

Post-Disturbance Tree Community Trajectories in a Neotropical Forest

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Abstract

Résumé de l'article.

Keywords

mot-clés, séparés par des virgules

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Contents

1	Introduction	1
2	Material and Methods	2
2.1	Study site	2
2.2	Inventories protocol and dataset collection	2
2.3	Composition and diversity metrics	3
3	Results	3
3.1	Taxonomic and functional composition	3
	Composition trajectories • Traits community weighted means	
3.2	Disturbance impact on diversity	4
	Taxonomic diversity • Functional diversity	
4	Discussion	4
4.1	A validation of the intermediate disturbance hypothesis	4
4.2	On the recovery of disturbed communities	7
4.3	Functional redundancy of disturbed ecosystems	7
5	Conclusions	8

1. Introduction

The large areas covered with tropical forests worldwide hold crucial economic, social and cultural value. They provide wood and multiple non-timber forest products, shelter for a diversified fauna, regulate the local climate, support the carbon, water and nutrient cycles, and ensure cultural and human well-being. The simultaneous increase of forests products demand and substantial climatic changes heightened the pressure on the remaining forests (Gibson *et al.*, 2011; Morales-Hidalgo *et al.*, 2015) and threatened the maintenance of communities structure, composition and functioning and their underlying dynamics (Anderson-Teixeira *et al.*, 2013; Sist *et al.*, 2015).

In tropical forests communities are shaped by a constant range of disturbance that changes the abiotic environment,

as the light, heat and water fluxes, and the biotic interaction and competitive pressure. The cornerstone of tropical forests ecology is then to understand their response to disturbance and the corresponding mechanisms (White & Jentsch, 2001; Chazdon, 2003). Forests response to disturbance has been largely studied through structural parameters rapid and convenient to measure, as aboveground biomass, tree height or stem density. These structural parameters have then been successfully modeled and assessed the maintenance of ecosystems processes and services (Denslow & Guzman, 2000; Blanc *et al.*, 2009; Rutishauser *et al.*, 2016). However the response of tree species diversity although it is determinant of ecosystems productivity, stability and functioning (Tilman *et al.*, 2014) and it would be most probably impacted by the biotic and abiotic changes after disturbance (Cazzolla Gatti *et al.*, 2014).

In the short-term diversity dynamics demonstrated negligible or even positive impacts of disturbance on communities diversity, which have been formalized by the intermediate disturbance hypothesis (IDH) stating a maximized species diversity at intermediate disturbance intensity (Molino & Sabatier, 2001; Kariuki *et al.*, 2006; Berry *et al.*, 2008). However, validations of the IDH in the long term remain scarce and mainly rely on the analysis of species richness that gives limited or misleading information on forests recovery and functioning (Martin *et al.*, 2015; Chaudhary *et al.*, 2016). More relevant monitoring would encompass communities composition, that are crucial for conservation issues, and evenness, that revealing ecological rules underlying communities' structure (Magurran, 1988; Lavorel & Garnier, 2002; Bellwood *et al.*, 2006). Furthermore, the functional approach accounting for species biological attributes would be insightful as it reveals species fitness and ecosystems functioning (Violle *et al.*, 2007; Moretti *et al.*, 2009; Baraloto *et al.*, 2012; Scheiter *et al.*, 2013). In that

respect major functional traits related to species ecology and performance were largely adopted through a relevant framework (Díaz *et al.*, 2005; Villéger *et al.*, 2008). The functional trait-based approach, for example, highlighted in tropical rainforests the environmental filters fostering disturbance resistant species with rapid growth and efficient resources acquisition (Molino & Sabatier, 2001; Haddad *et al.*, 2008). This translated by shifts from “conservative” slow-growing species dealing with scarce resources, to “acquisitive” fast-growing species with rapid and efficient use of abundant resources (TerSteege & Hammond, 2001; Reich, 2014; Hérault *et al.*, 2011). It was mirrored by shifts in key functional traits related to resource acquisition (leaf area, density and chlorophyll content, and stem specific gravity and bark thickness), tree growth and reproduction life history traits (seed mass and maximum height) (Wright *et al.*, 2004; Westoby & Wright, 2006; Chave *et al.*, 2009). A proper monitoring of communities response should therefore encompass taxonomic and functional diversity and composition measures to test the validity of the IDH in the long term for tropical forests, and clarify the resilience of communities evenness, composition, and also functioning. The trajectories followed by all these facets would highlight the role of deterministic processes, like competitive exclusion or abiotic selection, and the communities’ convergence maintaining intrinsic differences in diversity and composition, which is as much insights for future adaptive conservation strategies (Adler *et al.*, 2007).

Here we investigated over 30 years the response of 75 ha of forests plots set up on a gradient of disturbance intensity, from 10 to 60% of ecosystem biomass removed. We made use of a large functional traits database browsing major leaf, stem and seed traits and species maximum height to draw the trajectories over time of communities taxonomic and functional composition and diversity. Specifically, we (i) tested the validity of the IDH in the long term for tropical hyperdiverse forest and highlighted the ecological rules shaping their response to disturbance, (ii) clarified the different facets of communities resilience in terms of communities composition, diversity and functioning (iii) questioned the completeness of communities recovery given the altered functional redundancy. >>revoir la fin

2. Material and Methods

2.1 Study site

Paracou station in French Guiana (5°18'N and 52°53'W) is located in a lowland tropical rain forest corresponding to a tropical wet climate with mean annual precipitation averaging 2980 mm.y⁻¹ (30-y period) with a 3-months dry season (< 100 mm.months⁻¹) from mid-August to mid-November, and a one-month dry season in March (Wagner *et al.*, 2011). Elevation ranges between 5 and 50 m and mean annual temperature is 26°C. Soils correspond to thin Acrisols over a layer of transformed saprolite with low permeability generating lateral drainage during heavy rains. The experiment corresponds to a network of twelve 6.25ha plots that have undergone a gradient of three logging, thinning and fuel-wood treatments (Table 1). Disturbance treatments were attributed according to a randomized plot design with three

replicate blocks of four plots. The disturbance corresponds to averages of 10 trees removed per hectare with a diameter at 1.3 m height (DBH) above 50 cm for treatment 1 (T1), 32 trees/ha above 40 cm DBH for treatment 2 (T2) and 40 trees above 40 cm DBH for treatment 3 (T3). Treatments T2 and T3 besides included the thinning of trees by poison girdling (Blanc *et al.*, 2009).

2.2 Inventories protocol and dataset collection

The study site corresponds to a tropical rainforest with a dominance of Fabaceae, Chrysobalanaceae, Lecythidaceae and Sapotaceae botanical families. In the twelve experimental plots of the experiment, all trees above 10 cm DBH were mapped and measured annually since 1984. During inventories, trees were first identified with a vernacular name assigned by the field team, and afterward with a scientific name assigned by a botanist during regular botanical campaigns. In 1984, specific vernacular names were given to 62 commercial or common species whereas other less common species were identified under two identifiers only separating trees and palm trees. The botanical campaigns carried every 5 to 6 years to identify all trees at the species level only started in 2003 and identification practices varied among plots and successive campaigns. This raised methodological issues as vernacular names usually correspond to different botanical species, resulting in significant taxonomic uncertainties that had to be propagated to composition and diversity metrics through a Bayesian framework. The uncertainty propagation was done by the replenishment of inventories completed at genus level from real incomplete ones on the basis of vernacular/botanical names association.

Vernacular names were replaced through multinomial trials $M_v \left([s_1, s_2, \dots, s_N], [\alpha_1, \alpha_2, \dots, \alpha_3] \right)$ based on the observed association probability $[\alpha_1, \alpha_2, \dots, \alpha_3]$ between each vernacular name v and the species $[s_1, s_2, \dots, s_N]$ recorded in the inventory.

To avoid remaining identification caveats and consider complete inventories, the simulated inventories were then reported at genus. See appendix 1 and Aubry-Kientz *et al.* (2013) for the detailed methodology.

The functional diversity metrics used a dataset for 6 functional traits representing leaf economics (leaves thickness, toughness, total chlorophyll content and specific leaf area, the leaf area per unit dry mass) and wood economics (wood specific gravity and bark thickness), and life history traits (maximum specific height and seed mass).

The trait database came from the BRIDGE project [^1] where traits values were assessed from a selection of individuals located in nine permanent plots in French Guiana, including two in Paracou. Missing trait values were filled using multivariate imputation by chained equation (mice) restricted to samples pertaining to the next higher taxonomic level, in order to account for the phylogenetic signal of the functional traits. The dataset comprised 294 botanical species pertaining to 157 botanical genera.

Whenever a species inventoried was not in the dataset, it was attributed a set of traits values randomly sampled among species of the same next higher taxonomic level. As seed mass information corresponds to a classification into

Table 1. Intervention table, summary of the disturbance intensity for the 4 plot treatments in Paracou.

Treatment	Timber	Thinning	Fuelwood	%AGB lost
Control				0
T1	DBH \geq 50 cm, commercial species, \approx 10 trees/ha			[12% – 33%]
T2	DBH \geq 50 cm, commercial species, \approx 10 trees/ha	DBH \geq 40 cm, non-valuable species, \approx 30 trees/ha		[33% – 56%]
T3	DBH \geq 50 cm, commercial species, \approx 10 trees/ha	DBH \geq 50 cm, non-valuable species, \approx 15 trees/ha	40 cm \leq DBH \leq 50 cm, non-valuable species, \approx 15 trees/ha	[35% – 56%]

mass classes, no data filling process was applied so analysis were performed considering the 414 botanical species of the seed mass dataset. All composition and diversity metrics corresponded to the average obtained after 50 iterations of the taxonomic uncertainty propagation framework and of the filling process of missing trait values.

[¹] <http://www.ecofog.gf/Bridge/>

2.3 Composition and diversity metrics

To counter the remaining taxonomic uncertainty plots taxonomic composition and diversity were analysed at the genus level, *i.e.* referring to the genus of observed or trialed botanical names. The analysis of taxonomic and functional composition of plots along time was visualized in a two-dimensional ordination space based on non-metric dimensional scaling of successive floristic or functional inventories. Plots trajectories along time was reported comparatively to the inventories in 1989, 5 years after disturbance, which corresponded to first inventory with a sufficient degree of uncertainty (<30% of undetermined trees). The inventories dissimilarity compared to the reference 1989 inventory was reported using occurrence-based (Jaccard) and abundance-based (Bray-Curtis) similarity measures. The trajectory of inventories along time was visualized with the euclidean distance in the two-dimensional ordination space to the 1989 inventory. The functional trajectories of the leaf and stem and life traits were also visualized with the community weighted means (CWM), representing the average trait value in a community weighted by relative abundance of the species carrying each value (Díaz *et al.*, 2007; *et al.* Garnier, 2004). Species seed mass corresponded to 5 classes of increasing mass, seed mass trajectories were therefore reported as the proportion of each class in the inventories.

The taxonomic diversity was assessed through Richness and the Hill number translation of Shannon and Simpson indices (Hill, 1973). >>To tackle the unequal number of recruited trees among treatments the indices bias corrected estimator were used, following (Chao & Jost, 2015; Marcon, 2015).

These three indices belong to the set of HCDT or generalized entropy, respectively corresponding to the 0, 1 and 2

order of diversity (q), which proved well suited for diversity studies (Patil & C., 1982; Tothmeresz & Tóthmérész, 1995). The functional diversity was reported using the Rao index of quadratic entropy which combines species abundance distribution and average pairwise dissimilarity based on all functional and life traits.

3. Results

3.1 Taxonomic and functional composition

3.1.1 Composition trajectories

Over time, 828388 trees and 591 botanical species pertaining to 223 genus and 64 botanical families were recorded. Trajectories of taxonomic and functional composition after disturbance were examined through the ordination of successive inventories from 1989 (5 years after disturbance) in the two-dimensional space from NMDS analysis based on flora inventories and the corresponding functional composition. Classifications were performed using either abundance-based Bray-Curtis (Figure 1) or incidence-based Jaccard dissimilarity (data not shown).

Both taxonomic and functional composition were substantially affected by disturbance, and the maximum dissimilarity to 1984 reference inventory composition was positively correlated with the disturbance intensity. Until 30 years after disturbance, all disturbed plots taxonomic composition remained significantly dissimilar to that of the 1989 reference inventory composition (Figure 1). All plots, though, displayed a unimodal trajectory with a the return toward the taxonomic and functional composition of the 1989 reference inventory suggesting a shift towards a cyclic regime (Figure 2). For taxonomic composition, the maximum dissimilarity to 1984 inventory composition was reach around 20 years after disturbance for the T2 and T3 plots and for one T1 plot while control and other T1 plots continued to increase (Figure 2.a). For functional composition, the maximum dissimilarity to 1984 inventory composition was reach from 15 to 20 years after disturbance for the T2 and T3 plots while T1 and control plots continued to increase (Figure 2.b). The functional composition distancing from the reference inventory was also positively correlated with

disturbance intensity and similarly stabilized or reduced (for 5 of T1, T2 and T3 plots) from 20 years after disturbance (Figure 2).

The coordinates of the functional traits were measured in the two-dimensional ordination space that mapped plots evolution along time (graphs not showed) revealed a trajectory of disturbed plots toward acquisitive functional strategies (from high WD to high SLA and chlorophyll content).

3.1.2 Traits community weighted means

For all plots the trajectories of the community weighted means (CWM) were drawn for the 8 functional and life history traits (Leaf thickness, chlorophyll content, toughness and specific area, wood specific gravity and bark thickness and seed mass and maximum adult height) (Figure 3).

To compensate the intrinsic difference among plots the trajectories drawn correspond to the difference in value between the reference inventory in 1984 (5 year after disturbance) and the successive years inventoried.

Except for leaf chlorophyll content, which displayed higher difference between plots than among treatments which may be due to the completeness of dataset, all CWM trajectories corresponded to significant changes after disturbance. All functional traits and seed mass proportions displayed a unimodal trajectories but with different times at maximum and different values 30 years after disturbance. The weighted means of communities specific maximum height at adult stage (H_{max}), leaf toughness ($L_{toughness}$) and wood specific gravity (WD) remained significantly lower than their initial value and than these of the control plots (Figure 3). The weighted means of bark thickness ($Bark_{thick}$) similarly remained substantially higher than initially for all disturbed plots while the specific leaf area (SLA) had almost recovered its initial value and this of the undisturbed plots at the end of the experiment.

3.2 Disturbance impact on diversity

3.2.1 Taxonomic diversity

Trajectories of Richness, Shannon and Simpson taxonomic diversity were examined at genus level in relation to the 1989 inventories (5 years after disturbance) (Figure 4).

For undisturbed plots the Richness, Shannon and Simpson diversity remained comparable to the initial values 5 years after disturbance. After disturbance, the richness increased after low disturbance intensity, with a maximum increase of 14 botanical genres (for plot 3 after treatment 2), but followed a unimodal decrease with a return to initial values after intense disturbance. The taxonomic evenness (Shannon and Simpson diversities), however, significantly increased after all disturbance regime. The evenness followed a unimodal trajectory with a just beginning return towards initial values and a maximum reached around 20 years and positively correlated to the disturbance intensity ($\rho_{Spearman}^{Shannon} = 0.92$, and $\rho_{Spearman}^{Simpson} = 0.97$). Only two T3 plots, plots 8 and 12, remained increasing 30 years after disturbance 4), suggesting a similar but much delayed unimodal trajectory.

3.2.2 Functional diversity

For all undisturbed plots the Rao diversity remained comparable to the initial values, 5 years after disturbance (1989 inventories). The trajectories of all disturbed plots followed a unimodal trajectory with a maximum positively correlated to disturbance intensity ($\rho_{Spearman}$) (Figure 5). The plot 7 from treatment 1 was removed from the graphical representation for better readability, see appendix for full graph. Thirty years after disturbance all plots, whenever the initial disturbance intensity, regained diversity values similar to their initial value and to those of control plots.

4. Discussion

4.1 A validation of the intermediate disturbance hypothesis

The monitoring 30 years of disturbed forest communities confirmed the limited direct impact of low disturbance on species richness as it was found for impact survey of selective logging (Cannon, 1998; Baraloto *et al.*, 2012). Only the most disturbed plots had not fully achieved the ongoing recovery of genus richness, although all had already reached equivalent levels as those of some control plots. Such long time richness recovery had already been observed in several logging experiments, which also highlighted the role of random disturbance damage in the richness decrease (de Avila *et al.*, 2015; Hu *et al.*, 2018).

The evenness of all disturbed plots and the richness of low disturbance plots on the other hand mainly followed an asymptotic growth sharply increasing until 15 years after disturbance. Such increased evenness is explained by a much more homogeneous species distribution after disturbance. Communities composition after disturbance is either due to the old, pre-disturbance survivors or to the recruited trees. The composition of old survivors proved to mirror the initial community (Héroult & Pioniot, 2018), the observed composition turnover would stem from an enhanced the growth and survival of previously infrequent species which, along with the IDH, reorganizes the typical high dominance structure of hyperdiverse mature forests. This increase in taxonomic diversity was accompanied by an increased taxonomic dissimilarity to initial state along time, translating a taxonomic turnover benefiting to pioneers and light demanding species, as illustrated by the communities functional shifts towards resource-acquisitive strategies (sharp increase in the SLA, leaf thickness and bark thickness and decrease in wood density, leaf toughness and maximum height) (Westoby, 1998; Wright *et al.*, 2004; Reich, 2014). Post-disturbance changes in abiotic environment and competitive pressure then well favored pioneers outcompeting other species when abiotic resources are abundant but otherwise excluded in mature forests by long-lived, resistant and shade tolerant species. The trajectories of proportions among seed mass classes besides revealed the enhanced growth of small seeded, large dispersive, species and therefore the importance of species reproductive strategy which further supported the role of species dispersion and demographic strategy for the post-disturbance dynamics, as suggested by the IDH (TerSteege & Hammond, 2001; Flores *et al.*, 2006; Haddad *et al.*, 2008).

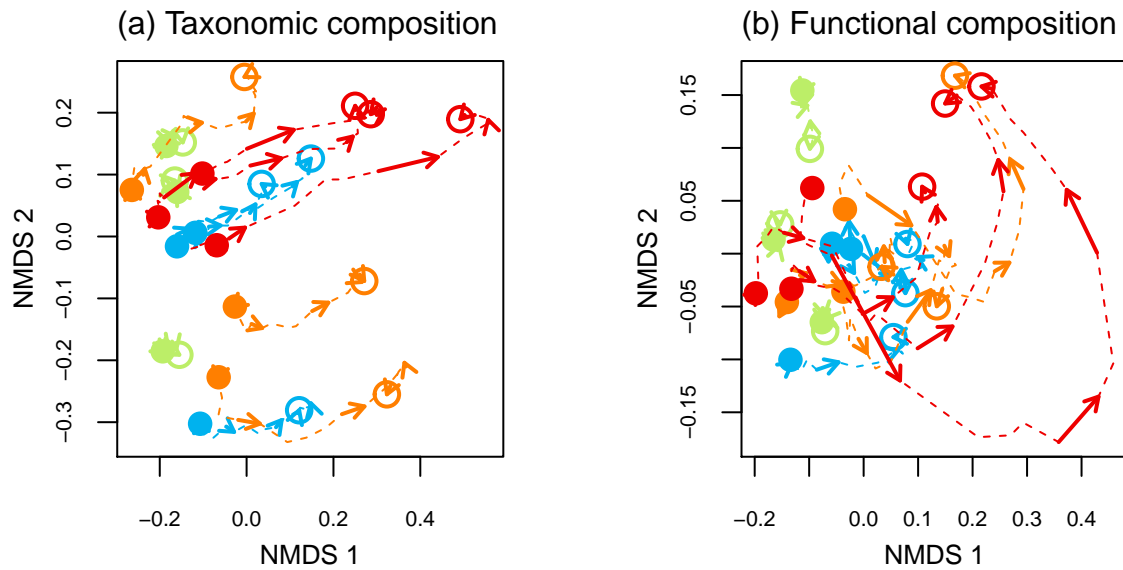


Figure 1. Trajectories of the plots in terms of **(a)** flora composition and **(b)** functional composition regarding the 6 leaf and stem functional traits, the maximum allometric height and seed mass class in the two-dimensional space from the NMDS performed for the 30 years after disturbance. Distance matrix for NMDS were computed from the Bray-curtis dissimilarity between successive inventories. Line colors represent the disturbance treatment (green for control, blue for T1, orange for T2 and red for T3).

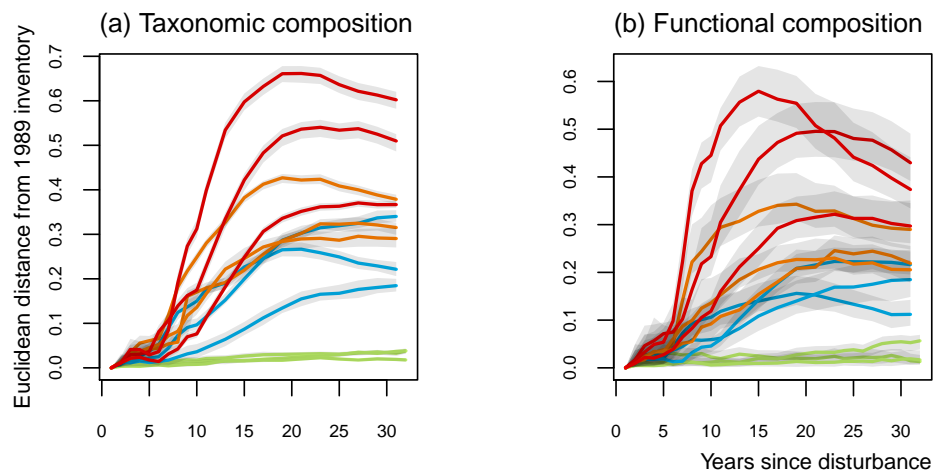


Figure 2. Trajectories of the distance to initial condition of the 30 sampled years in the two-dimensional space from the NMDS of **(a)** taxonomic composition at genus level and **(b)** functional composition. Distance are abundance-based Bray-Curtis metric. Line colors represent the disturbance treatment (green for control, blue for T1, orange for T2 and red for T3). The 0.025 and 0.975 percentile correspond to the variance observed for 50 iteration of the taxonomic uncertainty propagation and functional trait filling processes.

Community Weighted Means

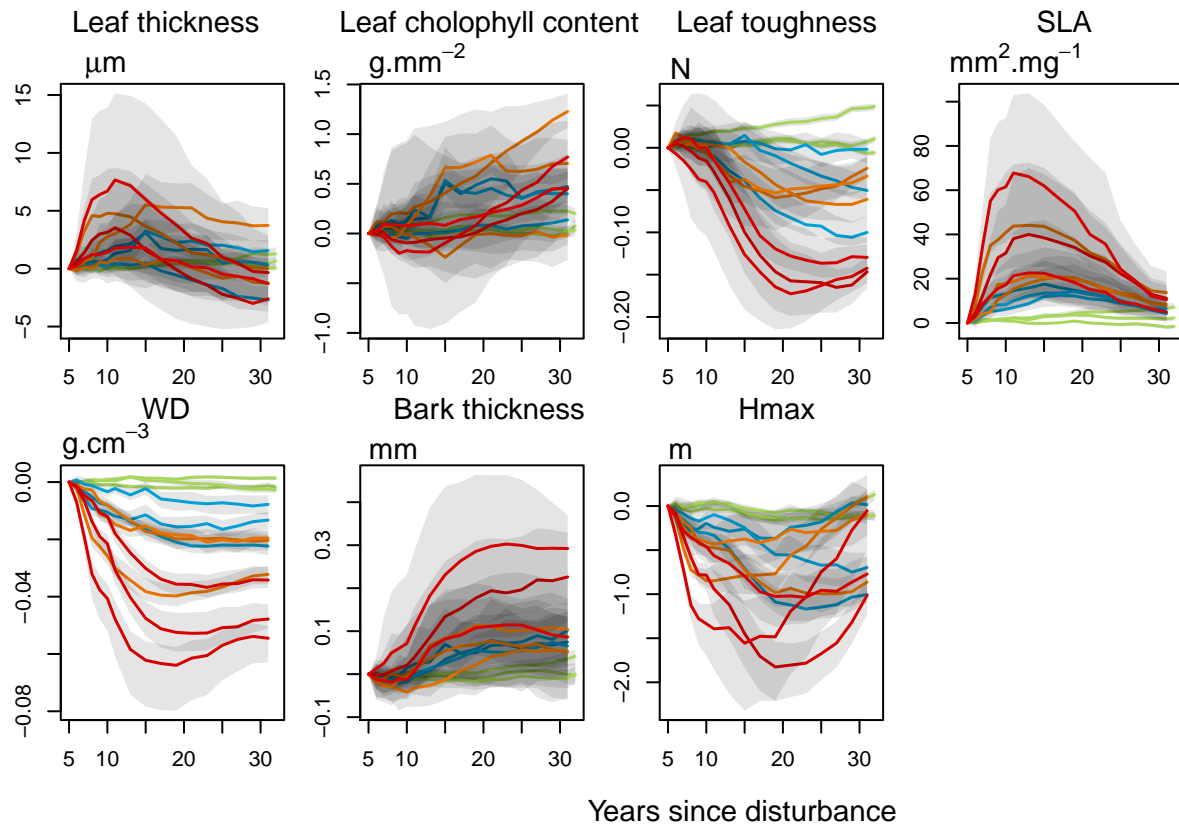


Figure 3. Trajectories of the communities weighted means (CWM) over 30 years after disturbance of 4 leaf traits (Leaf thickness, $L_thickness$, chlorophyll content, L_chloro , toughness, $L_toughness$ and specific area, SLA), 2 stem traits (wood specific gravity, WD , and bark thickness, $Bark-thick$) and one life trait (Specific maximum height at adult stage, $Hmax$). Trajectories correspond to the median (solid line) and 0.025 and 0.975 percentile (gray envelope) observed after 50 iteration of the taxonomic uncertainty propagation and the missing trait value filling processes. Initial treatments are represented by solid lines colors with green for control, blue for T1, orange for T2 and red for T3.

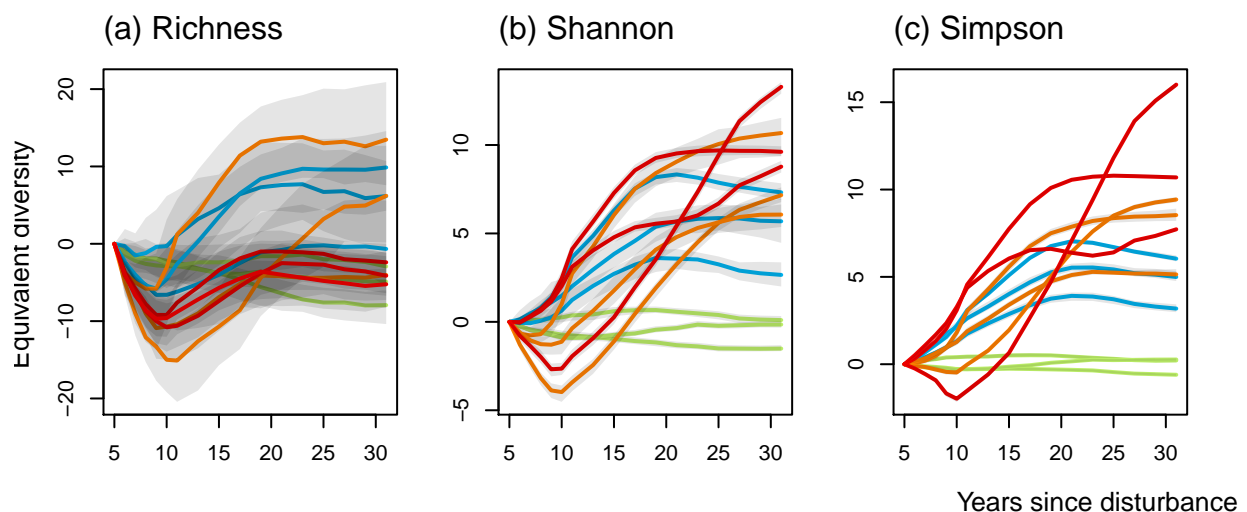


Figure 4. Trajectories of the difference to the 1989 inventories (5 years after disturbance) over 30 years after disturbance of plots communities (a) Richness, (b) Shannon and (c) Simpson diversities. Trajectories correspond to the median (solid line) and 0.025 and 0.975 percentile (gray envelope) observed after 50 iteration of the taxonomic uncertainty propagation. Initial treatments are represented by solid lines colors with green for control, blue for T1, orange for T2 and red for T3.

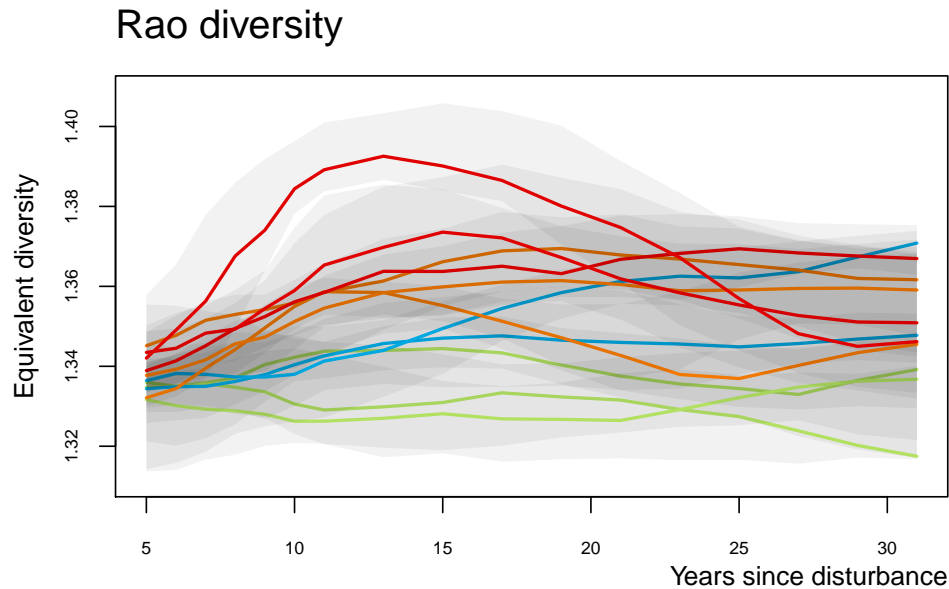


Figure 5. Trajectories of the Rao functional diversity over 30 years after disturbance. Trajectories correspond to the median (solid line) and 0.025 and 0.975 percentile (gray envelope) observed after 50 iteration of the taxonomic uncertainty propagation. Initial treatments are represented by solid lines colors with green for control, blue for T1, orange for T2 and red for T3, and the missing trait value filling processes.

4.2 On the recovery of disturbed communities

The functional diversity followed a hump-back trajectory which maximum was positively correlated to the disturbance intensity ($\rho_{\text{spearman}} =$) and after 30 years, all disturbed plots had recovered diversities close to their initial values. Similar hump-back trajectories were followed by all leaf and stem functional traits and life history traits, to the exception of leaf chlorophyll content. Although the return to initial values was still ongoing the recovery of functional diversity and average communities trait values was undeniable. This translated the recovery of ecosystems processes (Guariguata & Ostertag, 2001), as functional traits are the most direct link between biodiversity and ecosystem functioning (Díaz *et al.*, 2005). Same recovery trajectories were followed by taxonomic and functional composition which argued for communities convergence and the maintenance of plots initial difference (Hubbell *et al.*, 1999; Molino & Sabatier, 2001; Baraloto *et al.*, 2012). These composition difference, and probably also some abiotic parameters, besides strongly determined the maximum and time path of the trajectories which, despite an homogeneous trend were quite variable among plots.

4.3 Functional redundancy of disturbed ecosystems

Despite the consistent recovery of initial diversity and composition there was a time lag between the communities taxonomic and functional characteristics. Taxonomic composition had longer time path and while communities had recovered their functional diversity, their taxonomic composition and evenness remained higher than before disturbance.

This delay between functional and taxonomic dynamics was already observed for grasslands (Tilman, 1997; Mouillot *et al.*, 2011) and more recently for tropical forests (Lohbeck *et al.*, 2015; Guariguata & Ostertag, 2001). Communities functional diversity rely, according to the “vegetation quantity effect” (Grime, 1998), on the functional strategy of dominant species. Communities functional trajectory is then first driven by the increase of dominant species diversity and evenness following disturbance and then by the emergence of recruitment of species progressively resembling the old pre-disturbance community which decreased the diversity. Dominant species then restored the functional diversity and the dominant functional type of the community although the functional and taxonomic composition remained altered and the infrequent species of initial communities are still missing to plots recovery. The functional traits trajectories suggest that those species would match the dominant functional type therefore increasing communities functional redundancy. The functional overlap between species is typical of the huge biodiversity of tropical forests (Bellwood *et al.*, 2006), and proved far from recovery 03 years after disturbance. It is though a determinant of forests resilience and should be accounted for (Trenbath, 1999; Elmqvist *et al.*, 2003; Díaz *et al.*, 2005).

Long-term alteration of functional redundancy besides came along with persistent compositional changes which most probably impact disturbance resistant species (Haddad *et al.*, 2008) and probably lianas or epiphytes (Martin *et al.*, 2013), and the modification of environmental conditions like soils nutrient cycling and compaction (Olander *et al.*, 2005) forest resilience remains under question (Chazdon,

2003). New conditions would not only be longer lasting but self-maintained as tied to disturbance regime (Burslem *et al.*, 2000). Specifically, this would impair species contingent to undisturbed forests, threatening their maintenance, and run the risk to loose cornerstone species and trigger unexpected ecological consequences (Jones *et al.*, 1994; Díaz *et al.*, 2005; Gardner *et al.*, 2007).

5. Conclusions

Our study showed the significant impact of disturbance on tropical forests communities. The subsequent diversity trajectories confirmed the intermediate disturbance hypothesis debated for tropical forests through their correlation with disturbance intensity. Besides it revealed the contrasting response of taxonomic and functional characteristics, specifically the decoupling between communities taxonomic evenness and their functional diversity and dominant functional traits values. The long-term disturbance trajectories observed highlighted the unachieved but consistent recovery of communities assembly for the lowest disturbance intensity but questioned it after higher disturbance.

References

- Adler, P.B., HilleRisLambers, J. & Levine, J.M. (2007) A niche for neutrality. *Ecology Letters*, **10**, 95–104.
- Anderson-Teixeira, K.J., Miller, A.D., Mohan, J.E., Hudiburg, T.W., Duval, B.D. & DeLucia, E.H. (2013) Altered dynamics of forest recovery under a changing climate. *Global Change Biology*, **19**, 2001–2021.
- Aubry-Kientz, M., Hérault, B., Ayotte-Trépanier, C., Baraloto, C. & Rossi, V. (2013) Toward Trait-Based Mortality Models for Tropical Forests. *PLoS ONE*, **8**.
- Baraloto, C., Hérault, B., Paine, C.E.T., Massot, H., Blanc, L., Bonal, D., Molino, J.F.F., Nicolini, E.a. & Sabatier, D. (2012) Contrasting taxonomic and functional responses of a tropical tree community to selective logging. *Journal of Applied Ecology*, **49**, 861–870.
- Bellwood, D., Wainwright, P., Fulton, C. & Hoey, A. (2006) Functional versatility supports coral reef biodiversity. *Proceedings of the Royal Society B: Biological Sciences*, **273**, 101–107.
- Berry, N.J., Phillips, O.L., Ong, R.C. & Hamer, K.C. (2008) Impacts of selective logging on tree diversity across a rainforest landscape: The importance of spatial scale. *Landscape Ecology*, **23**, 915–929.
- Blanc, L., Echard, M., Hérault, B., Bonal, D., Marcon, E., Baraloto, C. & Chave, J. (2009) carbon stocks Dynamics of aboveground in a selectively logged tropical forest. *Ecological Applications*, **19**, 1397–1404.
- Burslem, D.F.R.P., Whitmore, T.C. & Brown, G.C. (2000) Short-term effects of cyclone impact and long-term recovery of tropical rain forest on Kolombangara, Solomon Islands. *Journal of Ecology*, **88**, 1063–1078.
- Cannon, C.H. (1998) Tree Species Diversity in Commercially Logged Bornean Rainforest. *Science*, **281**, 1366–1368.
- Cazzolla Gatti, R., Castaldi, S., Lindsell, J.A., Coomes, D.A., Marchetti, M., Maesano, M., Di Paola, A., Paparella, F. & Valentini, R. (2014) The impact of selective logging and clearcutting on forest structure, tree diversity and above-ground biomass of African tropical forests. *Ecological Research*, **30**, 119–132.
- Chao, A. & Jost, L. (2015) Estimating diversity and entropy profiles via discovery rates of new species. *Methods in Ecology and Evolution*, **6**, 873–882.
- Chaudhary, A., Burivalova, Z., Koh, L.P. & Hellweg, S. (2016) Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. *Scientific Reports*, **6**, 1–10.
- Chave, J., Coomes, D., Jansen, S., Lewis, S.L., Swenson, N.G. & Zanne, A.E. (2009) Towards a worldwide wood economics spectrum. *Ecology Letters*, **12**, 351–366.
- Chazdon, R.L. (2003) Tropical forest recovery: legacies of human impact and natural disturbances. *Perspectives in Plant Ecology, Evolution and Systematics*, **6**, 51–71.
- de Avila, A.L., Ruschel, A.R., de Carvalho, J.O.P., Mazzei, L., Silva, J.N.M., Lopes, J.d.C., Araujo, M.M., Dormann, C.F. & Bauhus, J. (2015) Medium-term dynamics of tree species composition in response to silvicultural intervention intensities in a tropical rain forest. *Biological Conservation*, **191**, 577–586.
- Denslow, J.S. & Guzman, G.S. (2000) Variation in stand structure, light and seedling abundance across a tropical moist forest chronosequence, Panama. *Journal of Vegetation Science*, **11**, 201–212.
- Díaz, S., Tilman, D., Fargione, J., Chapin III, F.S., Dirzo, R., Kitzberger, T., Gemmill, B., Zobel, M., Vilà, M., Mitchell, C., Wilby, A., Daily, G.C., Galetti, M., Laurance, W.F., Pretty, J., Naylor, R., Power, A., Harvell, A., Potts, S., Kremen, C., Griswold, T. & Eardley, C. (2005) Biodiversity Regulation of Ecosystem Services. *Ecosystems and human well-being: Current state and trends*, pp. 297–329 ST – Biodiversity Regulation of Ecosystem.
- Díaz, S., Lavorel, S., de Bello, F., Quétier, F., Grigulis, K. & Robson, T.M. (2007) Incorporating plant functional diversity effects in ecosystem service assessments. *Proceedings of the National Academy of Sciences*, **104**, 20684–20689.
- Elmqvist, T., Folke, C., Nystrom, M., Peterson, G., Bengtsson, J., Walker, B. & Norberg, J. (2003) Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment*, **1**, 488–494.
- et al. Garnier, E. (2004) Plant functional markers capture ecosystem properties during secondary succession. *Ecology*, **85**, 2630–2637.

- Flores, O., Gourlet-Fleury, S. & Picard, N. (2006) Local disturbance, forest structure and dispersal effects on sapling distribution of light-demanding and shade-tolerant species in a French Guianian forest. *Acta Oecologica*, **29**, 141–154.
- Gardner, T.A., Barlow, J., Parry, L.W. & Peres, C.A. (2007) Predicting the uncertain future of tropical forest species in a data vacuum. *Biotropica*, **39**, 25–30.
- Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E. & Sodhi, N.S. (2011) Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature*, **478**, 378–381.
- Grime, J. (1998) Benefits of plant diversity to ecosystems: immediate, filter and founder effects. *Journal of Ecology*, **86**, 902–910.
- Guariguata, M.R. & Ostertag, R. (2001) Neotropical secondary forest succession: changes in structural and functional characteristics. *Forest Ecology and Management*, **148**, 185–206.
- Haddad, N.M., Holyoak, M., Mata, T.M., Davies, K.F., Melbourne, B.A. & Preston, K. (2008) Species' traits predict the effects of disturbance and productivity on diversity. *Ecology Letters*, **11**, 348–356.
- Hérault, B., Bachelot, B., Poorter, L., Rossi, V., Bongers, F., Chave, J., Paine, C.E.T., Wagner, F. & Baraloto, C. (2011) Functional traits shape ontogenetic growth trajectories of rain forest tree species. *Journal of Ecology*, **99**, 1431–1440.
- Hérault, B. & Piponiot, C. (2018) Key drivers of ecosystem recovery after disturbance in a neotropical forest. *Forest Ecosystems*, **5**, 2.
- Hill, M.O. (1973) Diversity and Evenness : A Unifying Notation and Its Consequences. *Ecological Society of America*, **54**, 427–432.
- Hu, J., Herbohn, J., Chazdon, R.L., Baynes, J., Wills, J., Meadows, J. & Soheli, M.S.I. (2018) Recovery of species composition over 46 years in a logged Australian tropical forest following different intensity silvicultural treatments. *Forest Ecology and Management*, **409**, 660–666.
- Hubbell, S.P., Foster, R.B., O'Brien, S.T., Harms, K.E., Condit, R., Wechsler, B., Wright, S.J. & De Lao, S.L. (1999) Light-gap disturbances, recruitment limitation, and tree diversity in a neotropical forest. *Science (Washington D C)*, **283**, 554–557.
- Jones, C.G., Lawton, J.H. & Shachak, M. (1994) Organisms as ecosystem engineers. *Ecosystem management*, pp. 130–147. Springer.
- Kariuki, M., Kooyman, R.M., Smith, R.G.B., Wardell-Johnson, G. & Vanclay, J.K. (2006) Regeneration changes in tree species abundance, diversity and structure in logged and unlogged subtropical rainforest over a 36-year period. *Forest Ecology and Management*, **236**, 162–176.
- Lavorel, S. & Garnier, É. (2002) Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the holy grail. *Functional ecology*, **16**, 545–556.
- Lohbeck, M., Lebrija-Trejos, E., Martínez-Ramos, M., Meave, J.A., Poorter, L. & Bongers, F. (2015) Functional trait strategies of trees in dry and wet tropical forests are similar but differ in their consequences for succession. *PLoS ONE*, **10**, 1–15.
- Magurran, A.E. (1988) *Ecological diversity and its measurement*. Princeton, nj, prince edition.
- Marcon, E. (2015) Practical Estimation of Diversity from Abundance Data. *HAL archives-ouvertes*, p. 9.
- Martin, P.A., Newton, A.C. & Bullock, J.M. (2013) Carbon pools recover more quickly than plant biodiversity in tropical secondary forests. *Proceedings of the Royal Society B: Biological Sciences*, **280**, 20132236–20132236.
- Martin, P.A., Newton, A.C., Pfeifer, M., Khoo, M. & Bullock, J.M. (2015) Impacts of tropical selective logging on carbon storage and tree species richness: A meta-analysis. *Forest Ecology and Management*, **356**, 224–233.
- Molino, J.F. & Sabatier, D. (2001) Tree diversity in tropical rain forests: a validation of the intermediate disturbance hypothesis. *Science (New York, NY)*, **294**, 1702–1704.
- Morales-Hidalgo, D., Oswalt, S.N. & Somanathan, E. (2015) Status and trends in global primary forest, protected areas, and areas designated for conservation of biodiversity from the Global Forest Resources Assessment 2015. *Forest Ecology and Management*, **352**, 68–77.
- Moretti, M., De Bello, F., Roberts, S.P. & Potts, S.G. (2009) Taxonomical vs. functional responses of bee communities to fire in two contrasting climatic regions. *Journal of Animal Ecology*, **78**, 98–108.
- Mouillot, D., Villéger, S., Scherer-Lorenzen, M. & Mason, N.W. (2011) Functional structure of biological communities predicts ecosystem multifunctionality. *PLoS ONE*, **6**.
- Olander, L.P., Bustamante, M.M. & Asner, G.P. (2005) Surface Soil Changes Following Selective Logging in an Eastern Amazon Forest. *Earth Interaction*, **9**.
- Patil, G. & C., T. (1982) Diversity as a concept and its measurement: Rejoinder.
- Reich, P.B. (2014) The world-wide 'fast-slow' plant economics spectrum: A traits manifesto. *Journal of Ecology*, **102**, 275–301.
- Rutishauser, E., Hérault, B., Petronelli, P. & Sist, P. (2016) Tree Height Reduction After Selective Logging in a Tropical Forest. *Biotropica*, **48**, 285–289.

- Scheiter, S., Langan, L. & Higgins, S.I. (2013) Next-generation dynamic global vegetation models: learning from community ecology. *The New phytologist*, **198**, 957–69.
- Sist, P., Pacheco, P., Nasi, R. & Blaser, J. (2015) Management of natural tropical forests for the future. Technical report, IUFRO WFSE.
- TerSteege, H. & Hammond, D.S. (2001) Character Convergence, Diversity, and Disturbance in Tropical Rain Forest in Guyana. *Ecology*, **82**, 3197–3212.
- Tilman, D. (1997) The Influence of Functional Diversity and Composition on Ecosystem Processes. *Science*, **277**, 1300–1302.
- Tilman, D., Isbell, F. & Cowles, J.M. (2014) Biodiversity and Ecosystem Functioning. *Annual Review of Ecology, Evolution, and Systematics*, **45**, 471–493.
- Tothmeresz, B. & Tóthmérész, B. (1995) Comparison of different methods for diversity ordering. *Journal of Vegetation Science*, **6**, 283–290.
- Trenbath, B.R. (1999) Multispecies cropping systems in India - Predictions of their productivity, stability, resilience and ecological sustainability. *Agroforestry Systems*, **45**, 81–107.
- Villéger, M., Mason, J. & Mouillot, D. (2008) New multidimensional functional diversity indices for a multifaceted framework in functional ecology. *Ecology*, **89**, 2290–2301.
- Violle, C., Navas, M.L.L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I. & Garnier, E. (2007) Let the concept of trait be functional! *Oikos*, **116**, 882–892.
- Wagner, F., Hérault, B., Stahl, C., Bonal, D. & Rossi, V. (2011) Modeling water availability for trees in tropical forests. *Agricultural and Forest Meteorology*, **151**, 1202–1213.
- Westoby, M. (1998) A leaf-height-seed (LHS) plant ecology strategy scheme. *Plant and Soil*, **199**, 213–227.
- Westoby, M. & Wright, I.J. (2006) Land-plant ecology on the basis of functional traits. *Trends in Ecology and Evolution*, **21**, 261–268.
- White, P.S. & Jentsch, A. (2001) The Search for Generality in Studies of Disturbance and Ecosystem Dynamics. *Progress in Botany*, volume 62, pp. 399–450. Springer.
- Wright, I.J., Reich, P.B., Westoby, M., Ackerly, D.D., Baruch, Z., Bongers, F., Cavender-Bares, J., Chapin, T., Cornelissen, J.H.C., Diemer, M., Flexas, J., Garnier, E., Groom, P.K., Gulias, J., Hikosaka, K., Lamont, B.B., Lee, T., Lee, W., Lusk, C., Midgley, J.J., Navas, M.L., Niinemets, U., Oleksyn, J., Osada, N., Poorter, H., Poot, P., Prior, L., Pyankov, V.I., Roumet, C., Thomas, S.C., Tjoelker, M.G., Veneklaas, E.J. & Villar, R. (2004) The worldwide leaf economics spectrum. *Nature*, **428**, 821–827.