

ERRATA

Relationships among net primary productivity, nutrients and climate in tropical rain forest: a pan-tropical analysis

Cory C. Cleveland,^{1*} Alan R. Townsend,² Philip Taylor,³ Silvia Alvarez-Clare,⁴ Mercedes M. C. Bustamante,⁵ George Chuyong,⁶ Solomon Z. Dobrowski,⁷ Pauline Grierson,⁸ Kyle E. Harms,⁹ Benjamin Z. Houlton,¹⁰ Alison Marklein,¹⁰ William Parton,¹¹ Stephen Porder,¹² Sasha C. Reed,¹³ Carlos A. Sierra,¹⁴ Whendee L. Silver,¹⁵ Edmund V. J. Tanner¹⁶ and William R. Wieder³

Ecology Letters (2011) 14: 1313–1317

This is an errata to Cleveland *et al.* (2011).

Figure 1 includes a point in Mexico. However, original data from this lowland forest site were from a secondary (not primary) forest, and thus they were not included in the final lowland forest analysis.

In the Methods section, we stated, ‘We also included some data published in previous syntheses (Elsner *et al.* 2007; Townsend *et al.* 2007; LeBauer & Treseder 2008; Quesada *et al.* 2009), and examined relevant references cited therein for additional data’. However, the Quesada *et al.* (2009) citation was incorrectly reported in the references section; the correct reference is included in the list below. We regret this error given the importance of the soil P data reported in Quesada *et al.* (2010) to the relationships depicted in Fig. 3. We also note that data from the RAINFOR project (<http://www.geog.lccds.ac.uk/projects/rainfor>) were an important part of this synthesis, and we are grateful to all those involved in the RAINFOR project. A list of all references used to assemble the database is provided below, and all data (including references) are available at: <http://knb.ecoinformatics.org/knb/metacat/nceas.964/nceas>.

In the Abstract and Methods sections, we stated that surface soil P values represented measured concentrations from 0 to 10 cm depths. However, surface soil P concentrations used in the analyses represented concentrations from depths of < 30 cm.

In the Results section, we had classified lowland forests as those at a threshold elevation of 1000 m, and that this threshold corresponded to a mean annual temperature (MAT) breakpoint of 20.7 °C.

However, in the final analysis, two warm sites (24 °C MAT, elevation 1100 m) were included with ‘lowland forests’, and a cool (19.7 °C MAT) montane forest site at an elevation of 800 m was included with ‘upland forests’.

In the process of preparing the database for public distribution, we discovered several data reporting errors, and in a few cases, we were unable to relocate the original sources of the data used in the analyses. While none of these issues affected the overall conclusions of the article, they did lead to subtle changes in the relationships reported in Table 1, Figs 3 and 4, and Figure S2 (see Supporting Information), all of which have been reproduced correctly below.

Table 1 Summary of Pearson correlation coefficients between total soil P and covariates, *P*-values for individual pair-wise comparisons, and adjusted *P*-values for multiple comparisons. *P*-values were adjusted using Holm’s sequential Bonferroni correction (Holm 1979)

	Total soil P		Corrected <i>P</i> -value
	<i>r</i>	<i>P</i> -value	
Soil respiration	0.63	0.029	0.029
Total soil N	0.47	< 0.0001	< 0.0004
<i>k</i>	0.63	0.028	0.056
Foliar N	0.44	0.004	0.012
Foliar P	0.55	< 0.0001	< 0.0005

¹Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT 59812, USA

²Department of Ecology and Evolutionary Biology, Environmental Studies Program and INSTAAR, University of Colorado, Boulder, CO 80309, USA

³Department of Ecology and Evolutionary Biology and INSTAAR, University of Colorado, Boulder, CO 80309, USA

⁴Department of Biology & School of Natural Resources & Environment, University of Florida, Gainesville, FL 32611, USA

⁵Departamento de Ecología, Universidad de Brasilia, Brasília-DF, Brazil

⁶Department of Plant and Animal Sciences, University of Buea, POB 63 Buea, Cameroon

⁷Department of Forest Management, University of Montana, Missoula, MT 59812, USA

⁸School of Plant Biology M090, The University of Western Australia, 35 Stirling Highway, Crawley WA 6016, Australia

⁹Department of Biological Sciences, Louisiana State University, Baton Rouge, LA 70803, USA; Smithsonian Tropical Research Institute, Republic of Panama

¹⁰Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA

¹¹Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523-1499, USA

¹²Department of Ecology and Evolutionary Biology, Brown University, Providence, RI 02912, USA

¹³U.S. Geological Survey, Southwest Biological Science Center, 2290 S.W. Resource Blvd., Moab, UT 84532, USA

¹⁴Department of Biological Processes, Max-Planck-Institute for Biogeochemistry, 07745 Jena, Germany

¹⁵Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720, USA

¹⁶Department of Plant Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EA, UK

*Correspondence: E-mail: cory.cleveland@umontana.edu

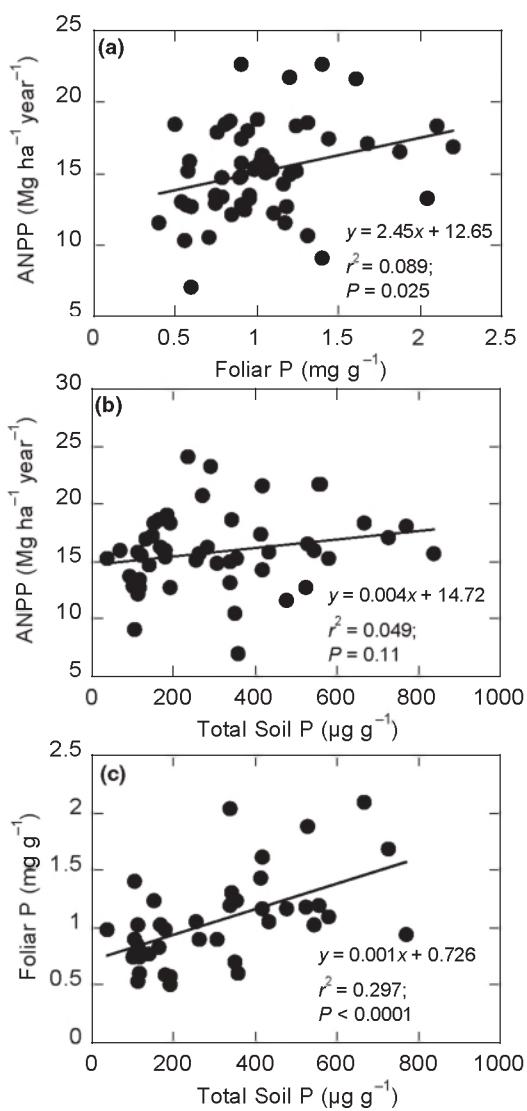


Figure 3 Relationships among P cycling variables and ANPP in lowland tropical forests. (a) Foliar P vs. ANPP; (b) total soil P vs. ANPP; (c) total soil P vs. foliar P.

REFERENCES

- Abe, H. (2007). *Forest Management Impacts on Growth, Diversity and Nutrient Cycling of Lowland Tropical Rainforest and Plantations, Papua New Guinea*. PhD Thesis, University of Western Australia, Perth, Australia.
- Adachi, M., Bekku, Y.S., Konuma, A., Kadir, W.R., Okuda, T. & Koizumi, H. (2005). Required sample size for estimating soil respiration rates in large areas of two tropical forests and of two types of plantation in Malaysia. *For. Ecol. Manage.*, 210, 455–459.
- Anderson, J.M., Proctor, J. & Vallack, H.W. (1983). Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak: III. Decomposition processes and nutrient losses from leaf litter. *J. Ecol.*, 71, 503–527.
- Aragão, L.E.O.C., Malhi, Y., Metcalfe, D.B., Silva-Espejo, J.E., Jiménez, E., Navarette, D. et al. (2009). Above- and below-ground net primary productivity across ten Amazonian forests on contrasting soils. *Biogeosciences*, 6, 2759–2778.
- Bigelow, S.W. (1993). Leaf nutrients in relation to stature and life form in tropical rain forest. *J. Veg. Sci.*, 4, 401–408.
- Bongers, F., Popma, J., Meave del Castillo, J. & Carabias, J. (1988). Structure and floristic composition of the lowland rain forest of Los Tuxtlas, Mexico. *Vegetatio*, 74, 55–80.
- Brown, S., Lugo, A.E., Silander, S. & Liegel, L. (1983). *Research History and Opportunities in the Luquillo Experimental Forest*. USDA Forest Service, Gen. Tech. Rep. SO-44. Southern Forest Experiment Station, New Orleans, LA.
- Carney, K.M. & Matson, P.A. (2006). The influence of tropical plant diversity and composition on soil microbial communities. *Microb. Ecol.*, 52, 226–238.
- Cavelier, J. & Estevez, J. (1996). Fine-root biomass in three successional stages of an Andean cloud forest. *Biotropica*, 28, 723–736.
- Chambers, J.Q., Higuchi, N., Schimel, J.P., Ferreira, L.V. & Melack, J.M. (2000). Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon. *Oecologia*, 122, 380–388.
- Chave, J., Condit, R., Lao, S., Caspersen, J.P., Foster, R.B. & Hubbell, S.P. (2003). Spatial and temporal variation of biomass in a tropical forest: results from a large census plot in Panama. *J. Ecol.*, 91, 240–252.
- Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S. & Perez, R. (2004). Error propagation and scaling for tropical forest biomass estimates. *Phil. Trans. R. Soc. Lond. B*, 359, 409–420.
- Chave, J., Condit, R., Muller-Landau, H.C., Thomas, S.C., Ashton, P.S., Bunyavejchewin, S. et al. (2008). Assessing evidence for a pervasive alteration in tropical tree communities. *PLoS Biol.*, 6, 455–462.
- Chave, J., Navarrete, D., Almeida, S., Alvarez, E., Aragao, L.E.O.C., Bonal, D. et al. (2010). Regional and seasonal patterns of litterfall in tropical South America. *Biogeosciences*, 7, 43–55.
- Chuyong, G.B., Newbery, D.M. & Songwe, N.C. (2000). Litter nutrients and retranslocation in a central African rain forest dominated by ectomycorrhizal trees. *New Phytol.*, 148, 493–510.
- Clark, D.B. & Clark, D.A. (2000). Landscape-scale variation in forest structure and biomass in a tropical rain forest. *For. Ecol. Manage.*, 137, 185–198.
- Clark, D.A., Brown, S., Kicklighter, D.W., Chambers, J.Q., Thominson, J.R., Ni, J. et al. (2001). Net primary production in tropical forests: an evaluation and synthesis of existing field data. *Ecol. Appl.*, 11, 371–384.
- Cleveland, C.C. & Townsend, A.R. (2006). Nutrient additions to a tropical rain forest drive substantial soil carbon dioxide losses to the atmosphere. *Proc. Natl. Acad. Sci. USA*, 103, 10316–10321.

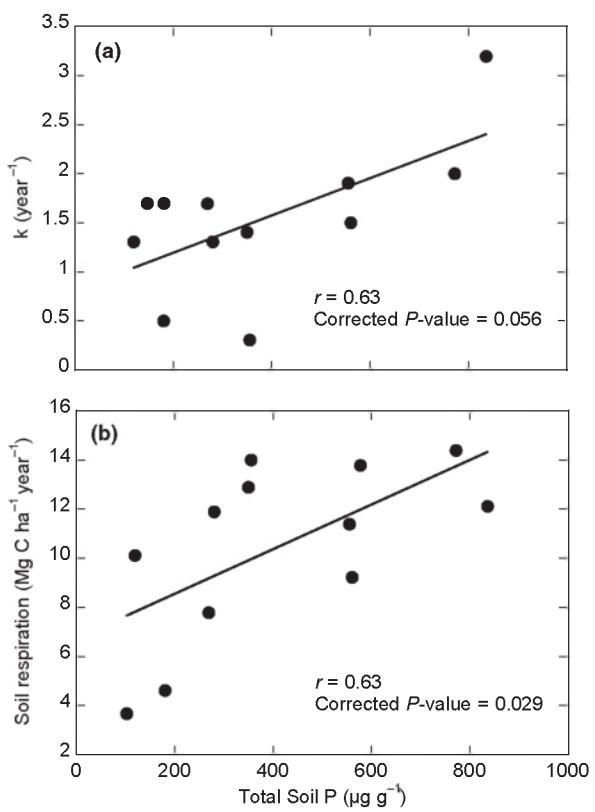


Figure 4 Total soil P vs.: (a) decomposition (k); and (b) soil respiration in lowland tropical forest. R -values represent Pearson correlation coefficients.

- Cleveland, C.C., Reed, S.C. & Townsend, A.R. (2006). Nutrient regulation of organic matter decomposition in a tropical rain forest. *Ecology*, 87, 492–503.
- Cleveland, C.C., Townsend, A.R., Taylor, P., Alvarez-Clare, S., Bustamante, M.M.C., Chuyong, G. *et al.* (2011). Relationships among net primary productivity, nutrients and climate in tropical rain forest: a pan-tropical analysis. *Ecol. Lett.*, 14, 939–947.
- Coley, P.D. (1983). Herbivory and defensive characteristics of tree species in a lowland tropical forest. *Ecol. Monogr.*, 53, 209–233.
- Condit, R., Aguilar, S., Hernandez, A., Perez, R., Lao, S., Angehr, G. *et al.* (2004). Tropical forest dynamics across a rainfall gradient and the impact of an El Niño dry season. *J. Trop. Ecol.*, 20, 51–72.
- Cornfort, I.S. (1970). Leaf-fall in a tropical rain forest. *J. Appl. Ecol.*, 7, 603–608.
- Crews, T., Fownes, J., Herbert, D., Kitayama, K., Mueller-Dombois, D., Riley, R. *et al.* (1995). Changes in soil phosphorus and ecosystem dynamics across a long soil chronosequence in Hawaii. *Ecology*, 76, 1407–1424.
- Cuevas, E. & Medina, E. (1986). Nutrient dynamics with Amazonian forest ecosystems I: nutrient flux in fine litter fall and efficiency of nutrient utilization. *Oecologia*, 68, 466–472.
- Cuevas, E. & Medina, E. (1988). Nutrient dynamics with Amazonian forests II: Fine root growth, nutrient availability, and leaf litter decomposition. *Oecologia*, 76, 222–235.
- De Camargo, P.B., Trumbore, S., Martinelli, L.A., Davidson, E.A., Nepstad, D.C. & Victoria, R.L. (1999). Soil carbon dynamics in regrowing forest of eastern Amazonia. *Global Change Biol.*, 5, 693–702.
- Denich, M., Kanashiro, M. & Vlek, P.L.G. (2000). The potential and dynamics of carbon sequestration in traditional and modified fallow systems of the eastern Amazon region, Brazil. In: *Global Climate Change and Tropical Ecosystems* (eds Lal, R., Kimble, J.M. & Stewart, B.A.). CRC Press, Boca Raton, pp. 213–229.
- DeWalt, S.J. & Chave, J. (2004). Structure and biomass of four lowland neotropical forests. *Biotropica*, 36, 7–19.
- Edwards, P.J. (1977). Studies of mineral cycling in a montane rain-forest in New-Guinea: 2. Production and disappearance of litter. *J. Ecol.*, 65, 971–992.
- Edwards, P.J. & Grubb, P.J. (1982). Studies of mineral cycling in a montane rain-forest in New-Guinea: 4. Soil characteristics and the division of mineral elements between the vegetation and soil. *J. Ecol.*, 70, 649–666.
- Elser, J., Bracken, M.E.S., Cleland, E.E., Gruner, D.S., Harpole, W.S., Hillebrand, H. *et al.* (2007). Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecol. Lett.*, 10, 1135–1142.
- Espeleta, J.F. & Clark, D.A. (2007). Multi-scale variation in fine root biomass in a tropical rain forest: a seven year study. *Ecol. Monogr.*, 77, 377–404.
- Fearnside, P.M. (1996). Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forest. *For. Ecol. Manage.*, 80, 21–34.
- Fernandes, S.A.P., Bernoux, M., Cerri, C.C., Feigl, B.J. & Piccolo, M.C. (2002). Seasonal variation of soil chemical properties and CO₂ and CH₄ fluxes in unfertilized and P-fertilized pastures in an Ultisol of the Brazilian Amazon. *Geoderma*, 107, 227–241.
- Frangi, J.L. & Lugo, A.E. (1985). Ecosystem dynamics of a subtropical floodplain forest. *Ecol. Monogr.*, 55, 351–369.
- Fyllas, N.M., Patiño, S., Baker, T.R., Bielefeld Nardoto, G., Martinelli, L.A., Quesada, C.A. *et al.* (2009). Basin-wide variations in foliar properties of Amazonian forest phylogeny, soils and climate. *Biogeosciences*, 6, 2677–2708.
- Garcia-Montiel, D.C., Neill, C., Melillo, J., Thomas, S., Steudler, P.A. & Cerri, C.C. (2000). Soil phosphorus transformations following forest clearing for pasture in the Brazilian Amazon. *Soil Sci. Soc. Am. J.*, 64, 1792–1804.
- Gleason, S.M., Williams, L.J., Read, J., Metcalfe, D.J. & Baker, P.J. (2008). Cyclone effects on the structure and production of a tropical upland rainforest: implications for life-history traits. *Ecosystems*, 11, 1277–1290.
- Gleason, S.M., Read, J., Ares, A. & Metcalfe, D.J. (2009). Phosphorus economics of tropical rainforest species and stands across soil contrasts in Queensland, Australia: understanding the effects of soil specialization and trait plasticity. *Funct. Ecol.*, 23, 1157–1166.
- Grace, J., San Jose, J., Meir, P., Miranda, H.S. & Montes, R.A. (2006). Productivity and carbon fluxes of tropical savannas. *J. Biogeogr.*, 33, 387–400.
- Grubb, P.J. & Edwards, P.J. (1982). Studies of mineral cycling in a montane rain-forest in New-Guinea: 3. The distribution of mineral elements in the above-ground material. *J. Ecol.*, 70, 623–648.
- Hall, S.J., Asner, G. & Kitayama, K. (2004). Land use, climate, and substrate controls over soil N dynamics and N-oxide emissions in Borneo. *Biogeochemistry*, 70, 27–58.
- Hirsch, A.I., Little, W.S., Houghton, R.A., Scott, N.A. & White, J.D. (2004). The net carbon flux due to deforestation and forest regrowth in the Brazilian Amazon: analysis using a process-based model. *Global Change Biol.*, 10, 908–924.
- Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scand. J. Stat.*, 6, 65–70.
- Houlton, B., Sigman, D. & Hedin, L. (2006). Isotopic evidence for large gaseous nitrogen losses from tropical rainforests. *Proc. Natl Acad. Sci. USA*, 103, 8745–8750.
- Hughes, R.F., Kauffman, J.B. & Jaramillo, V.J. (1999). Biomass, carbon, and nutrient dynamics of secondary forests in a humid tropical region of México. *Ecology*, 80, 1892–1907.
- Hutyra, L.R., Munger, J.W., Hammond-Pyle, E., Saleska, S.R., Restrepo-Coupe, N., Daube, B.C. *et al.* (2008). Resolving systematic errors in estimates of net ecosystem exchange of CO₂ and ecosystem respiration in a tropical forest biome. *Agric. Forest Meteorol.*, 148, 1266–1279.
- John, R., Dalling, J.W., Harms, K.H., Yavitt, J.B., Stallard, R.F., Mirabello, M. *et al.* (2007). Soil nutrients influence spatial distributions of tropical tree species. *Proc. Natl Acad. Sci. USA*, 104, 864–869.
- Johnson, C.M., Vieira, I.C.G., Zarin, D.J., Frizzano, J. & Johnson, A.H. (2001). Carbon and nutrient storage and primary and secondary forests in eastern Amazonia. *For. Ecol. Manage.*, 47, 245–252.
- Jordan, C.F. (1985). *Nutrient Cycling in Tropical Forest Ecosystems*. John Wiley and Sons, New York.
- Kasparyan, M., Garcia, M.N., Harms, K.E., Santana, M., Wright, S.J. & Yavitt, J.B. (2008). Multiple nutrients limit litterfall and decomposition in a tropical forest. *Ecol. Lett.*, 11, 35–43.
- Kira, T., Manokaran, N. & Appanah, S. (1998). NPP tropical forest: Pasoh, Malaysia, 1971–1973 (Dataset). Available at: <http://www.Daac.Oml.Gov>. Last accessed 18 October 2011.
- Kitayama, K. & Aiba, S. (2002). Ecosystem structure and productivity of tropical rain forests along altitudinal gradients with contrasting soil phosphorus pools on Mount Kinabalu, Borneo. *J. Ecol.*, 90, 37–51.
- Kitayama, K., Majalap-Lee, N. & Aiba, S. (2000). Soil phosphorus fractionation and phosphorus-use efficiencies of tropical rainforests along altitudinal gradients of Mount Kinabalu, Borneo. *Oecologia*, 123, 342–349.
- Kitayama, K., Aiba, S., Takyu, M., Majalap, N. & Wagai, R. (2004). Soil phosphorus fractionation and phosphorus-use efficiency of a Bornean tropical montane rain forest during soil aging with podzolization. *Ecosystems*, 7, 259–274.
- Klumpp, A., Domingos, M. & Klumpp, G. (2002). Foliar nutrient contents in tree species of the Atlantic rain forest as influenced by air pollution from the industrial complex of Cubatão, SE-Brazil. *Water Air Soil Poll.*, 133, 315–333.
- Kosugi, Y., Takanashi, S., Ohkubo, S., Matsuo, N., Tani, M., Mitani, T. *et al.* (2008). CO₂ exchange of a tropical rainforest at Pasoh in Peninsular Malaysia. *Agr. Forest Meteorol.*, 148, 439–452.
- Kursar, T.A. (1989). Evaluation of soil respiration and soil CO₂ concentration in a lowland moist forest in Panama. *Plant Soil*, 113, 21–29.
- Kursar, T.A. & Coley, P.D. (1991). Nitrogen content and expansion rate of young leaves of rain forest species: implications for herbivory. *Biotropica*, 23, 141–150.
- Laurance, W.F., Ferreira, L.V., de Merona, J.M.R. & Laurance, S.G. (1998). Rain forest fragmentation and the dynamics of Amazonian tree communities. *Ecology*, 79, 2032–2040.
- Laurance, W.F., Fearnside, P.M., Laurance, S.G., Delamonica, P., Lovejoy, T.E., de Merona, J.M.R. *et al.* (1999). Relationships between soils and Amazon forest biomass: a landscape-scale study. *For. Ecol. Manage.*, 118, 127–138.
- LeBauer, D.S. & Treseder, K.K. (2008). Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. *Ecology*, 89, 371–379.
- Leigh, E.G. Jr, Rand, A.S. & Windsor, D.M. (1982). *The Ecology of a Tropical Forest: Seasonal Rhythms and Long-term Changes*. Smithsonian Institution Press, Washington.
- Loescher, H.W., Oberbauer, S.F., Ghosh, H.L. & Clark, D.B. (2003). Environmental controls on net ecosystem-level carbon exchange and productivity in a Central American tropical wet forest. *Global Change Biol.*, 9, 396–412.
- Losos, E.C. & E.G. Leigh, J. (2004). *Tropical Forest Diversity and Dynamism: Findings From a Large-Scale Plot Network*. University of Chicago Press, Chicago.
- Malhi, Y., Baker, T.R., Phillips, O.L., Almeida, S., Alvarez, E., Arroyo, L. *et al.* (2004). The above-ground coarse wood productivity of 104 neotropical forest plots. *Global Change Biol.*, 10, 563–591.

- Markewitz, D., Davidson, E., Moutinho, P. & Nepstad, D. (2004). Nutrient loss and redistribution after forest clearing on a highly weathered soil in Amazonia. *Ecol. Appl.*, 14, S177–S199.
- Martínez-Yrízar, A., Maass, J.M., Pérez-Jiménez, A. & Sarukhan, J. (1996). Net primary productivity of a tropical deciduous forest in western Mexico. *J. Trop. Ecol.*, 12, 169–175.
- McDade, L.A., Bawa, K.S., Hespenheide, H.A. & Hartshorn, G.S. (1994). *La Selva: Ecology and Natural History of a Neotropical Rain Forest*. The University of Chicago Press, Chicago.
- McGroddy, M.E. & Silver, W.L. (2000). Variations in belowground carbon storage and soil CO₂ flux rates along a wet tropical gradient. *Biotropica*, 22, 614–624.
- McGroddy, M.E., Silver, W.L. & de Oliveira, R.C. (2004). The effect of phosphorus availability on decomposition dynamics in a seasonal lowland Amazonian forest. *Ecosystems*, 7, 172–179.
- Medina, E., Klinge, H., Jordan, C. & Herrera, R. (1980). Soil respiration in Amazonian rain forests in the Rio-Negro-Basin. *Flora*, 170, 240–250.
- Miller, A.J., Schuur, E.A.G. & Chadwick, O.A. (2001). Redox control of phosphorus pools in Hawaiian montane forest soils. *Geoderma*, 102, 219–237.
- Nardoto, G.B., Bustamante, M.M.C., Pinto, A.S. & Klink, C.A. (2006). Nutrient use efficiency at ecosystem and species level in savanna areas of Central Brazil and impacts on fire. *J. Trop. Ecol.*, 22, 191–201.
- Nardoto, G.B., Ometto, J.P.H.B., Ehleringer, J.R., Higuchi, N., Bustamante, M.M.D. & Martinelli, L.A. (2008). Understanding the influences of spatial patterns on N availability within the Brazilian Amazon forest. *Ecosystems*, 11, 1234–1246.
- Neill, C., Piccolo, M.C., Steudler, P.A., Melillo, J.M., Fiegl, B.J. & Cerri, C.C. (1995). Nitrogen dynamics in soils of forests and active pastures in the western Brazilian Amazon Basin. *Soil Biol. Biochem.*, 27, 1167–1175.
- Neill, C., Melillo, J.M., Steudler, P.A., Cerri, C.C., de Moraes, J.F.L., Piccolo, M.C. et al. (1997). Soil carbon and nitrogen stocks following forest clearing for pasture in the southwestern Brazilian Amazon. *Ecol. Appl.*, 7, 1216–1225.
- Nepstad, D.C., Moutinho, P., Dias-Filho, M.B., Davidson, E., Cardinot, G., Markewitz, D. et al. (2002). The effects of partial throughfall exclusion on canopy processes, aboveground production, and biogeochemistry of an Amazon forest. *J. Geophys. Res.*, 107, D20, 8085, doi: 10.1029/2001JD000360.
- Newbery, D. & Proctor, J. (1984). Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak: IV. Associations between tree distribution and soil factors. *J. Ecol.*, 72, 475–483.
- Ometto, J.P.H.B., Flanagan, L.B., Martinelli, L.A., Moreira, M.Z., Higuchi, N. & Ehleringer, J.R. (2002). Carbon isotope discrimination in forest and pasture ecosystems of the Amazon Basin, Brazil. *Global Biogeochem. Cycle*, 16, 1109–1118.
- Ostertag, R., Scatena, F.N. & Silver, W.L. (2003). Forest floor decomposition following hurricane litter inputs in several Puerto Rican forests. *Ecosystems*, 6, 261–273.
- Paoli, G.D. & Curran, L.M. (2007). Soil nutrients limit fine litter production and tree growth in mature lowland forest of Southwestern Borneo. *Ecosystems*, 10, 503–518.
- Paoli, G.D., Curran, L.M. & Zak, D.R. (2005). Phosphorus efficiency of Bornean rain forest productivity: evidence against the unimodal efficiency hypothesis. *Ecology*, 86, 1548–1561.
- Paoli, G.D., Curran, L.M. & Slik, J.W.F. (2008). Soil nutrient affect spatial patterns of aboveground biomass and emergent tree density in southwestern Borneo. *Oecologia*, 155, 287–299.
- Parron, L.M. (2004). *Aspectos Da Ciclagem De Nutrientes Em Função Do Gradiente Topográfico Em Uma Mata De Galeria No Distrito Federal*. PhD Thesis, University of Brasilia, Brazil.
- Parrotta, J.A., Francis, J.K. & Almeida, R.R. (1995). *Trees of the Tapajós: A photographic field guide. General Technical Report IITF-1*. USDA, Rio Piedras, Puerto Rico.
- Parton, W., Silver, W.L., Burke, I.C., Grassens, L., Harmon, M.E., Currie, W.S. et al. (2007). Global-scale similarities in nitrogen release patterns during long-term decomposition. *Science*, 315, 361–364.
- Pinto, A.S., Bustamante, M.M.C., Kisselle, K., Burke, R., Zepp, R., Viana, L.T. et al. (2002). Soil emissions of N₂O, NO and CO₂ in Brazilian Savannas: effects of vegetation type, seasonality and prescribed fires. *J. Geophys. Res.*, 107, 8089–8095.
- Porder, S., Clark, D.A. & Vitousek, P.M. (2006). Persistence of rock-derived nutrients in the wet tropical forests of La Selva, Costa Rica. *Ecology*, 87, 594–602.
- Portilho, K., Marques, D.F. & Wofsy, S.C. (2004). Carbon balance and vegetation dynamics in an old-growth Amazonian forest. *Ecol. Appl.*, 14, S55–S71.
- Powers, J.S., Treseder, K.K. & Lerdau, M.T. (2005). Fine roots, arbuscular mycorrhizal hyphae and soil nutrients in four neotropical rain forests: patterns across large geographic distances. *New Phytol.*, 165, 913–921.
- Proctor, J., Anderson, J.M., Fogden, S.L.C. & Vallack, H.W. (1983a). Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak: II. Litter standing crop and preliminary observations on herbivory. *J. Ecol.*, 71, 261–283.
- Proctor, J., Anderson, J.M., Chai, P. & Vallack, H.W. (1983b). Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak: I. Forest environment, structure and floristics. *J. Ecol.*, 71, 237–260.
- Pyle, E.H., Santoni, G.W., Nascimento, H.E.M., Hutyra, L.R., Vieira, S., Curran, D.J. et al. (2008). Dynamics of carbon, biomass, and structure in two Amazonian forests. *J. Geophys. Res.-Biogeosci.*, 113, G00B08, doi: 10.1029/2007JG000592.
- Quesada, C.A., Lloyd, J., Anderson, L.O., Fyllas, N.M., Schwarz, M. & Czimczik, C.I. (2009). Soils of amazonia with particular reference to the RAINFOR sites. *Biogeosciences Discuss.*, 6, 3851–3921.
- Quesada, C.A., Lloyd, J., Schwarz, M., Patiño, S., Baker, T.R., Czimczik, C. et al. (2010). Chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences*, 7, 1515–1541.
- Rai, S.N. & Proctor, J. (1986a). Ecological studies on four rain-forests in Karnataka, India. I. Environment, structure, floristics and biomass. *J. Ecol.*, 74, 439–454.
- Rai, S.N. & Proctor, J. (1986b). Ecological studies on four rain-forests in Karnataka, India: 2. Litterfall. *J. Ecol.*, 74, 455–463.
- Rentería, L.Y., Jaramillo, V.J., Martínez-Yrízar, A. & Pérez-Jiménez, A. (2005). Nitrogen and phosphorus resorption in trees of a Mexican tropical dry forest. *Trees Struct. Funct.*, 19, 431–441.
- Resende, J.C.F. (2001). *A ciclagem de nutrientes em áreas de Cerrado e a influência de queimadas controladas*. PhD Thesis, Universidade de Brasília, Brasília, Brazil.
- Rice, A.H., Pyle, E.H., Saleska, S.R., Hutyra, L., Palace, M., Keller, M. et al. (2004). Carbon balance and vegetation dynamics in an old-growth Amazonian forest. *Ecol. Appl.*, 14, S55–S71.
- Saldarriaga, J.G., West, D.C., Tharp, M.L. & Uhl, C. (1988). Long-term chronosequence of forest succession in the upper Rio Negro of Colombia and Venezuela. *J. Ecol.*, 76, 938–958.
- Santiago, L.S. (2007). Extending the leaf economics spectrum to decomposition: evidence from a tropical forest. *Ecology*, 88, 1126–1131.
- Santiago, L.S. & Mulkey, S.S. (2005). Leaf productivity along a precipitation gradient in lowland Panama: patterns from leaf to ecosystem. *Trees Struct. Funct.*, 19, 349–356.
- Santiago, L.S. & Wright, S.J. (2007). Leaf functional traits of tropical forest plants in relation to growth form. *Funct. Ecol.*, 21, 19–27.
- Santiago, L.S., Kitajima, K., Wright, S.J. & Mulkey, S.S. (2004). Coordinated changes in photosynthesis, water relations and leaf nutritional traits of canopy trees along a precipitation gradient in lowland tropical forest. *Oecologia*, 139, 495–502.
- Santiago, L.S., Schuur, E.A.G. & Silvera, K. (2005). Nutrient cycling and plant-soil feedbacks along a precipitation gradient in lowland Panama. *J. Trop. Ecol.*, 21, 461–470.
- Scatena, F.N., Silver, S., Siccama, T., Johnson, A. & Sanchez, M.J. (1993). Biomass and nutrient content of the Bisley experimental watersheds, Luquillo Experimental Forest, Puerto Rico, before and after hurricane Hugo. *Biotropica*, 25, 15–27.
- Schuur, E.A.G. & Matson, P.A. (2001). Net primary productivity and nutrient cycling across a mesic to wet precipitation gradient in Hawaiian montane forest. *Oecologia*, 128, 431–442.
- Schuur, E.A.G., Chadwick, O.A. & Matson, P.A. (2001). Carbon cycling and soil carbon storage in mesic to wet Hawaiian montane forests. *Ecology*, 82, 3182–3196.
- Schwendemann, L. & Veldkamp, E. (2006). Long-term CO₂ production from deeply weathered soils of a tropical rain forest: evidence for a potential positive feedback to climate warming. *Global Change Biol.*, 12, 1878–1893.
- Sierra, C.A., Harmon, M.E., Moreno, F.H., Orrego, S.A. & del Valle, J.I. (2007a). Spatial and temporal variability of net ecosystem production in a tropical forest: testing the hypothesis of a significant carbon sink. *Global Change Biol.*, 13, 838–853.
- Sierra, C.A., del Valle, J.I., Orrego, S.A., Moreno, F.H., Harmon, M.E., Zapata, M. et al. (2007b). Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. *For. Ecol. Manage.*, 243, 299–309.

- Silver, W.L. (1998). The potential effects of elevated CO₂ and climate change on tropical forest soils and biogeochemical cycling. *Clim. Change*, 39, 337–361.
- Silver, W.L., Scatena, F.N., Johnson, A.H., Siccamo, T.G. & Sanchez, M.J. (1994). Nutrient availability in a montane wet tropical forest: spatial patterns and methodological considerations. *Plant Soil*, 164, 129–145.
- Silver, W.L., Lugo, A.E. & Keller, M. (1999). Soil oxygen availability and biogeochemistry along rainfall and topographic gradients in upland wet tropical forest soils. *Biogeochemistry*, 44, 301–328.
- Silver, W.L., Neff, J., McGroddy, M., Veldkamp, E., Keller, M. & Cosme, R. (2000). Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian forest ecosystem. *Ecosystems*, 3, 193–209.
- Silver, W.L., Herman, D.J. & Firestone, M.K. (2001). Dissimilatory nitrate reduction to ammonium in upland tropical forest soils. *Ecology*, 82, 2410–2416.
- Silver, W.L., Thompson, A.W., Reich, A., Ewel, J.J. & Firestone, M.K. (2005). Nitrogen cycling in tropical plantation forests: potential controls on nitrogen retention. *Ecol. Appl.*, 15, 1604–1614.
- Sizer, N.C., Tanner, E.V.J. & Ferraz, I.D.K. (2000). Edge effects on litterfall mass and nutrient concentrations in forest fragments in central Amazonia. *J. Trop. Ecol.*, 16, 853–863.
- Smith, C.K., Gholz, H.L. & Oliveira, F.D. (1998). Fine litter chemistry, early-stage decay, and nitrogen dynamics under plantations and primary forest in Lowland Amazonia. *Soil Biol. Biochem.*, 30, 2159–2169.
- Smith, C.K., de Assis Oliveira, F., Gholz, H.L. & Baima, A. (2002). Soil carbon stocks after forest conversion to tree plantations in lowland Amazonia, Brazil. *For. Ecol. Manage.*, 164, 257–263.
- Sommer, R., Denich, M. & Vlek, P.L.G. (2000). Carbon storage and root penetration deep soils under small-farmer land-use systems in the eastern Amazon region, Brazil. *Plant Soil*, 219, 231–241.
- Sterrenberg, B.K. (1990). *Nutrient Availability During Vegetational Regrowth in a Lowland Tropical Rain Forest, Corcovado National Park, Costa Rica*. PhD Thesis, University of Texas, Austin, TX.
- Swamy, H.R. & Proctor, J. (1994a). Rain-forests and their soils in the Sringeri area of the Indian Western Ghats. *Global Ecol. Biogeogr.*, 4, 140–154.
- Swamy, H.R. & Proctor, J. (1994b). Litterfall and nutrient cycling in four rain-forests in the Sringeri area of the Indian Western Ghats. *Global Ecol. Biogeogr.*, 4, 155–165.
- Tanner, E.V.J. (1977). Four montane rain forests of Jamaica: a quantitative characterization of the floristics, the soils and the foliar mineral levels, and a discussion of the interrelations. *J. Ecol.* 65, 883–918.
- Tanner, E.V.J., Kapos, V., Freskos, S., Healey, J. & Theobald, A. (1990). Nitrogen and phosphorus fertilization of Jamaican montane forest trees. *J. Trop. Ecol.*, 6, 231–238.
- Tanner, E.V.J., Kapos, V. & Franco, W. (1992). Nitrogen and phosphorus fertilization effects on Venezuelan montane forest trunk growth and litterfall. *Ecology*, 73, 78–86.
- Tanner, E.V.J., Vitousek, P.M. & Cuevas, E. (1998). Experimental investigation of nutrient limitation of forest growth on wet tropical mountains. *Ecology*, 79, 10–22.
- Telles, E.C.C., de Camargo, P.B., Martinelli, L.A., Trumbore, S.E., da Costa, E.S., Santos, J. et al. (2003). Influence of soil texture on carbon dynamics and storage potential in tropical forest soils of Amazonia. *Global Biogeochem. Cycle*, 17, 1040–1051.
- Templer, P.H., Silver, W.L., Pett-Ridge, J., DeAngelis, K.M. & Firestone, M.K. (2008). Plant and microbial controls on nitrogen retention and loss in a humid tropical forest. *Ecology*, 89, 3030–3040.
- Townsend, A.R., Cleveland, C.C., Asner, G. & Bustamante, M.M.C. (2007). Controls of foliar N:P ratios in tropical rain forests. *Ecology*, 88, 107–118.
- Trumbore, S.E., Davidson, E.A., de Camargo, P.B., Nepstad, D.C. & Martinelli, L.A. (1995). Belowground cycling of carbon in forests and pastures of eastern Amazonia. *Global Biogeochem. Cycle*, 9, 515–528.
- Tucker, J.M., Brondizio, E.S. & Moran, E.F. (1998a). Rates of forest regrowth in eastern Amazonia: a comparison of Altamira and Bragantina regionas, Para state, Brazil. *Interviencia*, 23, 64–73.
- Tucker, J.M., Brondizio, E.S. & Moran, E.F. (1998b). Secondary succession in the Eastern Amazon: structural characterization and determinants of regrowth rates. In: *Ecology and Management of Tropical Secondary Forest: Science, People, and Policy* (eds Guariguata, M. & Finegan, B.) CATIEKIFOR, Costa Rica, pp. 49–67.
- Uhl, C. (1982). Tree dynamics in a species rich tierra firme forest in Amazonia, Venezuela. *Acta Cient. Venez.*, 33, 72–77.
- Uhl, C. (1987). Factors controlling succession following slash-and-burn agriculture in Amazonia. *J. Ecol.*, 75, 377–407.
- Uhl, C. & Jordan, C. (1984). Vegetation and nutrient dynamics during five years of succession following forest cutting and burning in the Rio Negro region of Amazonia. *Ecology*, 65, 1476–1490.
- Uhl, C. & Murphy, P.G. (1981). Composition, structure, and regeneration of a tierra firme forest in the Amazon Basin of Venezuela. *Trop. Ecol.*, 22, 219–237.
- Vandecar, K.L., Lawrence, D., Wood, T., Oberbauer, S.F., Das, R., Tully, K. et al. (2009). Biotic and abiotic controls on diurnal fluctuations in labile soil phosphorus of a wet tropical forest. *Ecology*, 90, 2547–2555.
- Vasconcelos, H.L. & Luizao, F.J. (2004). Litter production and litter nutrient concentrations in a fragmented Amazonian landscape. *Ecol. Appl.*, 14, 884–892.
- Vieira, L.S. & Dos Santos, P.C.T.C. (1987). *Amazônia: Seus Solos e Outros Recursos Naturais*. Agronômica Ceres, São Paulo.
- Vieira, S., de Camargo, P.B., Selhorst, D., da Silva, R., Hutyra, L., Chambers, J.Q. et al. (2004). Forest structure and carbon dynamics in Amazonian tropical rain forests. *Oecologia*, 140, 468–479.
- Vieira, S., Trumbore, S., Camargo, P.B., Selhorst, D., Chambers, J.Q., Higuchi, N. et al. (2005). Slow growth rates of Amazonian trees: consequences for forest carbon cycling. *Proc. Natl. Acad. Sci. USA*, 102, 18502–18507.
- Villela, D.M., Nascimento, M.T., de Aragão, L.E.O.C. & da Gama, D.M. (2006). Effect of selective logging on forest structure and nutrient cycling in a seasonally dry Brazilian Atlantic forest. *J. Biogeogr.*, 33, 506–516.
- Vitousek, P.M. (2004). *Nutrient Cycling and Limitation: Hawai'i as a Model System*. Princeton University Press, Princeton.
- Vitousek, P.M., Turner, D.R. & Kitayama, K. (1995). Foliar nutrients during long-term soil development in Hawaiian montane rain forest. *Ecology*, 76, 712–720.
- Wang, H. & Hall, C.A.S. (2004). Modeling the effects of Hurricane Hugo on spatial and temporal variation in primary productivity and soil carbon and nitrogen in the Luquillo Experimental Forest, Puerto Rico. *Plant Soil*, 263, 69–84.
- Weaver, P.L. & Murphy, P.G. (1990). Forest structure and productivity in Puerto Rico's Luquillo mountains. *Biotropica*, 22, 69–82.
- Wieder, W., Cleveland, C. & Townsend, A. (2009). Controls over leaf litter decomposition in wet tropical forests. *Ecology*, 90, 3333–3341.
- Wood, T.E. & Lawrence, D. (2008). No short-term change in soil properties following four-fold litter addition in a Costa Rican rain forest. *Plant Soil*, 307, 113–122.
- Wood, T.E., Lawrence, D. & Clark, D.A. (2006). Determinants of leaf litter nutrient cycling in a tropical rain forest: soil fertility versus topography. *Ecosystems*, 9, 700–710.
- Wood, T.E., Lawrence, D., Clark, D.A. & Chazdon, R.L. (2009). Rain forest nutrient cycling and productivity in response to large-scale litter manipulation. *Ecology*, 90, 109–121.
- Yavitt, J.B. (2000). Nutrient dynamics in soil derived from different parent material on Barro Colorado Island, Panama. *Biotropica*, 32, 198–207.
- Yavitt, J.B. & Wieder, R.K. (1988). Nitrogen, phosphorus and sulfur properties of some forest soils on Barro Colorado Island, Panama. *Biotropica*, 20, 2–10.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S2 ANPP vs. MAT (A and B) and MAP (C and D) in the upland and lowland forest sites in the database.

As a service to our authors and readers, this journal provides supporting information supplied by the authors. Such materials are peer-reviewed and may be re-organized for online delivery, but are not copy edited or typeset. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.