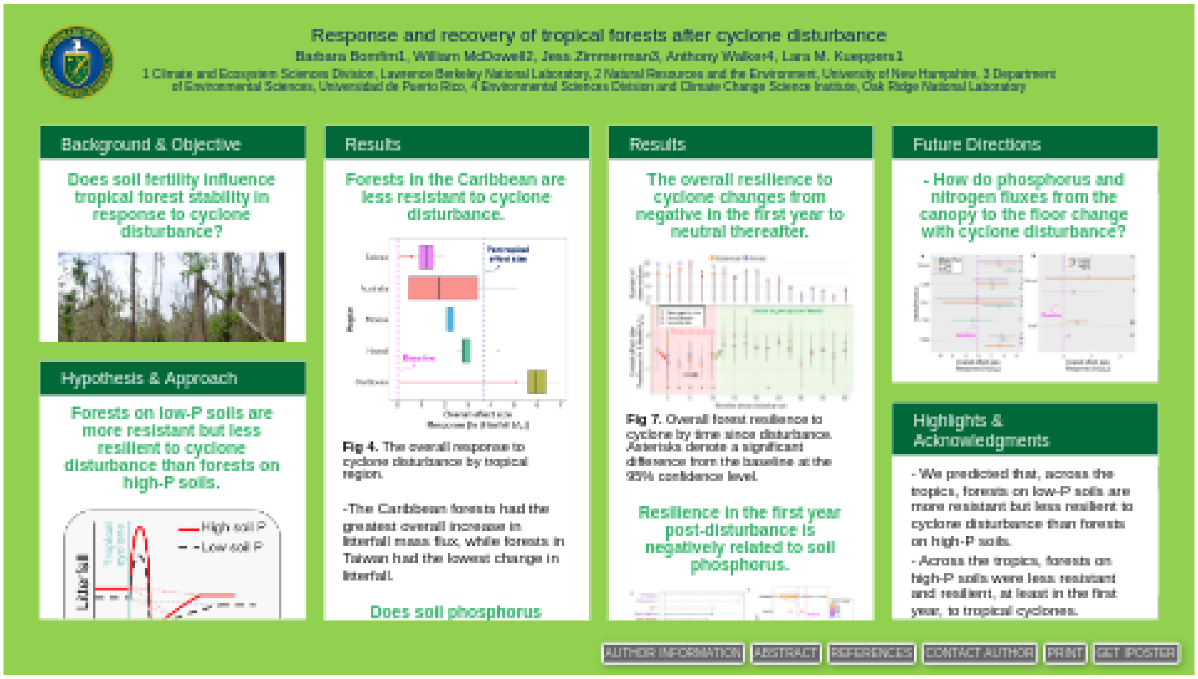
Response and recovery of tropical forests after cyclone disturbance



Barbara Bomfim 1*, William H. McDowell 2, Jess K. Zimmerman 3, Anthony P. Walker 4, Lara M. Kueppers 1

1 Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, 2 Natural Resources and the Environment, University of New Hampshire, 3 Department of Environmental Sciences, Universidad de Puerto Rico, 4 Environmental Sciences Division and Climate Change Science Institute, Oak Ridge National Laboratory
*Presenting author: bbomfim@lbl.gov

PRESENTED AT:

BACKGROUND & OBJECTIVE

Does soil fertility influence tropical forest stability in response to cyclone disturbance?

Damage caused by a hurricane in a Puerto Rican forest. Image credit: Dr. Maria Uriarte

- Quantifying ecosystem stability in response to disturbance is critical for predicting how disturbance regimes altered by climate change will affect ecosystem structure and function.

- Tropical cyclones, whose intensities are expected to increase with warming (Reed et al. 2020), dominate the disturbance regime experienced by forest ecosystems worldwide.

- Forest ecosystem dynamics are strongly influenced by interactions between cyclone disturbance regimes and nutrient availability.

- Uncertainty exists over the importance of soil fertility properties, like total soil phosphorus (P) concentration, in mediating forest resistance and recovery from cyclone disturbance.

To understand the role of soil P in mediating forest stability in response to cyclone, we investigated the response, resilience, and recovery of litterfall across a pantropical total soil P gradient.

HYPOTHESIS & APPROACH

Forests on low-P soils are more resistant but less resilient to cyclone disturbance than forests on high-P soils.

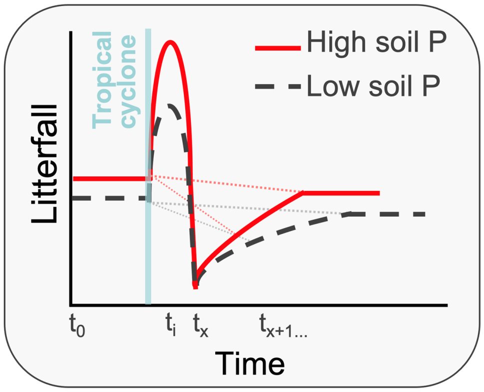


Fig 1. Graphical hypothesis.

The hypothesis was tested by a pantropical meta-analysis of published studies and data sets.

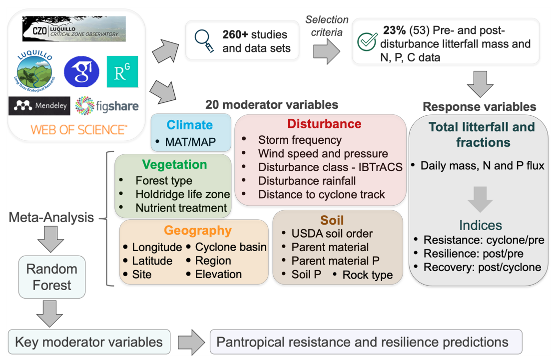


Fig 2. Schema of the research approach.

- **53** studies and data sets;

- **15** naturally-occurring and **1** simulated tropical cyclone;

- **23** sites within **5** regions - Taiwan, Australia, Mexico, Hawaii, and the Caribbean;

- **4** cyclone basins.

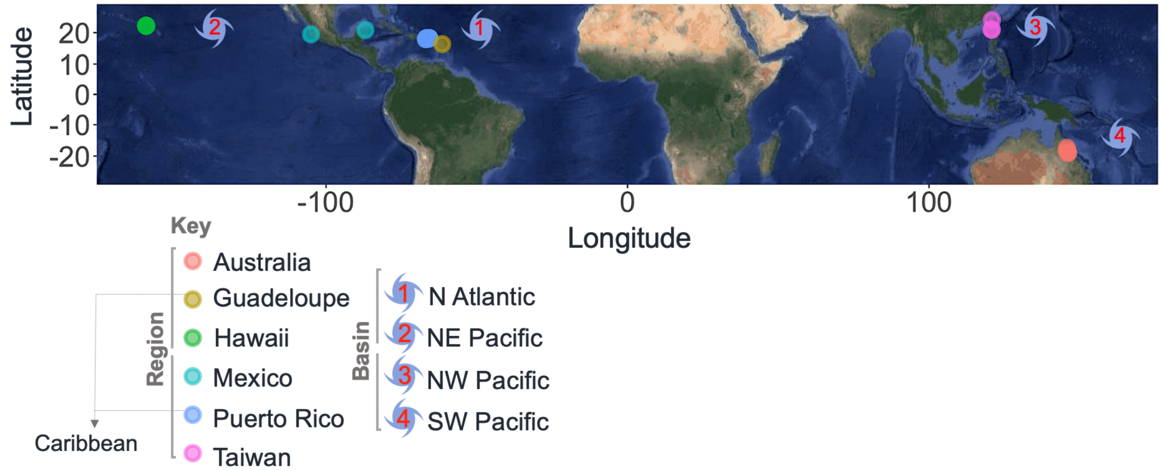


Fig 3. Study sites located in five regions and four cyclone basins.

Table 1. Studies included in this meta-analysis.

Region	Study	Holdridge life zone	Site	Soil parent material	Total soil P (mg/kg)	Storm frequency ($year^{-1}$)	Cyclone name and year
Australia	Gleason et al. 2008	Tropical rain	Wooroonooran 1	Basalt	1520	0.28	Larry 2006
			Wooroonooran 2	Metamorphic schist	240	0.28	
	Herbohn & Congdon 1993	Tropical rain	Mt Spec	Granite	130	0.28	Charlie 1988
	Benson & Pearson 1993	Subtropical lower montane wet	Birthday Creek	Granite	210	0.28	Charlie 1988
Caribbean	Zimmerman et al. 1995	Subtropical wet	El Verde	Volcaniclastic	340	0.21	Hugo 1989
	Walker et al. 1996						
	Lodge et al. 1991						
	Ramirez 2017	Subtropical wet	El VerdeTrim[a] & TrimDeb[b]	Volcaniclastic	340	0.21	CTE 2005
	Ostertag et al. 2003	Subtropical moist	Cubuy	Volcaniclastic	255	0.21	Georges 1998
		Subtropical wet	Bisley	Volcaniclastic	320	0.21	Georges 1998
	Lodge et al.1991	Subtropical wet	Bisley	Volcaniclastic	320	0.21	Hugo 1989
	Scatena et al. 1996	Subtropical wet	Bisley (watersheds 1 & 2)	Volcaniclastic	320	0.21	Hugo 1989
	Covich 2015	Subtropical wet	Bisley (La Prieta)	Volcaniclastic	320	0.21	Hugo 1989
	Liu et al. 2018	Subtropical wet	Bisley	Volcaniclastic	320	0.21	Irma & Maria 2017
	Ostertag et al. 2003	Subtropical lower montane wet	East Peak Palm forest	HA Volcaniclastic	140	0.21	Georges 1998
		Subtropical lower montane wet	East Peak Colorado	HA Volcaniclastic	317.3	0.21	Georges 1998
		Subtropical lower montane rain	East Peak Cloud forest	Volcanic siltstone	260	0.21	Georges 1998
	Walker et al. 1996	Subtropical lower montane rain	East Peak Cloud forest	Volcanic siltstone	260	0.21	Hugo 1989
	Lugo et al. 2011	Subtropical moist	Utuado	Noncarbonate sedimentary	330	0.21	Georges 1998
	Van Bloem et al. 2005	Subtropical dry	Guanica	Limestone	500	0.21	Georges 1998
	Liu et al. 2018	Subtropical dry	Guanica	Limestone	500	0.21	Irma & Maria 2017
		Subtropical wet	Rio Abajo	Limestone	820	0.21	Irma & Maria 2017
		Subtropical moist	Guayama	Residuum Coluviuum Volcanic	340	0.21	Irma & Maria 2017
	Beard et al. 2005	Subtropical wet	Bisley/El Verde [c]	Volcaniclastic	320	0.21	Bertha 1996
	Imbert & Portecop 2008	Tropical dry	Grande-Terre	Coral limestone	670	0.33	Hugo 1989
Hawaii	Herbert et al. 1999	Subtropical lower montane wet	Kokee	Basalt	220	0.12	Iniki 1992
	Harrington et al. 1997	Subtropical premontane dry	Makaha 1	Basalt	110	0.12	
		Subtropical lower montane wet	Milolii	Basalt	110	0.12	
			Kumuwela	Basalt	20	0.12	
			Halemanu	Volcanic ash	52	0.12	
Mexico	Whigham et al. 1991	Tropical dry	San Felipe	Limestone	2900	0.44	Gilbert 1988
	Martínez-Yrízar et al. 2018	Tropical dry	Chamela-Cuixmala	Rhyolitic Rhyodacitic Volcanic	291	0.33	Jova 2011
		Tropical dry	Chamela-Cuixmala	Rhyolitic Rhyodacitic Volcanic	291	0.37	Patricia 2015
Taiwan	Wang et al. 2013	Subtropical wet	Lienhuachi	Quartzitic sandstone	460.9	0.97	Kalmaegi 2008
	Liao et al. 2006	Tropical moist	Kengting III	Hengchun Limestone	87.9	0.97	Mindulle 2004
			Kengting IV		70.5	0.97	

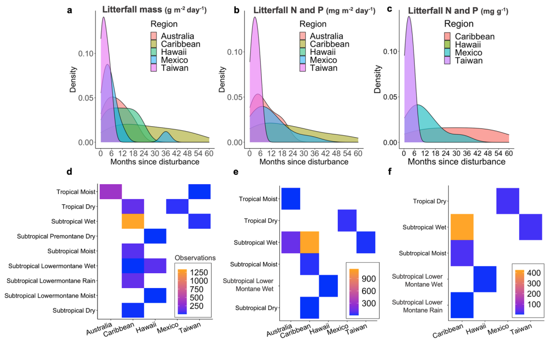


Fig. 4 a Litterfall mass flux, **b** nutrient flux and **c** concentration by region and time since disturbance, and **d-f** by Holdridge life zone and region.

Response variables

Using litterfall mass flux data during the first (< five) years post-disturbance, we calculated:

Response

$$Rp = \ln(\text{Litterfall } t_i/t_0)$$

R_p near zero indicates high resistance

Resilience

$$R_s = \ln(\text{Litterfall } t_x/t_0)$$

R_s near zero indicates high resilience

Recovery

$$R_c = \ln(\text{Litterfall } t_x/t_i)$$

Moderator variables

Using Random Forest for meta-analysis and multivariate random-effects models, we assessed the influence of soil phosphorus and 20 variables related to cyclone disturbance, soil, geology, geography, and vegetation (Fig. 2) on the stability indices.

RESULTS: RESPONSE

Across the tropics, response to cyclone disturbance is highest in the Caribbean.

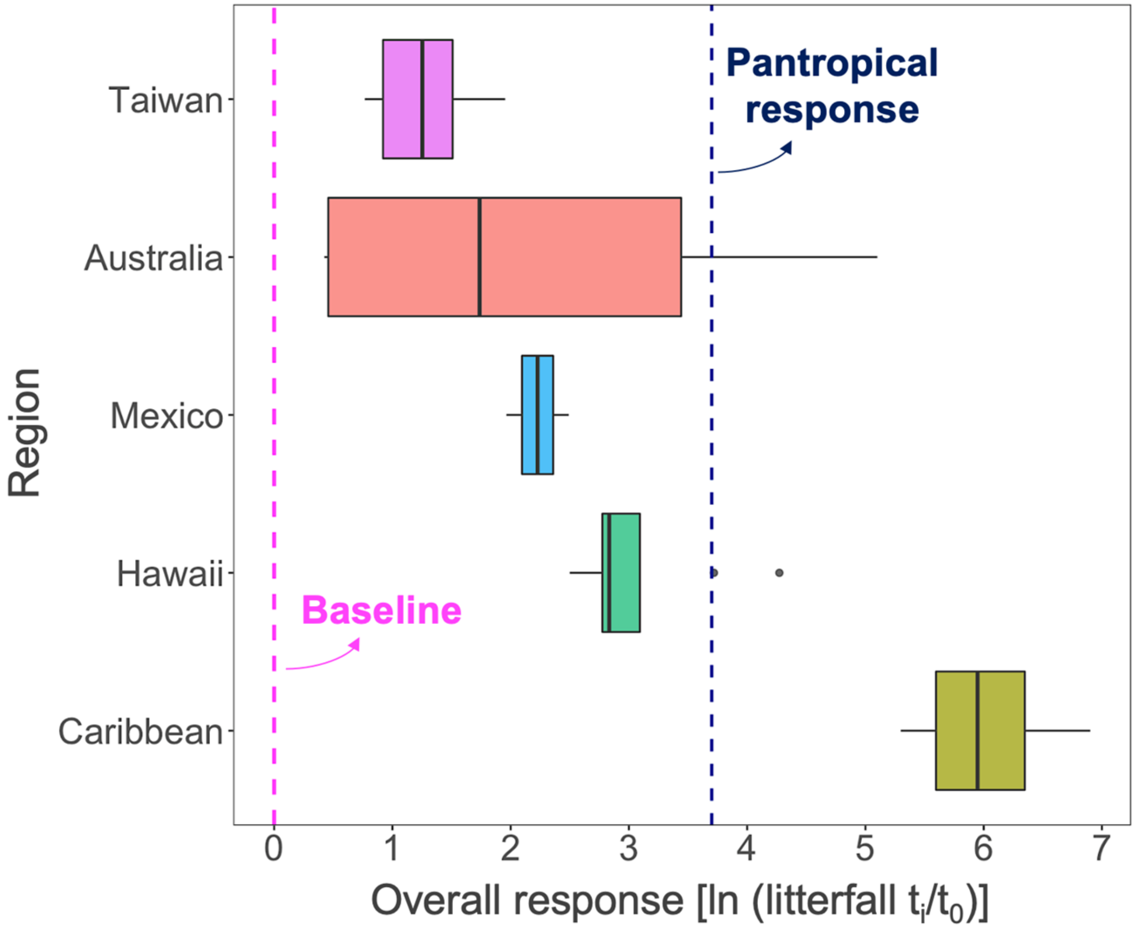


Fig. 5 The pantropical overall response to cyclone disturbance, and response by region.

- The pulse of litter was highest in the Caribbean and lowest in Taiwan.

Does soil P explain differential responses?

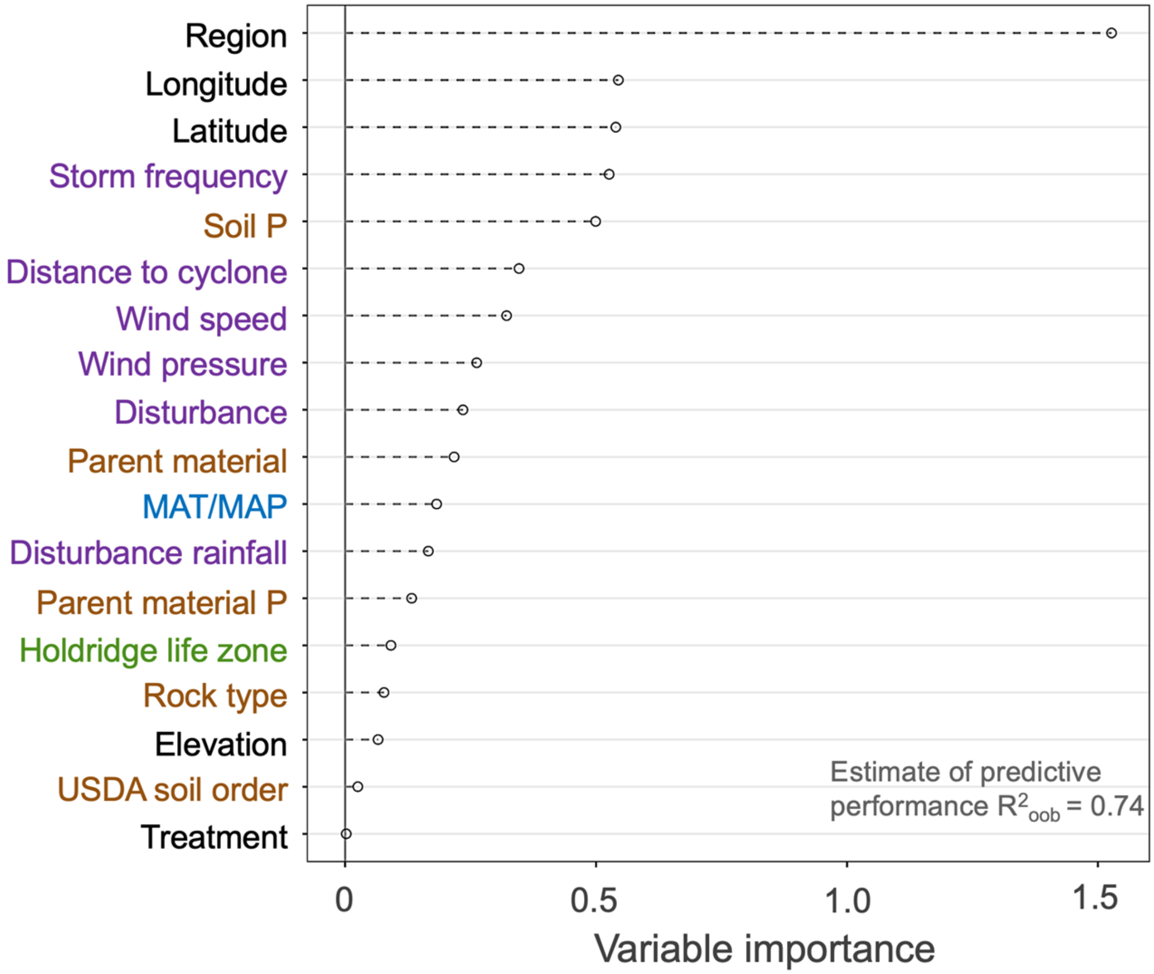


Fig. 6 Moderator variables ranked by their importance in explaining forest response to cyclone disturbance.

Total soil P is a significant predictor of forest response to tropical cyclone disturbance.

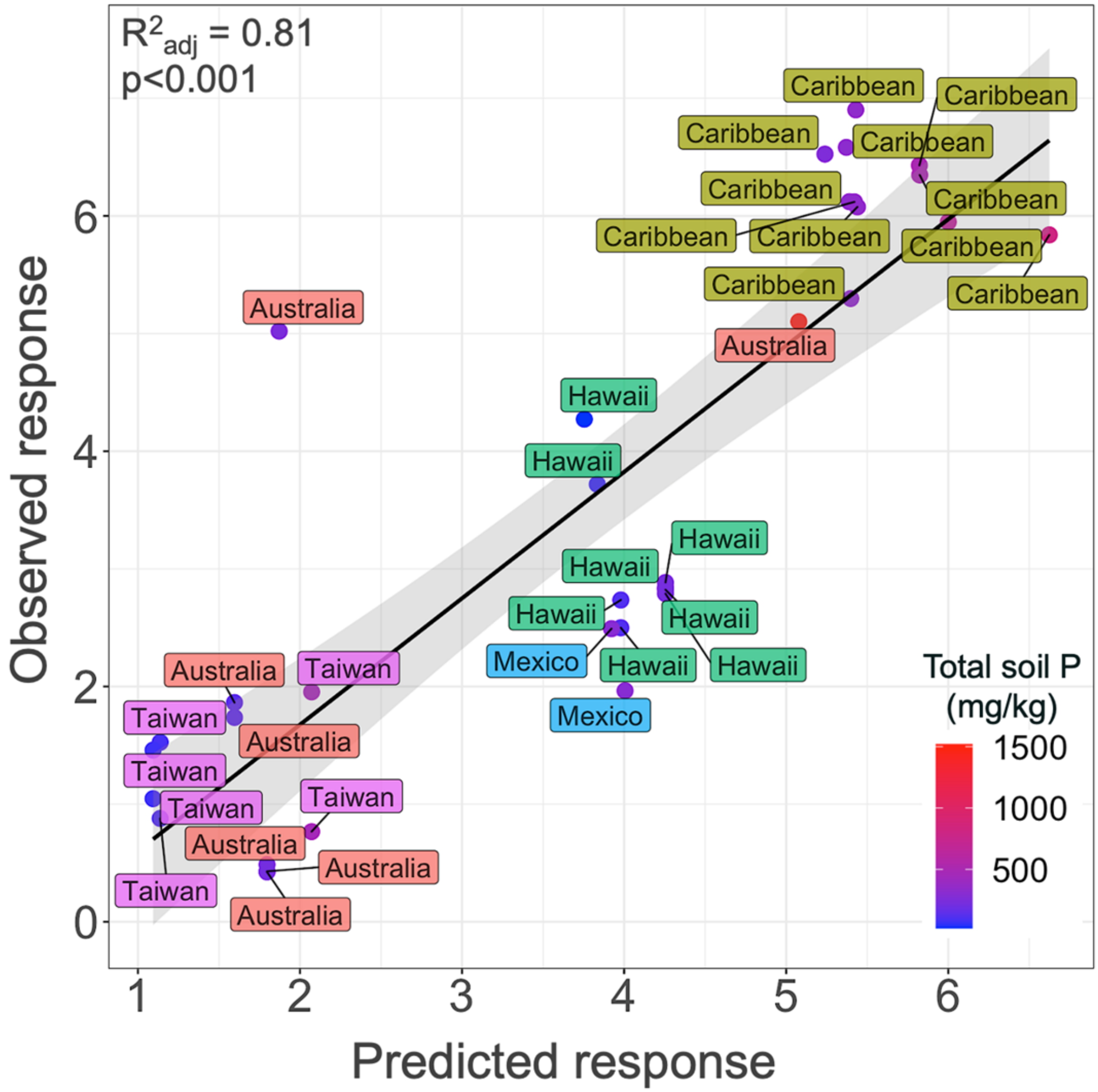


Fig. 7 Predictions of forest response (Rp: ln litterfall t_i/t_0) to cyclone disturbance by linear regression including total soil phosphorus (mg/kg) and study region as predictors.

Rp = 1.496 +

0.00173 soil P Australia

3.957 soil P (Caribbean)

1.321 soil P Hawaii

0.228 soil P Mexico

– 0.582 soil P Taiwan

RESULTS: RESILIENCE & RECOVERY

The overall resilience to cyclone changes from negative in the first year to neutral thereafter.

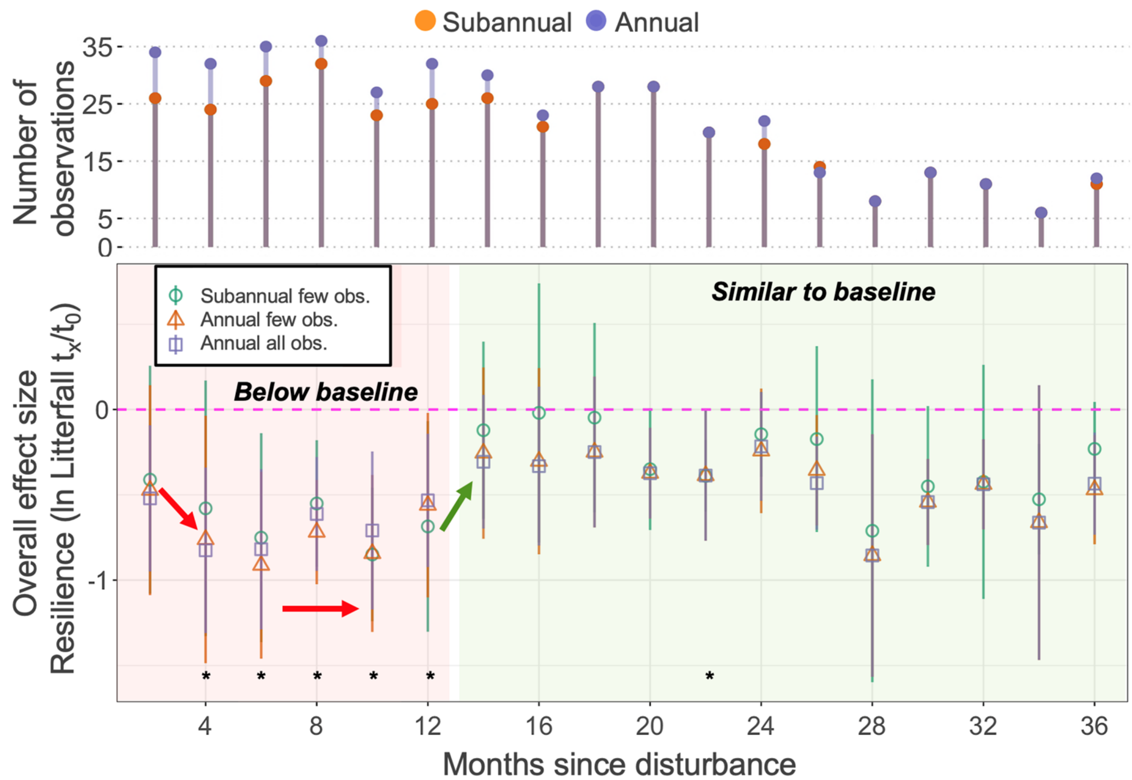


Fig. 8 Overall forest resilience to cyclone by time since disturbance. Asterisks denote a significant difference from the baseline at the 95% confidence level.

Resilience in the first year post-disturbance is negatively related to soil phosphorus.

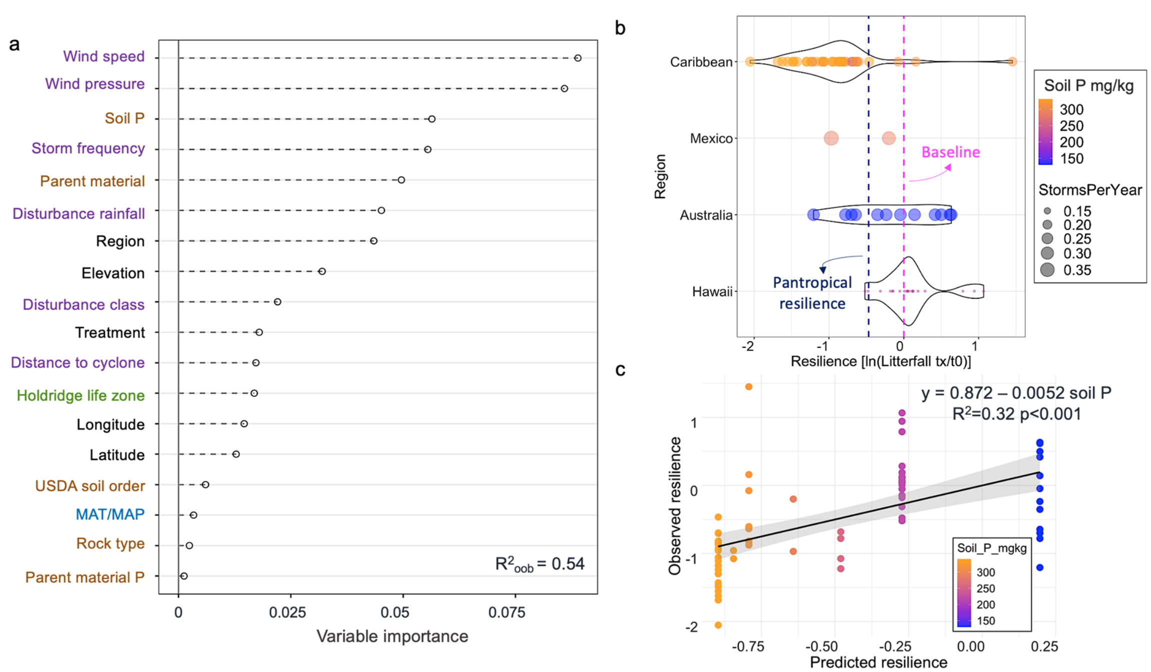


Fig. 9 (a) Predictor importance ranking using resilience calculated for the first 14 months post-cyclone response. (**b)** Resilience by total soil P, storm frequency (number of storms per year), and tropical region. (**c)** Resilience predictions using storm frequency and elevation as predictors.

Forest recovery after cyclone disturbance can be predicted by total soil P.

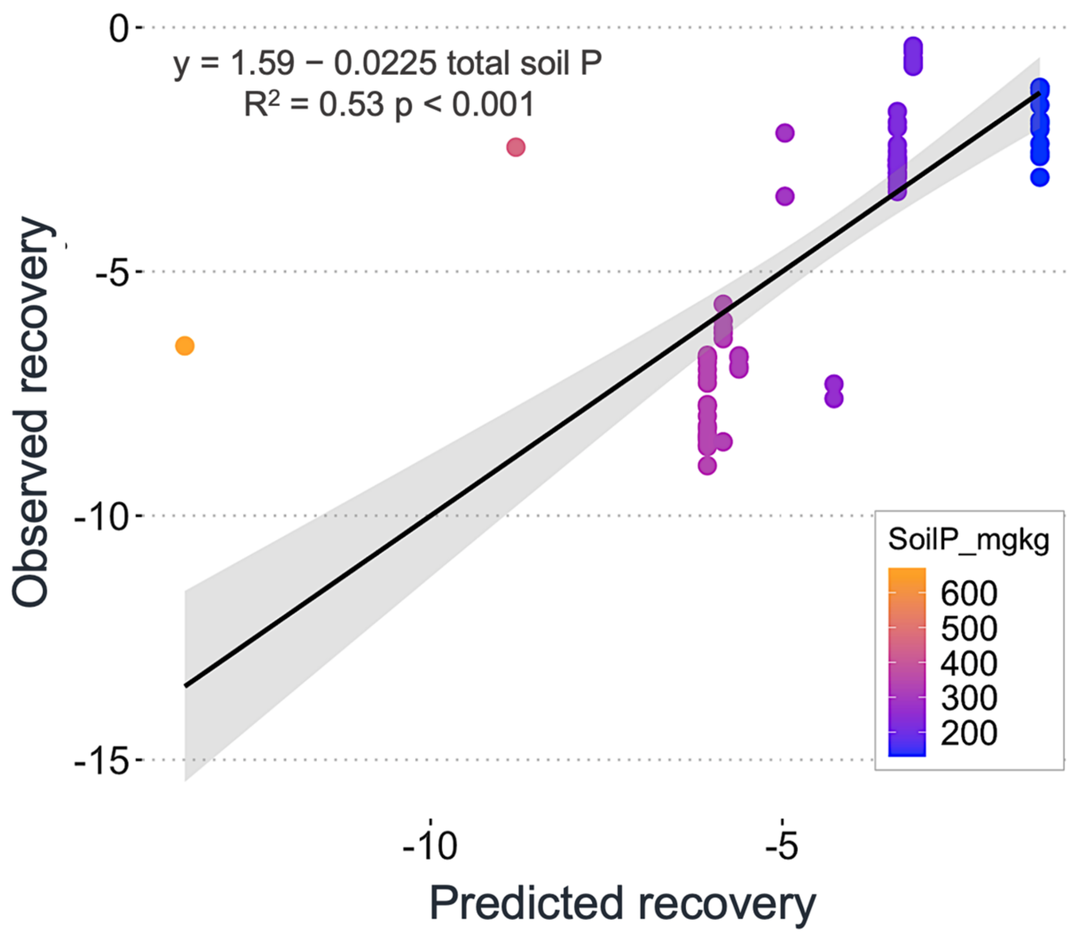


Fig. 10 Recovery index (ln litterfall t_x/t_i) predictions by linear regression, including total soil phosphorus as a significant predictor.

FUTURE DIRECTIONS

- How do P and N fluxes from the canopy to the floor change after cyclone disturbances?

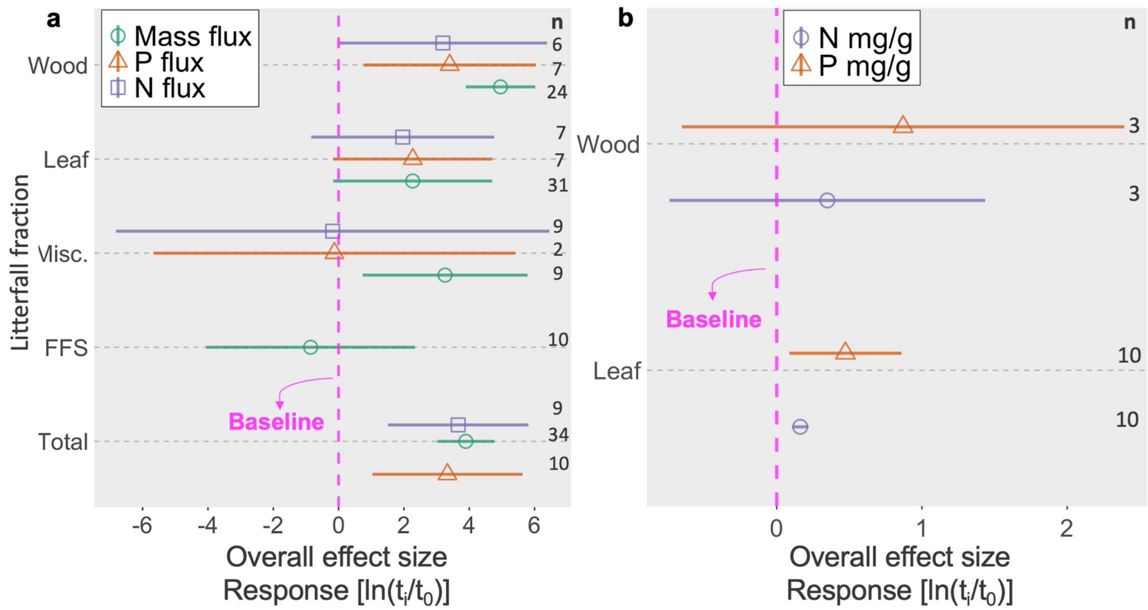


Fig. 11 The overall response of **a** litterfall mass, P and N fluxes (by fractions), and **b** wood and leaf fall N and P concentrations to cyclone disturbance.

- How does plant functional composition influence the response and resilience to cyclone disturbance?

- Can we extrapolate the response, resilience, and recovery predictions across the tropics?

HIGHLIGHTS & ACKNOWLEDGMENTS

- Across the tropics, forests on high-P soils were less resistant and resilient to tropical cyclones, at least in the first year post-disturbance.

- Forest recovery after tropical cyclone disturbance was negatively related to soil P concentration.

Acknowledgments

- U.S. Department of Energy Office of Science, Office of Biological and Environmental Research

- NGEE-Tropics project

- Luquillo LEF-LTER and Critical Zone Observatory

- USDA International Institute of Tropical Forestry (IITF)

- Ariel Lugo, USFS Puerto Rico

- Alonso Ramírez, North Carolina State University

- Whendee Silver, UC Berkeley

- Daniel Imbert, Université des Antilles

- Choy Huang and Hsueh-Ching, National Taiwan University

AUTHOR INFORMATION

Barbara Bomfim[1*], William McDowell[2], Jess K. Zimmerman[3], Anthony P. Walker[4], Lara M. Kueppers[1]

[1] Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory

[2] University of New Hampshire

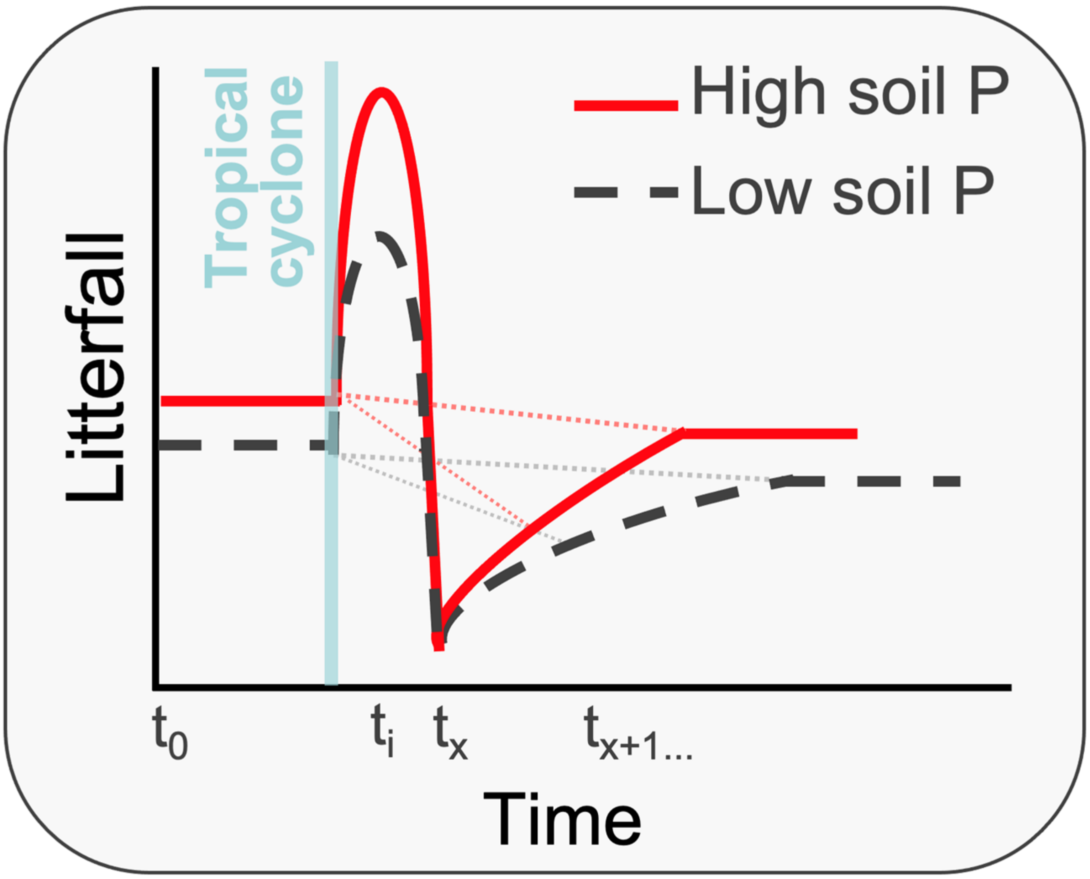
[3] University of Puerto Rico Rio Piedras

[4] Oak Ridge National Laboratory

* presenting author: bbomfim@lbl.gov

ABSTRACT

Tropical cyclones dominate the disturbance regime experienced by forest ecosystems in many parts of the world. Interactions between cyclone disturbance regimes and nutrient availability strongly influence forest ecosystem dynamics. However, uncertainty exists over the importance of soil fertility properties (i.e., total soil phosphorus-P concentration) in mediating forest resistance and recovery from cyclone disturbance. We hypothesized that forests on soils with low total P (e.g., developed on limited-P parent material) have a higher resistance to but a slower recovery from cyclone disturbance than forests on high P soils. We investigated cyclone impacts on litterfall, an essential conduit for nutrient recycling in forest ecosystems. We compiled site-level forest litterfall data from 56 studies and datasets associated with 15 naturally-occurring and one simulated tropical cyclone in 23 sites within five regions (Taiwan, Australia, Mexico, Hawaii, and the Caribbean) and four cyclone basins. We calculated the effect sizes of cyclone disturbance on the litterfall mass and nutrient (P and nitrogen-N) concentrations and fluxes during the first (< five) years post-disturbance across a total soil P gradient. We also assessed the effect of 20 covariates on the degree of cyclone impact on litterfall. Total litterfall mass flux increased by 4820% following cyclone disturbance. Such an initial increase in litterfall mass reflects the magnitude of cyclone-derived plant material input to the forest floor, which was highest in the Caribbean and lowest in Taiwan. Among 20 covariates, soil P and region were the best predictors of cyclone effects on total litterfall mass, explaining 80% of the variance. The effect sizes increased linearly with soil P and region, from significantly lower in Taiwan (low-P) to largest in the Caribbean (high-P). Total litterfall P and N fluxes increased significantly post-cyclone, whereas the increase in leaf P flux was twice as that in N flux. Results highlight the importance of understanding the interactions between disturbance and nutrient gradients in forest ecosystems to understand forest responses to altered cyclone regimes expected under climate change.



REFERENCES

Benson, L. J., & Pearson, R. G. (1993). Litter inputs to a tropical Australian rainforest stream. Australian Journal of Ecology, 18(4), 377–383. https://doi.org/10.1111/j.1442-9993.1993.tb00465.x

Brasell, H., Unwin, G., & Stocker, G. (1980). The Quantity, Temporal Distribution and Mineral-Element Content of Litterfall in Two Forest Types at Two Sites in Tropical Australia. Journal of Ecology, 68(1), 123-139. doi:10.2307/225924

Beard, K.H., Vogt, K.A., Vogt, D.J., Scatena, F.N., Covich, A.P., Sigurdardottir, R., Siccama, T.G. and Crowl, T.A. (2005), STRUCTURAL AND FUNCTIONAL RESPONSES OF A SUBTROPICAL FOREST TO 10 YEARS OF HURRICANES AND DROUGHTS. Ecological Monographs, 75: 345-361. https://doi.org/10.1890/04-1114

Cole, L. E. S., Bhagwat, S. A., & Willis, K. J. (2014). Recovery and resilience of tropical forests after disturbance. Nature Communications, 5(1), 3906.

Everham, E. M., & Brokaw, N. V. L. (1996). Forest damage and recovery from catastrophic wind. The Botanical Review, 62(2), 113–185.

Frangi, J., & Lugo, A. (1991). Hurricane Damage to a Flood Plain Forest in the Luquillo Mountains of Puerto Rico. Biotropica, 23(4), 324-335. doi:10.2307/2388248

Frangi, J. L., & Lugo, A. E. (1998). A Flood Plain Palm Forest in the Luquillo Mountains of Puerto Rico Five Years After Hurricane Hugo1. Biotropica, 30(3), 339–348. https://doi.org/10.1111/j.1744-7429.1998.tb00069.x

Gavito, M. E., Sandoval-Pérez, A. L., del Castillo, K., Cohen-Salgado, D., Colarte-Avilés, M. E., Mora, F., Santibáñez-Rentería, A., Siddique, I., & Urquijo-Ramos, C. (2018). Resilience of soil nutrient availability and organic matter decomposition to hurricane impact in a tropical dry forest ecosystem. Resilience of Tropical Dry Forests to Extreme Disturbance Events, 426, 81–90. https://doi.org/10.1016/j.foreco.2017.08.041

Gleason, S.M., Williams, L.J., Read, J. et al. Cyclone Effects on the Structure and Production of a Tropical Upland Rainforest: Implications for Life-History Tradeoffs. Ecosystems 11, 1277–1290 (2008). https://doi.org/10.1007/s10021-008-9192-6

Gleason, S., Read, J., Ares, A., & Metcalfe, D. (2009). Species-soil associations, disturbance, and nutrient cycling in an Australian tropical rainforest. Oecologia, 162, 1047–1058. https://doi.org/10.1007/s00442-009-1527-2

Harrington, Robin A.; Fownes, James H.; Scowcroft, Paul G.; Vann, Cheryl S. 1997. Impact of Hurricane Iniki on native Hawaiian Acacia koa forests: damage and two-year recovery. Journal of Tropical Ecology 13(4): 539-558 https://www.fs.usda.gov/treesearch/pubs/38336 (https://www.fs.usda.gov/treesearch/pubs/38336)

Heartsill-Scalley, T., Scatena, F.N., Lugo, A.E., Moya, S. and Estrada Ruiz, C.R. (2010), Changes in Structure, Composition, and Nutrients During 15 Yr of Hurricane−Induced Succession in a Subtropical Wet Forest in Puerto Rico. Biotropica, 42: 455-463. https://doi.org/10.1111/j.1744-7429.2009.00609.x

Hedges, L. V., Gurevitch, J., & Curtis, P. S. (1999). The Meta-Analysis of Response Ratios in Experimental Ecology. Ecology, 80(4), 1150–1156.

Herbert, D. A., Fownes, J. H., & Vitousek, P. M. (1999). HURRICANE DAMAGE TO A HAWAIIAN FOREST: NUTRIENT SUPPLY RATE AFFECTS RESISTANCE AND RESILIENCE. Ecology, 80(3), 908–920. https://doi.org/10.1890/0012-9658(1999)080[0908:HDTAHF]2.0.CO;2

Herbohn, J., & Congdon, R. (1993). Ecosystem dynamics at disturbed and undisturbed sites in north Queensland wet tropical rain forest. II. Litterfall. Journal of Tropical Ecology, 9(3), 365-380. doi:10.1017/S0266467400007422

Herbohn, J., & Congdon, R. (1998). Ecosystem Dynamics at Disturbed and Undisturbed Sites in North Queensland Wet Tropical Rain Forest. III. Nutrient Returns to the Forest Floor Through Litterfall. Journal of Tropical Ecology, 14(2), 217-229. Retrieved December 4, 2020, from http://www.jstor.org/stable/2560006

Hogan, J. A., Feagin, R. A., Starr, G., Ross, M., Lin, T.-C., O'connell, C., Huff, T. P., Stauffer, B. A., Robinson, K. L., Lara, M. C., Xue, J., Reese, B. K., Geist, S. J., Whitman, E. R., Douglas, S., Congdon, V. M., Reustle, J. W., Smith, R. S., Lagomasino, D., … Patrick, C. J. (2020). A Research Framework to Integrate Cross-Ecosystem Responses to Tropical Cyclones. BioScience, 70(6), 477–489.

Imbert, D., & Portecop, J. (2008). Hurricane disturbance and forest resilience: Assessing structural vs. Functional changes in a Caribbean dry forest. Forest Ecology and Management, 255(8), 3494–3501. https://doi.org/10.1016/j.foreco.2008.02.030

Jaramillo, V. J., Martínez-Yrízar, A., Maass, M., Nava-Mendoza, M., Castañeda-Gómez, L., Ahedo-Hernández, R., Araiza, S., & Verduzco, A. (2018). Hurricane impact on biogeochemical processes in a tropical dry forest in western Mexico. Resilience of Tropical Dry Forests to Extreme Disturbance Events, 426, 72–80. https://doi.org/10.1016/j.foreco.2017.12.031

Kim, D., Millington, A. C., & Lafon, C. W. (2019). Biotic and spatial factors potentially explain the susceptibility of forests to direct hurricane damage. Journal of Ecology and Environment, 43(1), 37.

Liao, J.-H., Wang, H.-H., Tsai, C.-C., & Hseu, Z.-Y. (2006). Litter production, decomposition and nutrient return of uplifted coral reef tropical forest. Forest Ecology and Management, 235(1), 174–185. https://doi.org/10.1016/j.foreco.2006.08.010

Lin, T.-C., Hogan, J. A., & Chang, C.-T. (2020). Tropical Cyclone Ecology: A Scale-Link Perspective. Trends in Ecology & Evolution, 35(7), 594–604. https://doi.org/10.1016/j.tree.2020.02.012

Liu, Xianbin; Zeng, Xiucheng; Zou, Xiaoming; González, Grizelle; Wang, Chao; Yang, Si. 2018. Litterfall Production Prior to and during Hurricanes Irma and Maria in Four Puerto Rican Forests. Forests. 9(6): 367-. https://doi.org/10.3390/f9060367.

Lloret, F., Keeling, E. G., & Sala, A. (2011). Components of tree resilience: Effects of successive low-growth episodes in old ponderosa pine forests. Oikos, 120(12), 1909–1920.

Lodge, D., Scatena, F., Asbury, C., & Sanchez, M. (1991). Fine Litterfall and Related Nutrient Inputs Resulting From Hurricane Hugo in Subtropical Wet and Lower Montane Rain Forests of Puerto Rico. Biotropica, 23(4), 336-342. doi:10.2307/2388249

Lugo, Ariel E.; Dominguez Cristobal, Carlos M.; Mendez, Noemi. 2011. Hurricane Georges accelerated litterfall fluxes of a 26 yr-old novel secondary forest in Puerto Rico. Pages 535-554 in Lupo, Anthony, ed. Recent Hurricane Research - Climate, Dynamics, and Societal Impacts. Rijeka, Croatia: Intech – Open Access Publisher. https://www.fs.usda.gov/treesearch/pubs/47275 (https://www.fs.usda.gov/treesearch/pubs/47275)

Lugo A. E.; Frangi, J. L. 2003. Changes in necromass and nutrients on the forest floor of a palm floodplain forest in the Luquillo mountains of Puerto Rico. Caribbean Journal of Science, Vol. 39, No. 3, https://www.fs.usda.gov/treesearch/pubs/30227 (https://www.fs.usda.gov/treesearch/pubs/30227)

Martínez-Yrízar, A., Jaramillo, V. J., Maass, M., Búrquez, A., Parker, G., Álvarez-Yépiz, J. C., Araiza, S., Verduzco, A., & Sarukhán, J. (2018). Resilience of tropical dry forest productivity to two hurricanes of different intensity in western Mexico. Resilience of Tropical Dry Forests to Extreme Disturbance Events, 426, 53–60. https://doi.org/10.1016/j.foreco.2018.02.024

Mitchell, S. J. (2013). Wind as a natural disturbance agent in forests: A synthesis. Forestry, 86(2), 147–157.

Ostertag, R., Scatena, F. N., & Silver, W. L. (2003). Forest Floor Decomposition Following Hurricane Litter Inputs in Several Puerto Rican Forests. Ecosystems, 6(3), 261–273.

Reed, K. A., Stansfield, A. M., Wehner, M. F., & Zarzycki, C. M. (2020). Forecasted attribution of the human influence on Hurricane Florence. Science Advances, 6(1), eaaw9253. https://doi.org/10.1126/sciadv.aaw925

Scatena, F., Silver, W., Siccama, T., Johnson, A., & Sanchez, M. (1993). Biomass and Nutrient Content of the Bisley Experimental Watersheds, Luquillo Experimental Forest, Puerto Rico, Before and After Hurricane Hugo, 1989. Biotropica, 25(1), 15-27. doi:10.2307/2388975

Scatena, F. N., Moya, S., Estrada, C., & Chinea, J. D. (1996). The First Five Years in the Reorganization of Aboveground Biomass and Nutrient Use Following Hurricane Hugo in the Bisley Experimental Watersheds, Luquillo Experimental Forest, Puerto Rico. Biotropica, 28(4), 424–440. JSTOR. https://doi.org/10.2307/2389086

Silver, W. L., Hall, S. J., & González, G. (2014). Differential effects of canopy trimming and litter deposition on litterfall and nutrient dynamics in a wet subtropical forest. Tropical Forest Responses to Large-Scale Experimental Hurricane Effects, 332, 47–55. https://doi.org/10.1016/j.foreco.2014.05.018

Shiels, A. B., González, G., & Willig, M. R. (2014). Responses to canopy loss and debris deposition in a tropical forest ecosystem: Synthesis from an experimental manipulation simulating effects of hurricane disturbance. Tropical Forest Responses to Large-Scale Experimental Hurricane Effects, 332, 124–133. https://doi.org/10.1016/j.foreco.2014.04.024 (https://doi.org/10.1016/j.foreco.2014.04.024)

Shiels, A. B., & González, G. (2014). Understanding the key mechanisms of tropical forest responses to canopy loss and biomass deposition from experimental hurricane effects. Tropical Forest Responses to Large-Scale Experimental Hurricane Effects, 332, 1–10. https://doi.org/10.1016/j.foreco.2014.04.024

S.J. Mitchell, Wind as a natural disturbance agent in forests: a synthesis, Forestry: An International Journal of Forest Research, Volume 86, Issue 2, April 2013, Pages 147–157, https://doi.org/10.1093/forestry/cps058

Van Bloem, S.J., Murphy, P.G., Lugo, A.E., Ostertag, R., Costa, M.R., Bernard, I.R., Colón, S.M. and Mora, M.C. (2005), The Influence of Hurricane Winds on Caribbean Dry Forest Structure and Nutrient Pools1. Biotropica, 37: 571-583. https://doi.org/10.1111/j.1744-7429.2005.00074.x

Vogt, K., Vogt, D., Boon, P., Covich, A., Scatena, F., Asbjornsen, H., . . . Ranciato, J. (1996). Litter Dynamics Along Stream, Riparian and Upslope Areas Following Hurricane Hugo, Luquillo Experimental Forest, Puerto Rico. Biotropica, 28(4), 458-470. doi:10.2307/2389088

Walker, L., Zimmerman, J., Lodge, D., & Guzman-Grajales, S. (1996). An Altitudinal Comparison of Growth and Species Composition in Hurricane-Damaged Forests in Puerto Rico. Journal of Ecology, 84(6), 877-889. doi:10.2307/2960559

Wang, H.−C., Wang, S.−F., Lin, K.−C., Lee Shaner, P.−J. and Lin, T.−C. (2013), Litterfall and Element Fluxes in a Natural Hardwood Forest and a Chinese−fir Plantation Experiencing Frequent Typhoon Disturbance in Central Taiwan. Biotropica, 45: 541-548. https://doi.org/10.1111/btp.12048

Whigham, D., Olmsted, I., Cano, E., & Harmon, M. (1991). The Impact of Hurricane Gilbert on Trees, Litterfall, and Woody Debris in a Dry Tropical Forest in the Northeastern Yucatan Peninsula. Biotropica, 23(4), 434-441. doi:10.2307/2388263

Zimmerman, J. K., Pulliam, W. M., Lodge, D. J., Quiñones-Orfila, V., Fetcher, N., Guzmán-Grajales, S., Parrotta, J. A., Asbury, C. E., Walker, L. R., & Waide, R. B. (1995). Nitrogen Immobilization by Decomposing Woody Debris and the Recovery of Tropical Wet Forest from Hurricane Damage. Oikos, 72(3), 314–322.

Data sets

Covich, A. 2015. Litterfall along topographic gradients at lower Bisley ver 449100. Environmental Data Initiative. https://doi.org/10.6073/pasta/f28b64f01a2f74eeaef2a6395d6b1eef (Accessed 2020-12-07).

Johnson, A., H. Xing (2020). LCZO -- Soil Survey -- Northeastern Puerto Rico and the Luquillo Mountain -- (2011-2012), HydroShare, http://www.hydroshare.org/resource/9211abc0a4fe4611a7c72ac31c35840c

Ramirez, A. 2017. Canopy Trimming Experiment (CTE) Litterfall ver 862752. Environmental Data Initiative. https://doi.org/10.6073/pasta/d0b205153e104cc5b411d8286a1ca037 (Accessed 2020-12-07).

Ramirez, A. 2018. Litterfall in tabonuco (subtropical wet) forest in the Luquillo Experimental Forest, Puerto Rico (MRCE Litterfall data) ver 1441410. Environmental Data Initiative. https://doi.org/10.6073/pasta/997366359135831a2e61268c5ca9945e (Accessed 2020-12-07).

Silver, W. 2018. Canopy Trimming Experiment Litterfall Nutrients Data ver 7. Environmental Data Initiative. https://doi.org/10.6073/pasta/bcbe47a10a08bc6ddca69fb2c59959ca (Accessed 2020-12-07).

Silver, W. and O. Gutierrez del Arroyo Santiago. 2018. CTE Soil Biogeochemistry 2014 ver 1. Environmental Data Initiative. https://doi.org/10.6073/pasta/a5777cd4cea388385ba253f7ea2d993a (Accessed 2020-12-07).

Zimmerman, J. 2017. Canopy Trimming Experiment (CTE) Plot Treatments ver 519602. Environmental Data Initiative. https://doi.org/10.6073/pasta/cfc838561b5432506a6002e317a8268f (Accessed 2020-12-07).