Carbon and Water Cycling in a Changing Amazon

Susan Trumbore

2020 Balzan Prize for Earth Dynamics

Balzan GPC Adviser: Sierd A.P.L. Cloetingh
Project Director: Susan Trumbore
Deputy Supervisors: Paulo Brando (IPAM), Henrik Hartmann (MPI-BGC)
Affiliated institution: MPI-BGC (Max Planck Institute for Biogeochemistry

Susan Trumbore is Director at the Max Planck Institute for Biogeochemistry in Jena (Germany), Honorary Professor in the Faculty of Chemistry and Geology at the Friedrich Schiller University of Jena, and Professor of Earth System Science at University of California, Irvine.

Summary

The research funds for *Carbon and Water Cycling in a Changing Amazon* supported research into the resilience of Amazon forests undertaken as a collaboration between Trumbore at the Max Planck Institute for Biogeochemistry, and Paulo Brando at the Institute for Amazon Research in Brasilia (IPAM), Brazil. The award funds were split between the two Institutions and mostly used to support three early career researchers. Two of these undertook field work at the Tanguro research station operated by IPAM in transitional forests close to savanna ecosystems in the arc of deforestation in southeastern Amazon, Mato Grosso Brazil. Leonardo Maracahipes-Santos (financed by IPAM) studied how some species adapt, while others bring new capabilities to survive in isolated riparian tree communities, and how fire affects mortality and resilience of intact forests. David Hererra-Ramírez (MPI-BGC) used radiocarbon to study the age and dynamics of tree storage reserves and came up with a hypothesis that can potentially be used to predict when trees have exhausted reserves and are at risk for mortality. The third early career researcher, David Urquiza-Muñoz, was supported as a finishing PhD student to document the role of large wind disturbances (blow-downs) across the Amazon basin, as well as the trajectories of recovery following those events. All three published research advancing understanding of how fire and climate change are altering the cycling of carbon and water in forest fragments in the Brazilian ‘arc of deforestation’, the location most associated with proposed Amazon ‘tipping points’. Leonardo Maracahipes-Sanots is now the scientific manager of the Tanguro field site; David Hererra-Ramírez is a G. Evelyn Hutchinson Postdoctoral fellow at the Yale Institute for Biospheric Studies; and David Urquiza-Muñoz will become a Professor at the National University of the Peruvian Amazon (**UNAP**) after a brief postdoc here at the MPI for Biogeochemistry. The Balzan funds were key to supporting the careers of three remarkable junior researchers.

The work at Tanguro Ranch is part of a larger and longer-term collaboration that follows forests recovering from multiple disturbances, including experimental fire and windthrows. Regular biomass and species surveys coordinated by Leonardo Maracahipes-Santos indicate that even highly degraded forests have the potential to recover carbon stocks, and that in terms of species composition they are not becoming 'savannas' if human disturbances cease. Simulation of carbon starvation during severe drought conducted by David Hererra-Ramírez provides a new way to use wood anatomical traits to predict which tree species will be most vulnerable to mortality. Finally, Urquiza-Muñoz's PhD thesis documented increased atmospheric instability across the Amazon Basin that resulted in a doubling in the number of damaging blowdowns over the past 40 years, and is exploring the impacts on biomass, carbon cycling and biodiversity.

Together this work has helped to document the resilience of Amazon forests to both human and natural disturbance, with consequences summarized in a recently published review resulting from workshops at Tanguro and Yale University (Brando et al. 2025 " Tipping Points of Amazonian Forests: Beyond Myths and Toward Solutions"). This paper draws on long-term research strategically supported by Balzan funds and provides a new way of framing debates around the future of Amazon forests. Rather than framing the Amazon's future as reaching a 'tipping point', a threshold that once crossed cannot be reversed, the paper summarizes evidence from Tanguro, in one of the most heavily impacted regions, that Amazon forests can be highly resilient if disturbances are not compounded or too frequent. This framing means that it is up to people to reduce direct disturbances like deforestation and fire, as well as to implement policies to reduce the magnitude of future climate change.

Background of the Project

Much of the concern regarding the future of Amazon forests stems from water and carbon cycle feedbacks between vegetation cover and climate. Particularly in the dry season, Amazon forests maintain a cooling function through evapotranspiration of water that fell during the previous wet season and is stored in deeper soil layers. Replacement of deep-rooting trees with shallow-rooting grasses or crops that cannot access this pool of deeper water leads to senescence, less water returned to the atmosphere, and therefore higher air temperatures in the dry season. In regions where deforested areas are large enough, the return of the rainy season can be delayed, leading to greater drought stress on forests and increased uncertainty in crop yields. In addition, hotter and drier forest litter at forest edges and during heat waves increases the severity of fires, causing increased mortality and further degradation of the surviving forests.

Much of the research in the Balzan Project was conducted in the southeastern Amazon, close to the boundary between continuous forest and savanna ecosystems, and in the 'arc of deforestation' where >20% of the original forest has been replaced, first by pasture and then industrial agriculture. Forests in this region are already experiencing rapid warming and longer dry seasons. Based on climate modeling, these forests should be close to a proposed system 'tipping point', where reductions in precipitation may impact the capacity of forests to maintain themselves during drought (Figure 1). Within the context of a larger, long-term collaboration, the Balzan funds supported postdoctoral and PhD researchers who worked on several projects that integrate filed, remote sensing and radiocarbon measurements to improve understanding vegetation and soil carbon cycling in this region and how that is interacting with changing climate and land use.

The original plans for research schools in the Amazon were funded separately through the Amazon Tall Tower Observatory and the Max Planck Society, as well as through Yale University. Rather than having a single workshop, workshops were held at Tanguro and at Yale University, again mostly with other funding. The Balzan funds were thus used almost exclusively for salaries of the junior researchers and their associated travel to conferences and for field research. The funding made a major difference to the careers of these three people, and will be elaborated in more detail below.

Figure 1. (Left panel) Location of the experimental area at "Tanguro Ranch" in the southern part of the Brazilian Amazon, in the 'arc of deforestation' that has a relatively long (4-5 month) dry season. The ranch is a patchwork of remnant forest and areas cleared originally for pasture that since 2000 have been converted to intensive agriculture. The ranch is the site of several experiments, including large plots subjected to experimental burning (bottom left panels) leaving intact (control) and fire-degraded forests (B1yr, B3yr). However, forests bordering the agricultural fields are also subject to exposure to warmer and drier conditions above the crops during the dry season (right panel) and our research also explored how this edge effect influenced vegetation and its vulnerability.

Dr. David Hererra-Ramírez. The anatomy of storage reserves in trees – a potential predictor for which species will be most likely to survive repeated disturbances.

Dr. David Hererra-Ramírez was supported by Balzan funds in his final year as a PhD student in the International Max Planck Research School, and during a one-year follow-up postdoc. He is currently a G. Evelyn Hutchinson Postdoctoral fellow at Yale University. During his PhD, Hererra-Ramirez demonstrated links between wood anatomy and how trees store their energy reserves (starch and fats; Figure 2). Using the Balzan funds, he showed that, although fiber-storing species incur higher metabolic costs related to maintaining living fibers (Herrera- Ramírez et al. 2023), they also tend to grow more slowly and have longer lifespans. These conservative, slow growing, high storage species have stronger tradeoffs between storage and growth. A novel aspect of Dr. Hererra-Ramírez 's work made possible with Balzan funds was to include radiocarbon measurements to determine the age of the carbon stored in tree stems. This involved development of new methods to purify and measure compounds like starch or lipids. Overall, the conservative, fiber-storing trees have lower mortality rates than fiber-storing species. Surprisingly, conservative species can seasonally remobilize older stored NSC towards younger sapwood, meaning that this stored carbon remains metabolically active and provides stored energy for respiration and tissue repair during stressful periods. Surprisingly, conservative species can seasonally remobilize older stored NSC towards younger sapwood, meaning that this older stored carbon remains metabolically active and provides energy for respiration and tissue repair during stressful periods. This characteristic may enable them to survive longer and therefore exhibit lower background and fire-related mortality rates.

Access and depletion of storage reserves and their influence on survival

Dr. Hererra-Ramírez's work provides a basis to predict resilience to disturbance from more simple measurements of the anatomical distribution of starch and lipids in tree stem tissues. To understand how these species access their stored nonstructural carbohydrate reserves when facing stress, such as physical damage, he conducted a girdling experiment (planned for 2020, but delayed by the pandemic and conducted with Balzan funding starting at the end of 2021). Similar-sized trees from three species with differing storage dynamics were identified. For 6 trees per species, Herrera-Ramirez cut the phloem, the outermost living tissues just below the bark that are used to transfer fresh photosynthetic products down the stem and into the roots; another 6 trees were left intact as controls. Girdling is used to simulate major physical damage (such as defoliation), which forces trees to remobilize reserves for respiration and tissue regeneration. After girdling, the evolution of the amount and age of stored carbohydrates was monitored for two years and continued until trees died.

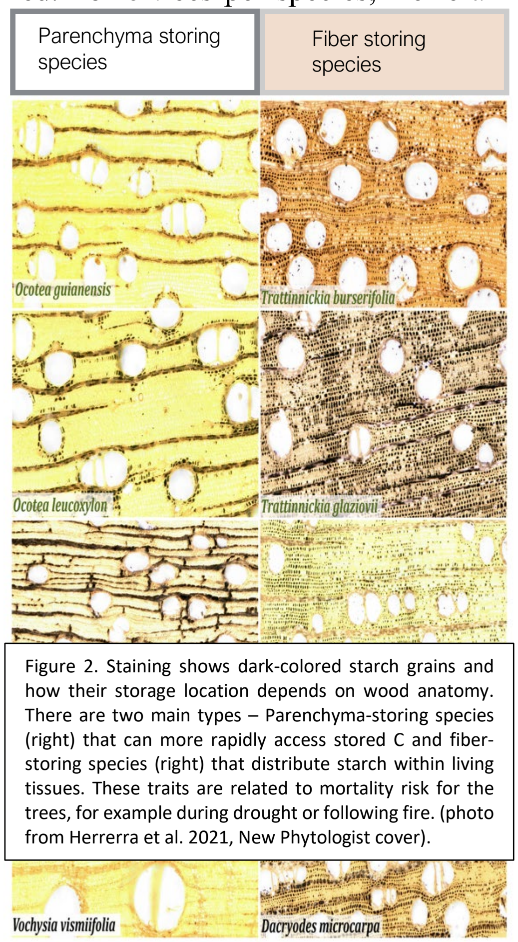


Figure 2. Staining shows dark-colored starch grains and how their storage location depends on wood anatomy. There are two main types – Parenchyma-storing species (right) that can more rapidly access stored C and fiber-storing species (right) that distribute starch within living tissues. These traits are related to mortality risk for the trees, for example during drought or following fire. (photo from Herrerra et al. 2021, New Phytologist cover).

The results show that after girdling trees can access older reserves within the first year, consuming starch stocks in the stem wood (Figure 3). Highly conservative species with fiber storage were able to access and respire older reserves, which increased progressively in age between March and August 2023, after girdling. Meanwhile, less conservative species, with storage limited to parenchyma tissues, quickly accessed their older reserves in March 2023, with no change in radiocarbon value by August 2023, suggesting that they had reached the maximum availability of reserves. By comparing the age of the respired CO_2 with the age of the stored NSC in the stem wood, how close trees were to using up their oldest stored reserves could be estimated in relative terms. This estimate can be used as an index to evaluate how close trees are to reaching a threshold of storage depletion, which can be thought of as the 'safety margin' before trees start to die.

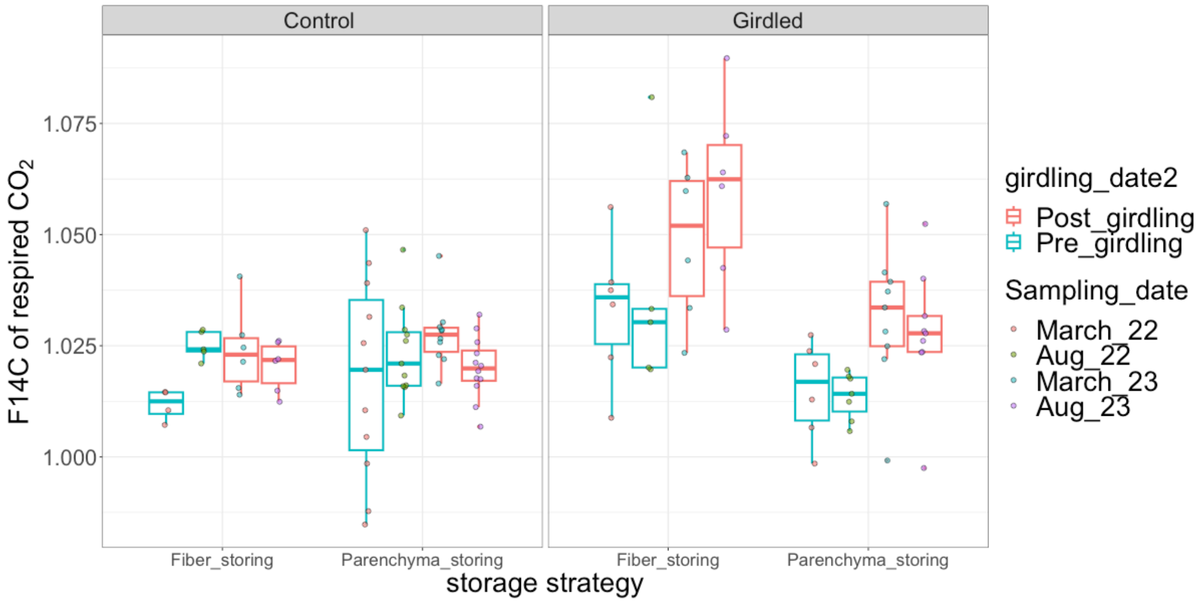


Figure 3: ^{14}C of respired CO_2 from stem wood of trees with two contrasting storage strategies subjected to girdling treatment. Pre-girdling measurements for each experimental group are shown in blue boxplots (March 2022 and August 2022). Girdling was applied in August 2022. Post-girdling measurements are shown in red boxplots (March 2023 and August 2023).

The girdled trees only started to die once the NSC safety margin had reached minimum levels, and individual deaths progressively increased until May 2025, when all the girdled trees had died. It was found that survival time was related to the NSC safety margin and to the parenchyma storage strategy. Shorter safety margins, crossing a critical threshold of 50% of the reserves depletion, were found for parenchyma storage species, and this was reflected in early mortality during the girdling experiment. This indicates that the closer trees were to the depletion threshold, the lower their probability of survival (Figure 4).

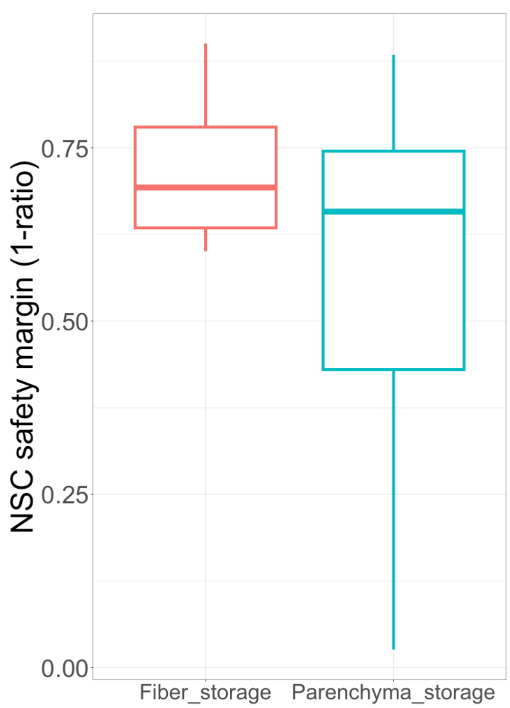


Figure 4: The metric called the NSC safety margin indicates how the radiocarbon values in C stored in and respired by girdled trees approach the threshold when usable reserves are exhausted. Comparison between fiber storage and parenchyma storage species are presented before girdling took place, and differences in the NSC safety margin agree with early mortality patterns observed in trees with a smaller safety margin (mainly parenchyma storage species). All trees died in 2025 after exhausting most of their reserves and getting closer to the safety margin of zero. This work should be submitted for publication soon.

In 2024, Herrera was awarded a G. Evelyn Hutchinson postdoctoral fellowship funded through Yale University, where he continued the girdling experiment. He has expanded on this research by studying the starch distribution in trees representing many different species and comparing their storage and growth strategies in more highly stressed forest edges and in areas recuperating from fire disturbance. He is currently working on the manuscript related to the girdling experiment, as it took time to get the radiocarbon data. His current research seeks to (1) expand the analysis of carbohydrate storage traits to compare new recruited species with those surviving prior disturbance, (2) link these to hydraulic traits, (3) assess their ability to predict mortality. This introduces a novel aspect to understanding the tradeoffs between 'thirst and hunger', i.e., hydraulic failure and C starvation in an environment subjected to repeated and increasingly intense drought stress.

Papers acknowledging Balzan Foundation support:

Herrera-Ramirez, D.; Hartmann, H.; Römermann, C.; Trumbore, S. E.; Muhr, J.; Maracahipes-Santos, L.; Brando, P.; Silvério, D.; Huang, J.; Kuhlmann, I. et al.: Anatomical distribution of starch in the stemwood influences carbon dynamics and suggests storage-growth trade-offs in some tropical trees. Journal of Ecology 111 (11), pp. 2532 - 2548 (2023).

A paper summarizing the girdling experiment and acknowledging Balzan research support will be submitted soon.

Dr. Leonardo Maracahipes-Santos explored how tree communities evolve in response to multiple stresses from land use, fire and drought.

Dr. Leonardo Maracahipes-Santos was employed as a postdoc using Balzan funds awarded to IPAM. Maracahipes-Santos investigated the resilience of tropical forests species in two different studies. The first (Maracahipes-Santos et al. 2023) compared riparian forests embedded in a larger forest environment (Figure 5) with those isolated and surrounded by croplands. These studies are important for understanding how land use change alters the services such as carbon storage and cooling through evapotranspiration, especially when changes occur too fast for species to adapt to new conditions.

Because of the high species diversity of these forests, his study also explored the ability of more general traits to understand the links between species change and forest functions such as carbon storage, or nutrient and water cycling. The results showed that deforestation and edge effects caused changes in the ecological strategies of surviving tree species in the riparian forest fragments. Conservative species showed some ability to adapt to altered conditions in degraded environments, while newly recruited 'pioneer' species brought more acquisitive strategies. Carbon storage in the crop-surrounded forests declined, and future research will continue to monitor how these important forests evolve over time.

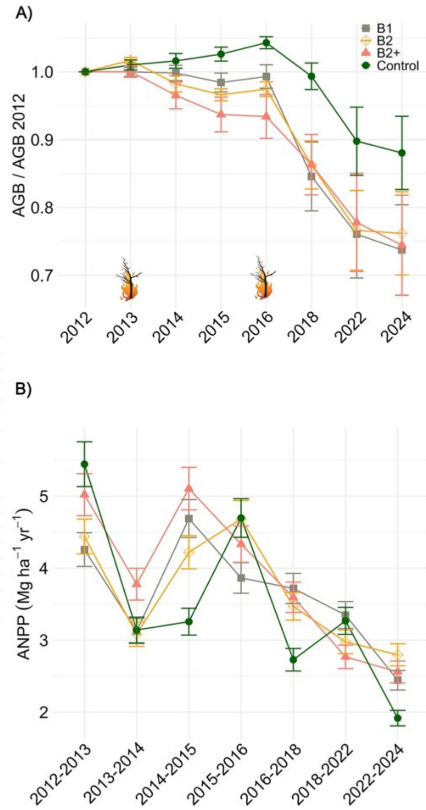
Figure 5. Locations on the reserve where transects (examples on the right) characterized species composition and functional traits to understand how they are affected in isolated riparian forests surrounded by cropland. From Maracahipes-Santos et al. 2023.

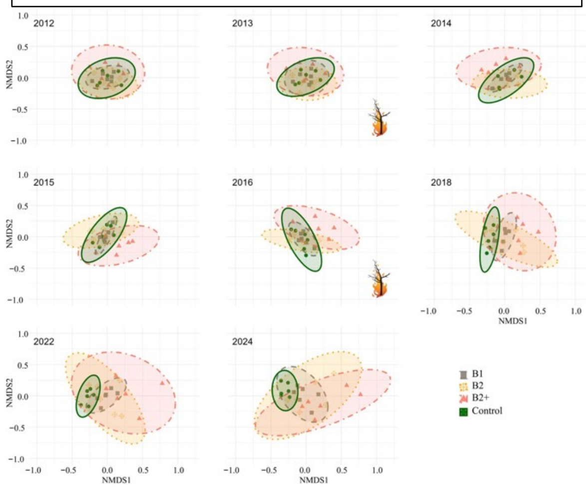
Figure 6. Location of the experimental fire plots within the Tanguro farm; (b) diagram of the six experimental block and their location within the Amazon (top right); (c) spatial distribution of treatments within each randomized block, composed of four 40 × 40 m plots. B1 = plots burned experimentally only in 2016; B2 = plots burned experimentally in 2013 and 2016; B2+ = plots burned experimentally in 2013 and 2016 with added fuel; control = unburned plots.

Much of Maracahipes-Santos' work funded by Balzan research funding focused on similar questions about how species and plant traits changed following fire that also altered burn severity (Figure 6). Maracahipes-Santos tracked changes in species composition, above ground biomass, and aboveground productivity (stem growth and litterfall) to understand the consequences for carbon cycling of fires.

Low intensity fires increased mortality of small trees and resulted in modest but significant changes in plant species diversity, composition, forest structure, biomass and productivity (Figure 7) with larger effects in plots with added fuel that experienced high-intensity fires. These results suggest that wildfires could exert long-term influences on the structure, composition, and functioning of forests. Relatively small changes in species composition, above-ground biomass and productivity also indicated that these transitional forests between Amazonia and Cerrado (savanna) are mostly resilient to even repeated low-intensity fires. However, with climate change, the Amazon fire regime is predicted to increase in intensity, with projections that up to 16% of forests in the southeastern Amazon—particularly in its drier zones—could burn in the coming decades. A key insight from the study is the role of increased fuel loads in promoting fire continuity and expanding the total burned area, which in turn amplifies tree mortality. As droughts and heatwaves become more frequent, these interactions may intensify, and edge effects could further compound fire severity. The longer-term fire study in Tanguro (see Figure 1) showed that fires along forest edges, where conditions are drier and hotter, can kill up to 90% of trees after repeated burns—significantly more than in forest interiors. Thus, it is not clear if the resilience of these forests can withstand fires under predicted future hotter and drier conditions.

Figure 7. (below) Measure of the similarity in composition of woody species in the Amazon-Cerrado transitional forest across the four experimental treatments: plots burned in 2013 (B1), 2013 and 2016 (B2) and plots burned twice with added fuel load (B2+) and control plots. Flaming tree graphics indicate the timing of experimental burns. (right) total aboveground biomass (AGB) divided by initial biomass in 2012 top right), and aboveground net primary productivity.
(ANPP; bottom right) in the four experimental treatments. Error bars indicate 95% confidence intervals. The plots together show that changes are not always significant (mostly in B2+).





Maracahipes-Santos also co-authored a third study that published the long-term record of soil moisture recorded at the main burned plots at Tanguro. These demonstrate the importance of deep (>5m) soil water for maintaining an evergreen forest canopy during the long local dry season. During the driest months of the year, burned forests showed significant reductions in soil moisture compared with unburned forests, an effect that was exacerbated during the strong drought event of 2015/2016. It also showed an overall increase in water use throughout the 8-m soil column from 2011 to 2018. This study informed the synthesis paper (Brando et al. 2025) and will also be used to explain a threshold effect of soil moisture that causes reductions in forest C uptake in both forest types (manuscript still in process).

Since the Balzan funding finished, Dr. Maracahipes-Santos has taken over the overall management of the Tanguro field station as an employee of IPAM. Other papers that are in progress involve the eddy covariance data and how the forest responds to severe drought.

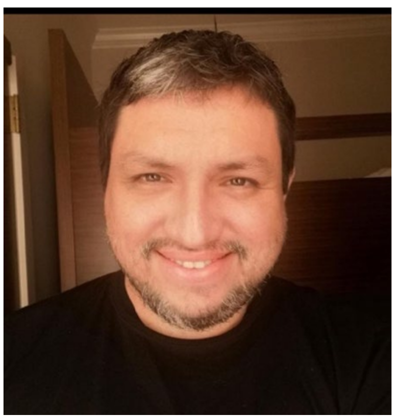
Papers acknowledging Balzan Foundation support:

Maracahipes-Santos, Leonardo, , D. Silvério, M. Macedo, L. Maracahipes., K.J. Jankowski, L. N. Paolucci, C. Neill and PM Brando (2023). Agricultural land-use change alters the structure and diversity of Amazon riparian forests. *Biological Conservation*, v252, 10.1016/j.biocon.2020.108862.

Maracahipes-Santos, Leonardo, L. Maracahipes, D. Silvério, M. Macedo, A. Silveiro, N. Potter, L. Paolucci, B. Starinchak, A. Alencar and PM Brando (2025). Amazonian forest resilience inferred from fire-induced changes in carbon stocks and tree diversity. *Environ. Res. Lett.* **20** 084017**DOI** 10.1088/1748-9326/ade60d

Silveiro, A. C., Silvério, D. V., Macedo, M. N., Coe, M. T., Maracahipes, L., Uribe, M., et al. (2024). Droughts amplify soil moisture losses in burned forests of southeastern Amazonia. Journal of Geophysical Research: *Biogeosciences*, 129, e2024JG008011. 10.1029/2024JG008011.

Jose David Urquiza-Muñoz: The distribution of natural windthrow disturbance



Balzan research funds remaining at MPI-BGC after David Hererra-Ramirez departed for Yale were used to support the research of a finishing PhD student, David Urquiza-Muñoz. The goal of Urquiza-Muñoz's research has been to (1) map spatial and temporal patterns in the occurrence of large (>30 hectare) windthrows across the entire Amazon Basin between 1985 and 2020. (2) to analyze how windthrow events specifically impact the forest's physical structure and the diversity and spatial distribution of tree species using filed work and (3) to use remote sensing to characterize the recovery trajectories of windthrown forests at broader scales.

Windthrows – strong winds associated with convective storms that can uproot and snap tree stems – represent an important natural disturbance mechanism in forest ecosystems in the Amazon Basin (Figure 7A). They influence forest structure, species composition, and carbon dynamics by creating large gaps and initiating ecological succession. 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.

Figure 7A. Aerial (left) and ground views of a large-scale windthrow event in Central Amazon, Brazil. Photo credits: left, Adriana Simonetti; right, Daniel Magnabosco Marra.

Using Landsat satellite data, Urquiza-Muñoz created a series of cloud-free (or minimal cloud) images that allowed him to document the spatial distribution and temporal trends in large (≥ 30-hectare) windthrows across the entire Amazon basin between 1985 and 2020. He made two interesting observations. First, while windthrows occur over ~70% of the Amazon Basin, most occurred within a relatively small portion of the total area (Figure 8).

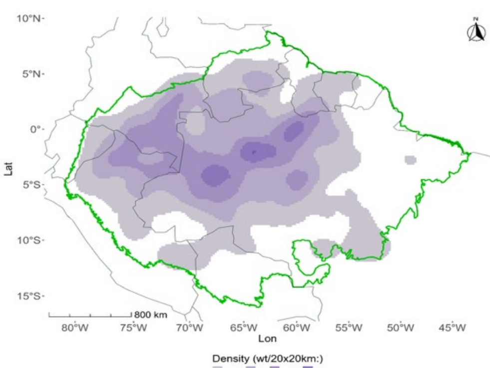


Figure 8. Windthrow 'hotspots ' over the Amazon Basin. The legend shows the average number of windthrows within an area of 200 square kilometers that occurred between 1985 and 2020. About half of the windthrows detected were found in the ~10% of the Amazon Basin that where more than 1.5 windthrows occurred. The green line indicates the areal extent of the Amazon Basin.

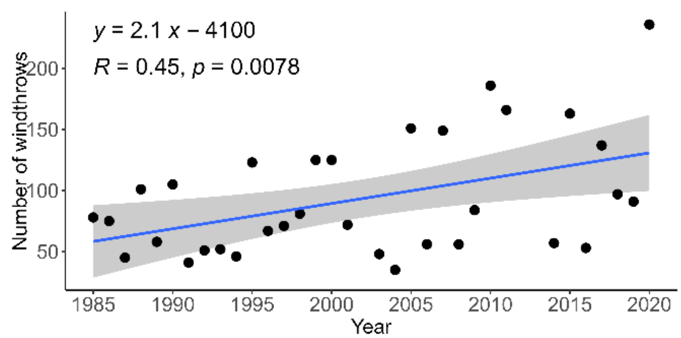


Figure 9. Record of windthrows demonstrating an increase in the average frequency of windthrow events (>30 ha) between 1985 and 2020 across the Amazon Basin. New data show this trend continues, and that 2024 (like 2020) was a year of many windthrows.
Source for Figures 8 and 9: Urquiza-Munoz et al. 2024.

Second, over this 35-year period, the number of windthrows and total wind-damaged areas on average approximately doubled (Figure 9). This rising frequency of windthrow events is related to increased incidence of afternoons with severe atmospheric instability, conditions that give more energy to the convective storms and create downbursts that can cause windthrows. 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.

These results are important because they strongly suggest that climate change is accelerating windthrow activity in the Amazon, which can have consequences for carbon cycling and species composition, especially in the hotspot regions where windthrows tend to be larger and occur more frequently.

Papers acknowledging Balzan Foundation support:

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:10.1029/2023AV00103

A second paper documenting succession in recovery after windthrow is under review.

Key Synthesis: Tipping points of Amazonian forests: Beyond myths and toward solutions

Although the budget planned for a Balzan-sponsored workshop, in the end funds were used to support travel for Trumbore and others of the Balzan team to travel back and forth to Brazil and to participate in workshops in Tanguro and at Yale University. These workshops led to the publication of a synthesis article led by Professor Paulo Brando, the PI for the IPAM partner in this research. The paper builds on the understanding from research at Tanguro about the resilience of these forests in the face of multiple disturbances including experimental fire and windthrows, and the multiple years of observations of forest dynamics and water and carbon fluxes in forest plots subjected to experimental fire and experiencing windthrows and edge effects.

The hypothesis of a 'tipping point' for Amazon forests implies strong feedbacks connecting climate warming, forest cover loss (aided by deforestation), regional drying and warming, and the risk of wildfires that cause high mortality. In climate models that simulate deforestation of the magnitude in the state of Mato Grosso, where the Tanguro ranch is located, the prediction is that a tipping point will soon be reached and forest will be replaced by fire-degraded systems that may resemble savannas because of grass invasion. Indeed, the original fire experiments begun at Tanguro in 2003 aimed to test whether a forest would 'tip' into a savanna given repeated experimental fire.

Observations (including those in Maracahipes-Santos et al. 2025) show instead that these forests found close to the transition to savanna vegetation are relatively resilient to low-intensity fires, though mortality increased following higher-intensity fires associated with hot droughts or elevated fuel loading. Work at Tanguro also demonstrated that intense fire leaves the remaining forest more susceptible to a subsequent disturbance like windthrow. Nonetheless, after more than a decade after experimental burns ceased biomass is increasing again, even in edge areas (this is one of the forthcoming manuscripts). Also, the species colonizing are more generalists (found in both forest and savanna) rather than specific to savanna ecosystems, and trees are outshading and eliminating the grasses that had invaded the burned plots. Interestingly, the ecosystem fluxes of water and carbon were not too different between the control and degraded experimental forests, though the edge areas in burned plots close down earlier in the dry season, especially in years with extreme drought. Overall, the data indicate that, under current conditions, the feedbacks built into climate models are too strong, and that remnant and even highly degraded forests are resilient in terms of water and carbon cycling. In the longer term, it is unknown how and if edge forests or degraded forests will recover species composition, as this depends on the vectors introducing species and reproductive success of remaining individuals.

The Brando et al. (2025) paper seeks to change the conversation away from 'tipping points', and towards emphasis of the resilience of these systems if disturbances can be minimized. Figure 10 (reproduced from Figure 5 in the paper) summarizes two frameworks for viewing forest responses. The first represents the 'domino effect' of tipping points, where once a critical threshold is crossed, strong feedbacks make large and continued change inevitable, and recovery is difficult or impossible. The second represents the 'hammer effect', where feedbacks are weaker and the degree of degradation will depend on the frequency of hammer blows and how much recovery can take place between them.

The important difference is that the 'domino' framework means that after a certain point change is inevitable, while the 'hammer' framework means that people can take concrete actions that can have real consequences for maintaining forests and the services they provide.

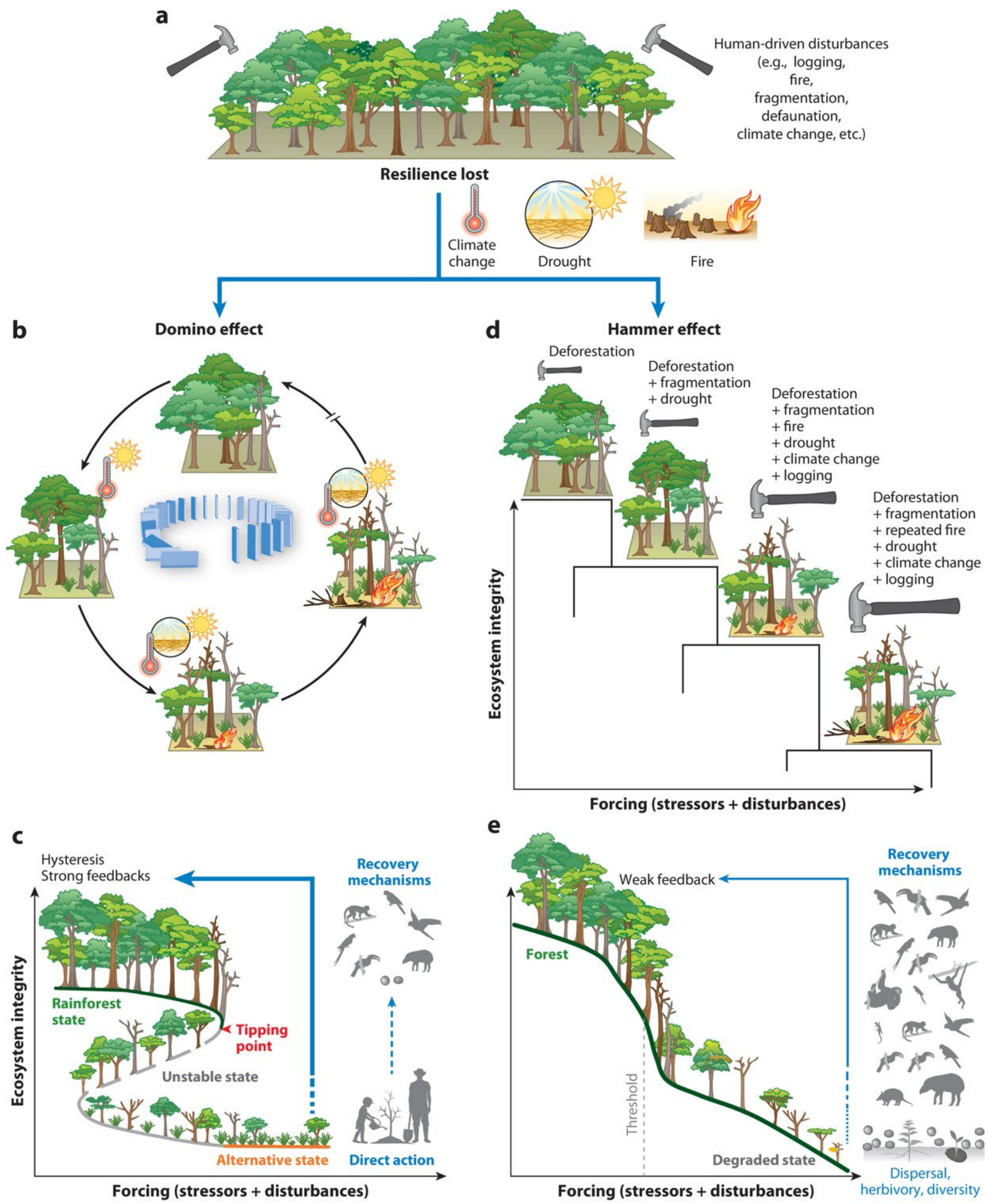
While this paper is the culmination of contributions from many co-authors, the Balzan funds, by supporting key Tanguro researchers and the continuity of the long-term data providing evidence for the 'hammer' framework, made a significant contribution. The paper and in particular the new framing are already having an impact on the conversation around tipping points.

Paper acknowledging Balzan support to ST, LM-S and IPAM:

Brando, P. M., Barlow, J., Macedo, M. N., Silvério, D. V., Ferreira, J. N., Maracahipes, L., Anderson, L., Morton, D. C., Alencar, A., Paolucci, L. N., Jacobs, S., Stouter, H., Randerson, J., Flores, B. M., Starinchak, B., Coe, M., Pires, M. M., Rattis, L., Armenteras, D., Artaxo, P., Ordway, E. M., Trumbore, S. E., Staver, C., Berenguer, E., Menor, I. O., Maracahipes-Santos, L., Potter, N., Spracklen, D. V., & Uribe, M. (2025). Tipping points of Amazonian forests: Beyond myths and toward solutions. *Annual review of environment and resources, 50*, 97-131. doi:10.1146/annurev-environ-111522-112804.

Acknowledgement

Finally, on a personal note, I want to thank the Balzan Foundation again for both the award and for the research funding. It had a large impact on the careers of the three junior scientists who received direct support and provided key support for the research at Tanguro. By alleviating the need to write an additional proposal for funding, it also allowed me and Paulo Brando the grace to think, discuss and synthesize. We are still in the process of getting the papers out – there should be at least four more that acknowledge the Balzan funding to be published in the next year.



Brando PM, et al. 2025
Annu. Rev. Environ. Resour. 50:97–131

Figure 10. Potential pathways of forest recovery. Forests have been degraded by several drivers (*a*), or hammer blows. As a result, two conceptual models of ecosystem trajectories could occur in the Amazon. First, the degraded state (*b*) illustrates the domino effect, which assumes tipping points and nonlinear responses in response to stressors, whereby small changes in a driver (e.g., climate) may trigger irreversible ecosystem shifts due to strong feedbacks. While the system can fluctuate within boundaries, significant stress can push it into a degraded state, making recovery challenging. Second, the resilient state (*d*) illustrates the hammer effect, which assumes that human-driven disturbances (hammer blows) are the primary drivers of Amazon ecosystem degradation. Repeated blows can cause the ecosystem to cross thresholds beyond which recovery is difficult but possible. These two conceptual models can also be represented as a system having hysteresis (*c*) or nonlinear transformations associated with different potential drivers (*e*).