CWS) values reported in a previous study (10.75 m $s^{-1}$ to 34.5 m $s^{-1}$), where CWS is the wind speed needed to provoke a turning moment at the base of the trunk sufficient to result in tree failure[15]. In 2020 alone, approximately 39,650 hectares were affected. These figures are conservative, as they include only the area of contiguous damage. Our study also excludes more frequent but smaller events under 30 hectares.

The rising frequency of windthrow events closely correlates with changing atmospheric conditions, particularly the intensification of convective storms. Climate models project further increases in atmospheric instability in the future, implying a greater likelihood of extreme storms in tropical regions as global temperatures rise. While research is ongoing, current evidence strongly suggests that climate change is a key driver accelerating windthrow activity in the Amazon.

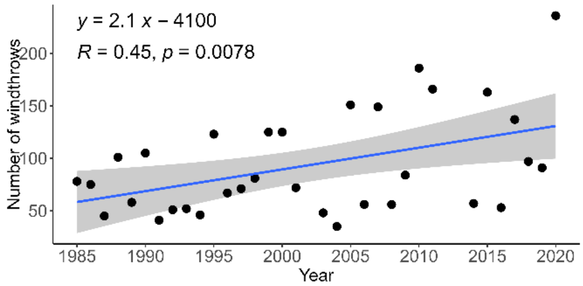


**Figure 2**. Fourfold increase in frequency of windthrow events (>30 ha) between 1985 and 2020 across the Amazon Basin. Source: Urquiza-Munoz et al. 2024 *AGU Advances*, DOI:10.1029/2023AV001030

## Windthrows alter forest composition

Windthrows create gaps in the forest canopy, promoting fast-growing and soft-wooded tree species that have shorter lifespans and lower carbon storage capacity. These shifts in the functional composition of the forest can also increase its vulnerability to future disturbances, such as extreme droughts and wildfires. Changes in forest structure affect water cycling, nutrient dynamics, and overall ecosystem health, with cascading effects on regional climate and human communities. Thus, while disturbances can create new niches that maintain high biodiversity, repeated strong disturbances can disrupt delicate ecological balances, impacting species that have low growth rates and are adapted to stable old-growth conditions.

**Figure 3.** Ground views of a large-scale windthrow event in Central Amazon, Brazil. Picture: Daniel Magnabosco Marra, INVENTA/ATTO Project.

## Windthrow hotspots and impacts on carbon storage

While large windthrows are rare events across much of the Amazon Basin, half of the windthrows that occur are clustered in specific "hotspot" regions[6], especially in the central and western Amazon (Fig. 4). In these areas, large windthrow events can recur within just a few hundred years. When trees are uprooted or snapped, the carbon they have stored over centuries is released back into the atmosphere as their tissues decompose. Although some studies indicate that in affected areas, forests can recover much of the biomass lost to wind damage within decades[14], this recovery is partly due to fast-growing pioneer species and no study yet has tracked recovery beyond a few decades after damage. In 'hotspot' regions, the rising frequency of windthrow events increases the potential for forests to be disturbed again before fully regaining their carbon stocks or original species composition.

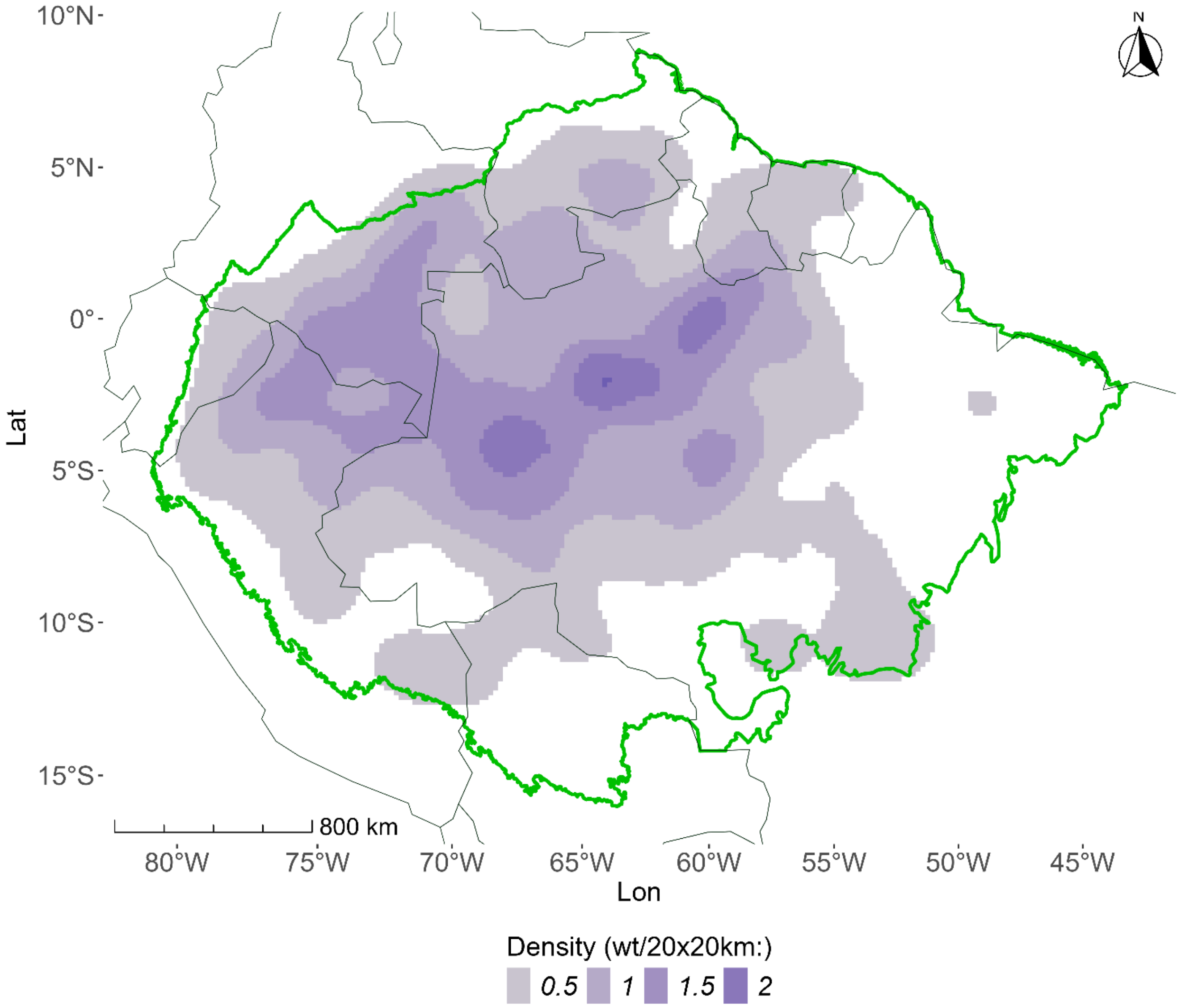


**Figure 4.** Windthrow hotspots over the Amazon Basin. The green line indicates the areal extent of the Amazon Basin. Source: Urquiza-Munoz et al. 2024 *AGU Advances*, DOI:10.1029/2023AV001030). The legend shows the average number of windthrows within an area of 200 square kilometers that occurred between 1985 and 2020. About half of the windthrows detected were found in the ~10% of the Amazon Basin that are in 'hotspots'.

## Recommendations

Safeguarding the health and functioning of Amazon forests is critical to ensuring climate stability and sustaining ecological balance worldwide. Addressing the potential threat of increasing future windthrow damage requires a multi-faceted approach involving international cooperation, scientific investment, and local engagement.

- To strengthen forest monitoring and early warning systems by investing in high-resolution satellite monitoring and advanced remote sensing technologies to quickly detect and map both small- and large-scale windthrow events across the entire Amazon Basin, delivering real-time data to support timely assessment and response.

- To support long-term field studies to monitor forest recovery, biomass dynamics, shifts in functional composition and further cascading (e.g., soils and fauna) effects of windthrow events. These data are essential for validating remote sensing products and enhancing our understanding of the vulnerability and resilience of Amazon forests to wind disturbances.

The rising frequency of large-scale windthrows in the Amazon signals a changing climate and poses an increasing threat to one of Earth's most vital ecosystems. By recognizing the increase in the frequency of windstorms and adopting proactive, evidence-based policies to limit climate change, we can enhance the Amazon's resilience, preserve its biodiversity, and secure its crucial role in regulating biogeochemical cycles and the climate.

## References

1. Marra, D.M.; Chambers, J.Q.; Higuchi, N.; Trumbore, S.E.; Ribeiro, G.H.P.M.; Dos Santos, J.; Negrón-Juárez, R.I.; Reu, B.; Wirth, C. (2014): Large-Scale Wind Disturbances Promote Tree Diversity in a Central Amazon Forest. PLoS ONE 2014, 9, e103711.
2. Magnabosco Marra, D.; Trumbore, S.E.; Higuchi, N.; Ribeiro, G.H.P.M.P.M.; Negrón-Juárez, R.I.; Holzwarth, F.; Rifai, S.W.; dos
3. Santos, J.; Lima, A.J.N.N.; Kinupp, V.F.; et al. (2018): Windthrows Control Biomass Patterns and Functional Composition of Amazon Forests. Glob. Chang. Biol., 24, 5867–5881.
4. Rifai, S.W.; Urquiza Muñoz, J.D.; Negrón-Juárez, R.I.; Ramírez Arévalo, F.R.; Tello-Espinoza, R.; Vanderwel, M.C.; Lichstein, J.W.; Chambers, J.Q.; Bohlman, S.A. (2016): Landscape-Scale Consequences of Differential Tree Mortality from Catastrophic Wind Disturbance in the Amazon. Ecol. Appl., 26, 2225–2237.
5. Rehbein, A.; Ambrizzi, T.; Mechoso, C.R. (2018): Mesoscale Convective Systems over the Amazon Basin. Part I: Climatological Aspects. Int. J. Clim., 38, 215–229.
6. Urquiza-Muñoz, J. D., Trumbore, S. E., Negrón-Juárez, R. I., Feng, Y., Brenning, A., Vasquez-Parana, C. M., Marra, D. M. (2024): Increased occurrence of large-scale windthrows across the Amazon Basin. AGU Advances, 5(6): e2023AV001030. doi: 10.1029/2023AV001030.
7. Medonca, A. C.d.; Dias-Junior, C. Q.; Acevedo, O. C.; Santana, R. A.; Costa, F. D.; Negron-Juarez, R. I.; Manzi, A. O.; Trumbore, S. E.; Marra, D. M. (2023): Turbulence regimes in the nocturnal roughness sublayer: Interaction with deep convection and tree mortality in the Amazon. Agricultural and Forest Meteorology 339. doi: 10.1016/j.agrformet.2023.109526.
8. Emmert, L.; Negrón-Juárez, R. I.; Chambers, J. Q.; Santos, J. d.; Lima, A. J. N.; Trumbore, S. E.; Marra, D. M. (2023): Sensitivity of optical satellites to estimate windthrow tree-mortality in a Central Amazon Forest. Remote Sens., 15(16). doi: doi.org/10.3390/rs15164027.
9. Feng, Y.; Negrón-Juárez, R.I.; Romps, D.M.; Chambers, J.Q. (2023): Amazon Windthrow Disturbances Are Likely to Increase with Storm Frequency under Global Warming. Nat. Commun. 14, 101.
10. Aleixo, I.; Norris, D.; Hemerik, L.; Barbosa, A.; Prata, E.; Costa, F.; Poorter, L. (2019): Amazonian rainforest tree mortality driven by climate and functional traits. Nat. Clim. Chang. 9, 384–388. https://doi.org/10.1038/s41558-019-0458-0
11. Chambers, J.Q.; Negron-Juarez, R.I.; Marra, D.M.; Di Vittorio, A.; Tews, J.; Roberts, D.; Ribeiro, G.H.P.M.; Trumbore, S.E.; Higuchi,N. The Steady-State Mosaic of Disturbance and Succession across an Old-Growth Central Amazon Forest Landscape. Proc. Natl.Acad. Sci. USA 2013, 110, 3949–3954.
12. Esquivel-Muelbert, A.; Phillips, O.L.; Brienen, R.J.W.; Fauset, S.; Sullivan, M.J.P.; Baker, T.R.; Chao, K.J.; Feldpausch, T.R.; Gloor, E.; Higuchi, N.; et al. Tree Mode of Death and Mortality Risk Factors across Amazon Forests. Nat. Commun. 2020, 11, 5515.
13. Gora, E.M.; Esquivel-Muelbert, A. Implications of Size-Dependent Tree Mortality for Tropical Forest Carbon Dynamics. Nat. Plants 2021, 7, 384–391.
14. Urquiza Muñoz, J.D.; Magnabosco Marra, D.; Negrón-Juarez, R.I.; Tello-Espinoza, R.; Alegría-Muñoz, W.; Pacheco-Gómez, T.; Rifai, S.W.; Chambers, J.Q.; Jenkins, H.S.; Brenning, A.; et al. Recovery of Forest Structure Following Large-Scale Windthrows in the Northwestern Amazon. *Forests* 2021, *12*, 667. https://doi.org/10.3390/f12060667
15. Peterson, C.J.; Gabriel Henrique Pires de Mello Ribeiro, Robinson Negrón-Juárez; Magnabosco Marra, D.; Chambers, J.Q.; Higuchi, N.; Lima, A;, Cannon, J.B. Critical wind speeds suggest wind could be an important disturbance agent in Amazonian forests, Forestry: An International Journal of Forest Research, 2019, 92, 4, 444–459, https://doi.org/10.1093/forestry/cpz025

## Contact

**David Urquiza**
Max Planck Institute for Biogeochemistry,
Dept. Biogeochemical Processes
Hans-Knöll-Str. 10, 07745 Jena, Germany
jurquiza@bgc-jena.mpg.de

**Daniel Magnabosco Marra**
Julius-Kühn-Institut
Institut für Waldschutz
Messeweg 11/12
38104, Braunschweig
daniel.magnabosco@julius-kuehn.de