ELECTRONIC SUPPLEMENTARY MATERIAL

Using avian functional traits to assess the impact of land-cover change on ecosystem processes linked to resilience in tropical forests

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Expanded Methods

Study design

Data were collected in two study regions: the municipality of Paragominas (1.9 Mha) and parts of the municipalities of Santarém, Mojuí dos Campos and Belterra (~1 Mha). These two regions are situated in different areas of endemism (Belém and Tapajós, respectively). They also differ in their histories of human occupation and use. The city of Santarém was founded in 1661, and northern Santarém municipality has been densely settled by small-scale farmers for more than a century. In contrast, Paragominas was founded in 1959 and the municipality had a very low population density prior to its colonization by cattle ranchers in the 1950s and 1960s, and the boom in the timber industry during the 1980s and 1990s. Large-scale, mechanized agriculture became established in both regions only in the early 2000s, and has increased rapidly in recent years, currently occupying approximately 40,000 and 60,000 ha in Santarém and Paragominas, respectively.

Fieldwork was coordinated by a research consortium of 30 institutions and partner organisations (Gardner et al. 2013) in the Sustainable Amazon Network (RAS; http://www.redeamazoniasustentavel.org), a multi-disciplinary initiative assessing the sustainability of land-use systems in the Brazilian Amazon. The RAS sampling design is based on a sample of 18 third- or fourth-order hydrological catchments (c. 5000 ha) in each region, which were delineated using a digital elevation model and SWAT (Soil and Water Assessment Tool) for ARCGIS 9.3. Catchments are distributed over a gradient of forest cover in 2009 (10–100% in Santarém; 6–100% in Paragominas) with detailed ecological information collected from study transects and individual farms within each catchment. The 36 study catchments were selected to capture the full deforestation gradient, including all current land-use practices and major soil types. For lists of species identified, and links to digital vouchers supporting identifications, see Lees et al. (2012; 2013).

Ecological data were collected from a sample of 300 m study transects in every catchment, distributed using a stratified-random sampling design, where a standard density of transects (1 per 400 ha) was distributed across the catchment in proportion to the percentage cover of total forest and production areas. For example, if half of the landscape was covered by forest, then half of the transects were allocated to forest. In catchments with very low levels of forest cover we sampled additional forest transects to ensure a minimum sample of three transects in all catchments. Within each of these two land-use categories (forest and non-forest), sample transects were distributed randomly with a minimum separation of 1500 m to minimize spatial dependence. The use of this stratified-random sampling design provided a balance between the need for: (1) proportional sampling of forest and non-forest areas, and a sufficient density and coverage of sample points to capture major differences in landscape structure and composition among different catchments; and (2) a well-dispersed set of sampling points across forest and non-forest areas that captured important environmental heterogeneities within each catchment and across the region as a whole, helping to minimize problems of pseudoreplication. The final distribution of sampling points among habitat categories is presented in Moura et al. (2013).

Land-cover categories

Transects were classified *a posteriori* into five land-cover types, using 2010 Landsat images and a decision tree classification algorithm (Gardner et al. 2013), as (i) primary forest—the region's original climax physiognomy that has never been clear-felled for agriculture, and for which no recent evidence of logging or fire events was detected; (ii) disturbed forest—primary forests that have never been clear-felled but have suffered recent logging or fire events; (iii) secondary forests—forests that have developed after complete clearance; (iv) pasture and (v) arable—typically soybean fields or rice. We subdivided primary forests into (i) and (ii) based on 20 year chronosequence of Landsat images for each transect, calibrated by interviews with local farmers, as well as our own ground-truthed surveys. The former remote sensing analysis was carried out using a time series of georeferenced 30-m spatial resolution Landsat images from 1990–2010 in Santarém, and from 1988 to 2010 in Paragominas. Images were first corrected for atmospheric haze and smoke interference and then classified using a decision tree algorithm (see Gardner et al. 2013). The ground-truthed survey included a combination of physical evidence of selective logging (debris and stumps) and understory fires (charcoal and fire scars on stems found during field surveys) (see Berenguer et al. 2014).

Environmental variables

Vegetation surveys for all woody plants (trees and lianas) and palms above 10 cm DBH (Diameter at Breast Height) were conducted in 10 x 250 m plots, subdivided into 10 x (10 x 15 m) parcels. Smaller individuals (2.5 to 10 cm DBH) were sampled in five subplots of 5 x 20 m. All individuals were identified to species or morphospecies level with herbarium samples collected wherever appropriate. Along each forest transect, 5 hemispherical photos were taken at a 50 m intervals in order to determine the canopy openness of each area. The camera was placed 1 m from the ground and faced north. Canopy openness was determined with the software Gap LightAnalizer 2.0 (Frazer et al. 1999) which calculates the percentage of the canopy covered by trees crowns.

Bird surveys

Birds provide a useful system for understanding how complex tropical forest ecosystems respond to landscape disturbance for two main reasons. First, they are the best-known class of organisms, with comprehensive datasets available on ecological roles and interspecific variation on their life histories (Vandewalle et al. 2010). Second, they are relatively time- and cost-effective to sample (Gardner et al. 2008).

We surveyed birds at all main study transects. In each transect, three point count stations were located at 0, 150 and 300 m. We carried out six surveys per transect (two repetitions of three 15 minute, 75 m fixed-width surveys). Repetitions were carried out within the same week but not on the same day; all species identified were recorded. Fieldwork in Paragominas was carried out by A.C.L. and N.G.M. between 28 July and 20 November 2010 and then again from 18 to 29 May 2011. Fieldwork in Santarém was conducted by A.C.L., N.G.M., Christian Borges Andretti and Bradley J.W. Davis from 16 October 2010 to 8 February 2011. All observers had extensive experience of conducting bird surveys in Brazil. Point counts were recorded with solid state recorders to facilitate identification of bird calls which were not identified in the field. Surveys were not carried out on days with persistent rain and/or strong winds. If a species' identification was ever in doubt playbacks were used to lure the vocalizing bird for visual confirmation. Playbacks were not used systematically to increase the detectablity of any given species during the point count surveys. Any effect of seasonality (presence/absence of austral/boreal migrants, fluctuations in vocalization activity, etc.) was minimized by systematically rotating surveys between catchments of varying total forest cover and between habitat types.

All bird surveys in dense tropical forest suffer from the problem imperfect detection because some species are far less detectable than others, particularly by sight. We have minimised this problem by ensuring that all surveys were conducted by experienced fieldworkers skilled at identifying avian acoustic signals. Detection of bird species by songs and calls is standard in tropical forests, and around 90% of our survey detections were auditory rather than visual, reducing the potential bias caused by reliance on visual detection. Another potential bias relates to sampling intensity as our sampling regime resulted in fewer surveys undertaken in open habitats. However, reduced sampling is offset by increased detectability of bird species in open habitats which means that a similar proportion of resident species can be detected with fewer survey visits. In support of this view, we note that relatively few species were excluded from analyses because of their rarity in non-forest land-cover (see Dataset 1, sheet 3), and that species accumulation curves indicate that surveys were near-asymptotic in all habitats (Moura et al. 2013).

Biometric traits

We compiled a functional trait dataset from museum specimens collected as near as possible to the study localities. We took seven morphometric measurements from all specimens: beak length, width and depth, wing length, Kipp's distance (the distance between the tip of the longest primary/wing tip and the first secondary feather measured on the folded wing), tail length and tarsus length.

The rationale for selecting these measurements was as follows. Beak size and shape predict the size and type of food items selected by birds (Wheelright 1985; Miles et al. 1987) and thus provide a long-established index of dietary niche (Schoener 1965; Hsu et al. 2014; Tobias et al. 2014). Similarly, tarsus, tail, and wing length are locomotory traits associated with substrate use and foraging manoeuvre (Miles and Ricklefs 1984; Miles et al. 1987; Tobias et al. 2014). Finally, Kipp's distance gives further insight into wing shape and flight ability, thus providing information about dispersal limitation and gap-crossing ability (Dawideit et al. 2009; Lees and Peres 2009; Claramunt et al. 2012).

All three beak measurements were taken at or from the anterior edge of the nostrils: (1) width, (2) length to the tip of the beak and (3) depth (as vertical height). Wing length was the distance between the carpal joint and the wing tip of the unflattened wing. Kipp's distance was measured from the tip of the first secondary and the tip of the longest primary on the closed wing. Tail length was taken from the point at which the two central rectrices meet the skin to the tip of the longest rectrix. Tarsus length was measured from the middle of the rear ankle joint, i.e. the notch between the tibia and tarsus, to the end of the last scale of the acrotarsium. All measurements were taken with digital callipers to the nearest 0.01 mm, apart from wing length and tail length, which were measured using an end-ruler to the nearest mm.

To account for intra-specific variability, we aimed to measure at least two males and two females for each species. This was not possible for 48 monomorphic species (12% of total) lacking four specimens of known sex, so in these cases we included unsexed specimens where necessary. On average, we measured 5.6 ± 2.8 specimens per species (3.0 ± 2.2 males; 2.4 ± 0.9 females; 1.9 ± 1.1 unsexed). We generated a mean value for each morphological trait by averaging data across all (male, female and unsexed) specimens for each species. Most specimens were accessed in the Museu Paraense Emílio Goeldi, Belém, Brazil (n = 1399 specimens) to ensure that the phenotypes measured were sampled in the same region as our bird surveys. Gaps were filled using specimens stored at the Natural History Museum, Tring, UK (n = 394 specimens), as well as smaller samples of specimens at the

Lousiana State University Museum of Zoology and the American Museum of Natural History. Full details of the sex, locality, source and acquisition numbers for specimens used in this study are presented in Dataset 1 (sheet 2).

Habitat classification

Within the tropics, species occurring in more structurally dense habitats (e.g. forest) are expected to be less dispersive than more open-habitat specialists (e.g. grassland) (Weir et al. 2009). Empirical studies show that forest species may fail to cross even narrow breaks in habitat easily crossed by open country species (Moore et al. 2008; Lees and Peres 2009). This is thought to occur both because of the behavioral inhibition of forest species to cross gaps (Harris and Reed 2002) and because the adaptations required for movement amongst dense vegetation (e.g. short and rounded wings) are not favourable for long distance flight (Stratford and Robinson 2005). Species were assigned to one of two habitat categories according to whether they are (i) regularly detected in forest or (ii) almost exclusively restricted to non-forested habitats, following Bregman et al. (2014). We defined forest as any type of evergreen or deciduous woodland lacking gaps between tree canopies.

Analyses

To quantify the functional trait structure of avian communities, we used Functional Diversity (FD) and Functional Dispersion (F_{DIS}) because they focus on different components of community structure. The key difference is that *FD* is the sum of branch lengths of a given trait or set of traits, whereas F_{DIS} is the mean distance of all species to the community mean trait value. Branch lengths are calculated from a dendrogram of trait similarity (Petchey and Gaston 2002). This means that *FD* is strongly correlated with species richness, whereas F_{DIS} is not (Laliberte and Legendre 2010). We retain *FD* because it is a standard measure in the literature and performs relatively well in simulations (Kraft and Ackerly 2010), and we add F_{DIS} as an additional measure because it has the advantage of being more sensitive to changes in the overall spread, or 'dispersion' of traits (Laliberte and Legendre 2010).

All analyses were conducted in *R* (R Development Core Team 2014). Both functional diversity metrics were calculated using species presence-absence data: *FD* was calculated using the '*Picante*' package (Kembel et al. 2010); F_{DIS} was calculated using the '*FD*' package (Laliberte and Legendre 2010); GLMMs were fitted using the '*glmmADMB*' package (Skaug et al. 2011).

Expanded Discussion

The results of mean community trait analyses can be interpreted in the light of specific changes in community composition. For example, we found that the beaks of forest and non-forest species were on average shorter, wider and deeper in disturbed habitats (figure S2c). Among insectivores, we attribute this shift to the loss of species with long and slender beaks (e.g. *Campylorhamphus*, *Galbula*), and the prevalence of species with shorter, wider beaks (e.g. *Stelgidopteryx*), whereas for frugivores it can perhaps be explained by the predominance of oscine passerines (e.g. *Thraupis*, *Euphonia*) in agricultural landscapes.

Our results revealed that the locomotory trait (tarsus:tail/wing ratio) decreased for forest insectivores in degraded habitats (figure S2d), again suggesting a shift in the dominant foraging behaviour within communities. Community-wide changes in locomotory traits are presumably driven by the loss of terrestrial and semi-terrestrial insectivores (e.g. *Sclerurus*, *Formicarius*) with long legs and short wings, and colonisation by vagile arboreal or open country insectivores (e.g. *Tyrannus*) with short legs and long wings (Barlow et al. 2006). In frugivores, a similar decrease in the locomotory trait of non-forest species with disturbance (figure S2h) is largely driven by the loss of ground-dwelling frugivores (e.g. *Psophia*), and the persistence of canopy frugivores.

Mean hand-wing index increases across the disturbance gradient, particularly for forest insectivores (figure S2b) and non-forest frugivores (figure S2f). This suggests that better dispersers typically dominate communities in degraded forests and agricultural areas. Forest insectivores, in particular, are often highly dispersal-limited, with many species unable or unwilling to make prolonged flights across open areas (Moore et al. 2008, Lees and Peres 2009). These species have smaller hand-wing index, and tend to suffer both increased extinction and reduced likelihood of subsequent recolonisation in fragmented or degraded forests (Canaday 1996, Stratford and Stouffer 1999, Sekercioglu et al. 2002, Lees and Peres 2008, Tobias et al. 2013).

Limitations

One limitation of this study is the lack of temporal replication. Fluctuations in species richness and abundance over time are widespread in nature (Boulinier et al. 1998) but adequate time series for communities remain rare (Debinski and Holt 2000). We note that further changes in bird community structure and composition are perhaps likely in our system because land-cover change in parts of these landscapes has been a relatively recent phenomenon (Gardner et al. 2013), suggesting that many communities still owe an extinction debt (Tilman et al. 1994, Wearn et al. 2012). Thus, even if bird communities are currently capable of maintaining ecosystem function, local extinctions may further reduce functionality in future.

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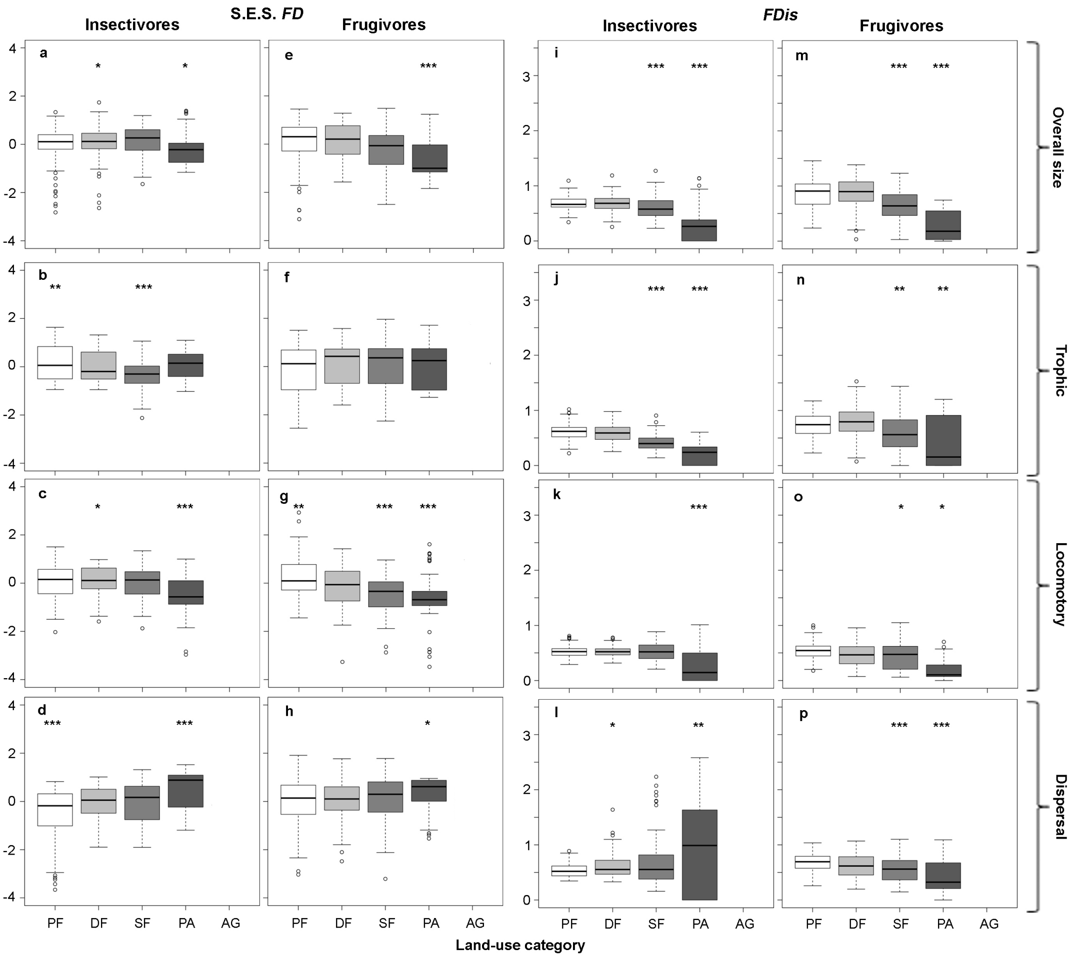

Figure S1. Standardized effect size (SES) of Functional Diversity (*FD*) and functional dispersion (F_{DIS}) for four functional traits of forest insectivores (a–d, i–l) and frugivores (e–h, m–p) in 330 avian communities across five land uses: primary forest (PF), disturbed primary forest (DF), secondary forest (SF), pasture (PA) and arable agriculture (AG). Data from Santarém and Paragominas are pooled. Asterisks indicate that observed FD was significantly different from null expectations, or that observed F_{DIS} was significantly different from the primary forest F_{DIS} (* <0.05, ** <0.01, *** <0.001). All statistical results are from two-tailed Wilcoxon signed-ranks tests.

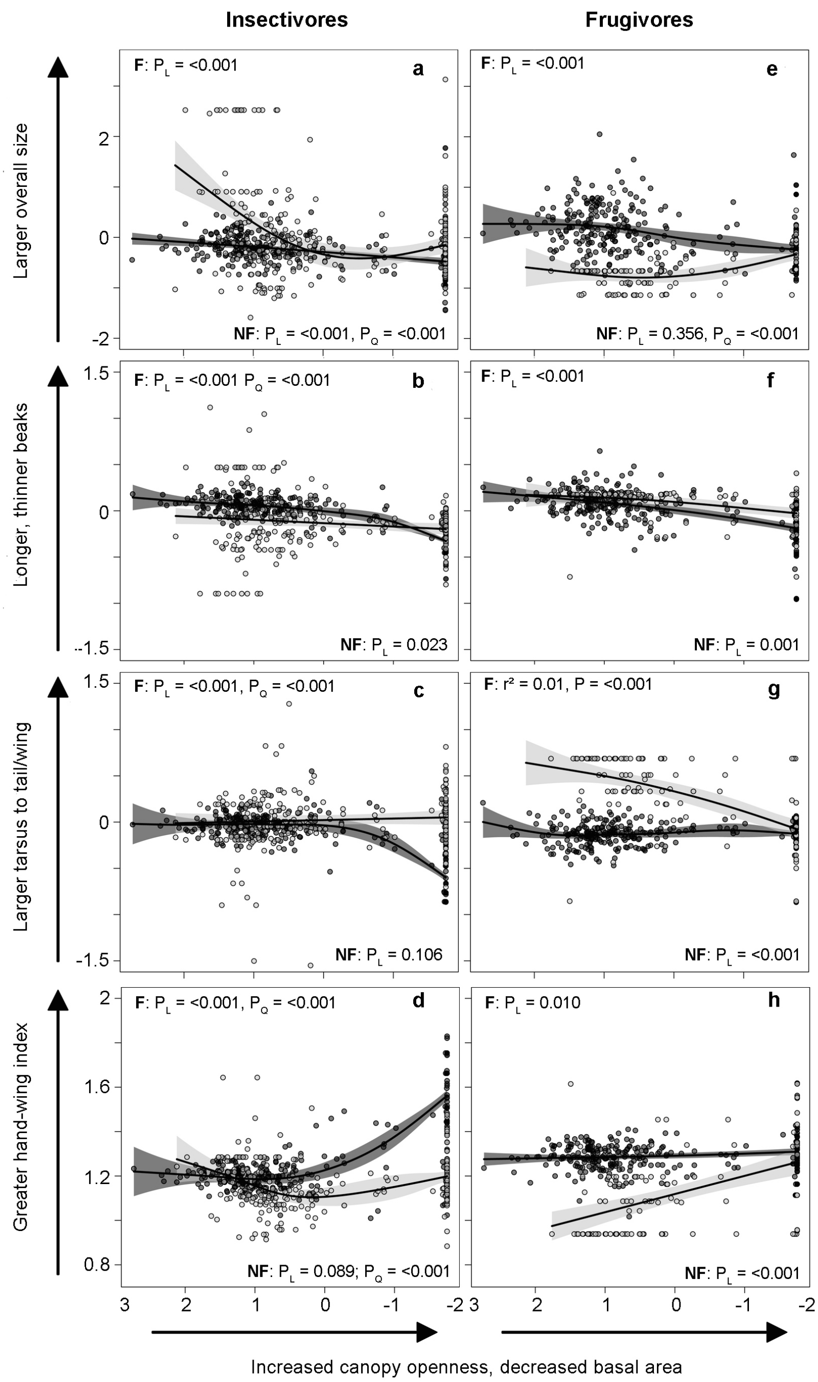

Figure S2. Change in functional traits in 330 avian communities distributed across a land-use gradient for insectivores (a–d) and frugivores (e–h). Forest species (8 models) are shown in dark grey; non-forest species (8 models) in light grey (lines show model fit from Generalised Additive Modelling; shaded areas show standard error ± 1.96 S.E). All data were derived from principal component analyses; see the electronic supplementary material, table S3.4, S3.5 and S3.12. Significance (*P*) values for linear (P_L) and quadratic (P_Q) forms of the environmental PC axis are from Generalised Linear Modelling (see table S13 for more details).

Table S1 Principal Component Analysis (PCA) for insectivorous birds showing Eigenvalues and the proportion of variance explained. PC1 from both trophic and locomotory trait analyses were combined in a secondary PCA to create an axis representing overall body size. The second PC for both trophic and locomotory traits captured variation independent of body size.

Functional trait	PC	Proportion variance	PCA loadings		
			Tarsus length	**Tail length**	**Wing chord**
Locomotory	1	0.695	0.471	0.604	0.642
	2	0.237	0.864	-0.464	-0.197
			Beak length	**Beak width**	**Beak depth**
Trophic	1	0.790	0.532	0.593	0.604
	2	0.154	0.842	-0.446	-0.304
			Trophic PC1	**Locomotory PC1**	
Body size	1	0.812	0.707	0.707	

Table S2 Principal Component Analysis (PCA) for frugivorous birds showing Eigenvalues and the proportion of variance explained. PC1 from both trophic and locomotory trait analyses were combined in a secondary PCA to create an axis representing overall body size. The second PC for both trophic and locomotory traits captured variation independent of body size.

Functional trait	PC	Proportion variance	PCA loadings		
			Tarsus length	**Tail length**	**Wing chord**
Locomotory	1	0.847	0.560	0.565	0.606
	2	0.119	0.726	-0.687	-0.458
			Beak length	**Beak width**	**Beak depth**
Trophic	1	0.931	0.567	0.590	0.574
	2	0.056	0.760	-0.108	-0.641
			Trophic PC1	**Locomotory PC1**	
Body size	1	0.686	0.707	0.707	

Table S3 Results of Principal Component Analysis (PCA) for environmental variables (mean canopy openness and mean basal area). Eigenvalues and the proportion of variance explained are presented for PC1 and PC2.

	PC	**Proportion variance**	**PCA Loadings**	
			Mean canopy openness	Mean basal area
Environmental variables	1	0.924	-0.707	0.707
	2	0.076	0.707	0.707

Table S4 Differences in *FD* of insectivore and frugivore communities, comparing between all combinations of land-use categories: primary forest (PF), disturbed primary forest (DF), secondary forest (SF), pasture (PF) and agriculture (AG). Analyses are two-tailed Wilcoxon tests.

		Insectivores		Frugivores	
Group	Land use	*V*	Wilcoxon *P*	*V*	Wilcoxon *P*
All	PF vs DF	3695	0.742	4148	0.082
	PF vs SF	4515	**<0.001**	4075	**<0.001**
	PF vs PA	6055	**<0.001**	5311	**<0.001**
	PF vs AG	2185	**<0.001**	–	–
	DF vs SF	3511	**<0.001**	2732	**0.013**
	DF vs PA	4688	**<0.001**	3686	**<0.001**
	DF vs AG	1679	**<0.001**	–	–
	SF vs PA	2606	0.056	2772	**<0.002**
	SF vs AG	1238	**<0.001**	–	–
	PA vs AG	1447	**<0.001**	–	–
Forest	PF vs DF	3917	0.307	4029	0.171
	PF vs SF	4901	**<0.001**	4026	**<0.001**
	PF vs PA	4641	**<0.001**	5383	**<0.001**
	PF vs AG	–	–	–	–
	DF vs SF	3654	**<0.001**	2684	**0.023**
	DF vs PA	3540	**<0.001**	3805	**<0.001**
	DF vs AG	–	–	–	–
	SF vs PA	2611	**<0.001**	2853	**<0.001**
	SF vs AG	–	–	–	–
	PA vs AG	–	–	–	–
Non-forest	PF vs DF	313	0.549	–	–
	PF vs SF	404	0.846	–	–
	PF vs PA	330	**0.002**	–	–
	PF vs AG	245	0.175	–	–
	DF vs SF	1029	0.466	–	–
	DF vs PA	787	**<0.001**	–	–
	DF vs AG	613	**0.048**	–	–
	SF vs PA	735	**<0.001**	–	–
	SF vs AG	622	0.232	–	–
	PA vs AG	1461	**<0.001**	–	–

Table S5 Comparison of *FD* in disturbed habitats relative to primary forest for insectivore and frugivore communities. Analyses are two-tailed Wilcoxon tests (i.e. testing whether the observed values are significantly different from the null expectation in either direction). Bold denotes significant differences. The standardised effect size (SES) is provided along with the standard error (SE). Analyses were run separately for individual functional traits in different land-use categories: primary forest (PF), disturbed primary forest (DF), secondary forest (SF), pasture (PF) and agriculture (AG). The number of communities statistically different from the null expectation are given (with the total number of communities for each test in brackets). Sample size can differ within categories because guild communities sometimes contained too few species to be included in analyses.

		Insectivores				Frugivores			
Group	Land use	SES (mean + SE)	No. communities < expectation (sample)	*V*	Wilcoxon *P*	SES (mean + SE)	No. communities < expectation (sample)	*V*	Wilcoxon *P*
All	PF	0.046 (0.665)	33 (97)	2757	0.172	0.083 (0.863)	43 (97)	2717	0.221
	DF	0.073 (0.567)	26 (74)	1670	0.129	0.027 (0.859)	44 (74)	1418	0.872
	SF	-0.162 (0.573)	34 (59)	670	0.105	-0.211 (0.809)	41 (59)	541	**0.010**
	PA	0.015 (0.589)	40 (74)	1487	**0.594**	-0.288 (0.645)	50 (59)	357	**<0.001**
	AG	0.167 (0.693)	8 (23)	178	0.235	–	–	–	–
Forest	PF	-0.043 (0.725)	55 (97)	2248	0.645	0.024 (0.796)	49 (97)	2385	0.977
	DF	0.061 (0.699)	37 (74)	1636	0.182	0.100 (0.930)	37 (74)	1482	0.613
	SF	-0.195 (0.743)	37 (59)	674	0.112	-0.038 (0.868)	33 (59)	777	0.417
	PA	-0.274 (0.553)	35 (48)	385	**0.037**	-0.481 (0.465)	52 (57)	157	**<0.001**
	AG	–	–	–	–	–	–	–	–
Non-forest	PF	0.660 (1.446)	8 (17)	104	0.207	–	–	–	–
	DF	0.611 (1.272)	17 (41)	591	**0.037**	-0.431 (0.365)	7 (8)	2	**0.023**
	SF	-0.369 (0.637)	34 (46)	211	**<0.001**	-0.356 (0.814)	19 (22)	49	**0.010**
	PA	-0.061 (0.941)	43 (74)	1202	0.319	1.84 (0.789)	0 (10)	55	**0.002**
	AG	0.244 (1.097)	12 (23)	147	0.800	–	–	–	–

Table S6 Comparison of *FDis* in disturbed habitats relative to primary forest for insectivore and frugivore communities. Analyses are two-tailed Wilcoxon tests (i.e. testing whether the observed values are significantly different from the null expectation in either direction). Bold denotes significant differences. Analyses were run separately for individual trait syndromes in different land-use categories: primary forest (PF), disturbed primary forest (DF), secondary forest (SF), pasture (PF) and agriculture (AG).

		Insectivores		Frugivores	
Group	Land use	*V*	Wilcoxon *P*	*V*	Wilcoxon *P*
All	PF vs DF	3150	0.172	3613	0.942
	PF vs SF	3670	**0.003**	4406	**<0.001**
	PF vs PA	2292	**<0.001**	6370	**<0.001**
	PF vs AG	590	**<0.001**	1135	**<0.001**
	DF vs SF	2965	**<0.001**	3328	**<0.001**
	DF vs PA	1979	**0.004**	4814	**<0.001**
	DF vs AG	512	**0.002**	864	**<0.001**
	SF vs PA	1008	**<0.001**	3308	**<0.001**
	SF vs AG	268	**<0.001**	649	**<0.001**
	PA vs AG	653	0.053	634	**0.003**
Forest	PF vs DF	2958	**0.049**	3516	0.821
	PF vs SF	3148	0.296	4238	**<0.001**
	PF vs PA	4615	**<0.001**	6202	**<0.001**
	PF vs AG	1643	**<0.001**	1137	**<0.001**
	DF vs SF	2649	0.035	3225	**<0.001**
	DF vs PA	3579	**<0.001**	4659	**<0.001**
	DF vs AG	1252	**<0.001**	862	**<0.001**
	SF vs PA	2711	**<0.001**	3241	**<0.001**
	SF vs AG	979	**<0.001**	651	**<0.001**
	PA vs AG	928	**<0.001**	613	**0.004**
Non-forest	PF vs DF	812	**0.001**	126	**0.049**
	PF vs SF	622	**<0.001**	144	**0.004**
	PF vs PA	464	**<0.001**	138	**0.036**
	PF vs AG	129.5	**<0.001***	–	–
	DF vs SF	1515	0.768	549	0.147
	DF vs PA	1242	**<0.001**	461	0.758
	DF vs AG	315	**<0.001**	–	–
	SF vs PA	1048	**<0.001**	848	0.322
	SF vs AG	278	**<0.001**	–	–
	PA vs AG	601	**0.018**	–	–

Table S7 Comparison of *FD* in disturbed habitats relative to primary forest for insectivore and frugivore communities (all species), with analyses run separately for individual functional traits in different land-cover categories. Analyses are two-tailed Wilcoxon tests (i.e. testing whether observed values are significantly different from the null expectation in either direction). Bold denotes significant differences. The standardised effect size (SES) is provided along with the standard error (SE). Land-cover categories: primary forest (PF), disturbed primary forest (DF), secondary forest (SF), pasture (PF) and agriculture (AG). Sample size differs within categories because guild communities sometimes contained too few species to be included in analyses.

		Insectivores				Frugivores			
Functional trait	Land cover	Mean SES (SE)	No. communities < expectation (sample)	*V*	Wilcoxon *P*	SES (mean + SE)	No. communities < expectation (sample)	*V*	Wilcoxon *P*
Body size	PF	0.115 (0.597)	35 (97)	3109	**0.008**	0.076 (1.171)	30 (97)	3076	**0.012**
	DF	0.089 (0.575)	34 (74)	1619	0.213	0.204 (0.753)	22 (74)	1972	**0.002**
	SF	-0.064 (0.567)	32 (59)	815	0.600	-0.327 (1.057)	31 (59)	708	0.183
	PA	0.173 (0.378)	20 (74)	2131	**<0.001**	-0.646 (0.795)	41 (59)	297	**<0.001**
	AG	0.207 (0.633)	7 (23)	184	0.170	-0.210 (1.112)	2 (4)	4	0.875
Trophic traits	PF	0.189 (0.576)	43 (97)	3439	**<0.001**	-0.053 (0.860)	44 (97)	2222	0.580
	DF	-0.025 (0.531)	48 (74)	1401	0.944	0.083 (0.853)	29 (74)	1472	0.651
	SF	-0.376 (0.505)	49 (59)	328	**<0.001**	-0.119 (0.966)	26 (59)	766	0.371
	PA	-0.281 (0.276)	64 (74)	213	**<0.001**	-0.227 (0.892)	28 (59)	628	0.053
	AG	0.301 (0.439)	7 (23)	227	**0.005**	–	–	–	–
Locomotory traits	PF	0.073 (0.544)	41 (97)	2865	0.080	0.044 (0.815)	48 (97)	2485	0.700
	DF	0.062 (0.479)	32 (74)	1669	0.130	0.016 (0.895)	28 (74)	2485	0.304
	SF	-0.097 (0.556)	35 (59)	683	0.128	-0.042 (0.908)	25 (59)	913	0.836
	PA	0.280 (0.487)	19 (74)	2210	**<0.001**	-0.581 (1.015)	38 (59)	399	<0.001
	AG	0.246 (0.533)	8 (23)	195	0.086	–	–	–	–
Dispersal trait	PF	-0.195 (0.755)	44 (97)	2166	0.450	0.072 (0.752)	41 (97)	2963	**0.035**
	DF	-0.032 (0.607)	33 (74)	1480	0.620	-0.081 (0.823)	34 (74)	1337	0.788
	SF	-0.143 (0.595)	26 (59)	746	0.296	0.071 (0.843)	23 (59)	1046	0.226
	PA	0.375 (0.468)	12 (74)	2394	**<0.001**	0.363 (0.691)	16 (59)	1336	**<0.001**
	AG	0.611 (0.427)	2 (23)	273	**<0.001**	0.059 (0.965)	1 (4)	6	0.875

Table S8 Comparison of *FD* in disturbed habitats relative to primary forest for insectivore and frugivore communities (forest-dependent species), with analyses run separately for individual functional traits in different land-cover categories. Analyses are two-tailed Wilcoxon tests (i.e. testing whether observed values are significantly different from the null expectation in either direction). Bold denotes significant differences. The standardised effect size (SES) is provided along with the standard error (SE). Land-cover categories: primary forest (PF), disturbed primary forest (DF), secondary forest (SF), pasture (PF) and agriculture (AG). The number of communities statistically different from the null expectation are given (with the total number of communities for each test in brackets). Sample size may differ within categories because guild communities sometimes contained too few species to be included in analyses.

		Insectivores				Frugivores			
Functional trait	Land cover	Mean SES (SE)	No. communities < expectation (sample)	*V*	Wilcoxon *P*	SES (mean + SE)	No. communities < expectation (sample)	*V*	Wilcoxon *P*
Body size	PF	-0.016 (0.812)	36 (97)	2907	0.057	0.018 (0.995)	30 (97)	2798	0.130
	DF	0.068 (0.758)	26 (74)	1832	**0.017**	0.128 (0.742)	31 (74)	1649	0.160
	SF	0.124 (0.689)	20 (49)	1107	0.094	-0.232 (0.912)	32 (49)	669	0.104
	PA	-0.144 (0.690)	36 (48)	390	**0.042**	-0.712 (0.720)	46 (57)	165	**<0.001**
	AG	–	–	–	–	–	–	–	–
Trophic traits	PF	0.176 (0.701)	46 (97)	3219	**0.002**	-0.116 (0.973)	47 (97)	2038	0.224
	DF	-0.025 (0.605)	47 (74)	1364	0.901	0.091 (0.815)	31 (74)	1495	0.564
	SF	-0.294 (0.619)	44 (49)	438	**<0.001**	0.042 (0.912)	24 (49)	943	0.664
	PA	0.119 (0.573)	18 (48)	726	0.160	-0.098 (0.910)	26 (57)	682	0.253
	AG	–	–	–	–	–	–	–	–
Locomotory traits	PF	0.060 (0.691)	40 (97)	2921	0.050	0.239 (0.776)	40 (97)	3126	**0.007**
	DF	0.100 (0.603)	32 (74)	1753	**0.049**	-0.143 (0.854)	39 (74)	1186	0.279
	SF	-0.032 (0.638)	29 (49)	979	0.480	-0.452 (0.795)	42 (49)	398	**<0.001**
	PA	-0.512 (0.803)	34 (48)	259	**<0.001**	-0.632 (1.047)	47 (57)	363	**<0.001**
	AG	–	–	–	–	–	–	–	–
Dispersal traits	PF	-0.509 (1.120)	58 (97)	1526	**0.002**	0.011 (0.914)	41 (97)	2725	**0.211**
	DF	-0.101 (0.769)	35 (74)	1339	0.796	-0.015 (0.994)	31 (74)	1575	0.314
	SF	-0.067 (0.849)	26 (49)	835	0.709	0.092 (1.009)	36 (49)	1058	0.193
	PA	0.545 (0.745)	18 (48)	968	**<0.001**	0.303 (0.747)	14 (57)	1151	**0.010**
	AG	–	–	–	–	–	–	–	–

Table S9 Comparison of *FD* in disturbed habitats relative to primary forest for insectivore and frugivore communities (non-forest species), with analyses run separately for individual functional traits in different land-cover categories. Analyses are two-tailed Wilcoxon tests (i.e. testing whether observed values are significantly different from the null expectation in either direction). Bold denotes significant differences. The standardised effect size (SES) is provided along with the standard error (SE). Analyses were run separately for individual functional traits in different land-cover categories: forest (PF), disturbed primary forest (DF), secondary forest (SF), pasture (PA) and agriculture (AG). The number of communities statistically different from the null expectation are given (with the total number of communities for each test in brackets). Sample size may differ within categories because guild communities sometimes contained too few species to be included in analyses.

		Insectivores				Frugivores			
Functional trait	Land cover	Mean SES (SE)	No. communities < expectation (sample)	*V*	Wilcoxon *P*	SES (mean + SE)	No. communities < expectation (sample)	*V*	Wilcoxon *P*
Body size	PF	0.493 (1.084)	7 (17)	110	0.120	–	–	–	–
	DF	0.389 (0.971)	17 (41)	601	0.027	0.047 (0.936)	4 (8)	18	**1**
	SF	-0.571 (1.018)	31 (46)	239	<0.001	-0.098 (1.004)	15 (22)	103	0.463
	PA	0.170 (0.847)	22 (74)	1884	**0.008**	0.495 (0.732)	2 (10)	48	**0.037**
	AG	0.256 (0.918)	8 (23)	184	0.170	–	–	–	–
Trophic traits	PF	0.674 (1.536)	5 (17)	110	**0.120**	–	–	–	–
	DF	0.105 (1.099)	19 (41)	450	0.808	-0.261 (1.131)	5 (8)	16	0.844
	SF	0.237 (1.019)	22 (46)	640	**0.282**	-0.193 (1.011)	14 (22)	97	0.354
	PA	-0.168 (0.548)	50 (74)	854	0.004	0.354 (1.022)	4 (10)	40	0.232
	AG	0.236 (0.516)	9 (23)	199	0.065	–	–	–	–
Locomotory traits	PF	-0.067 (0.995)	10 (17)	68	0.712	–	–	–	–
	DF	-0.307 (0.766)	31 (41)	257	**0.024**	0.130 (0.881)	4 (8)	20	0.844
	SF	0.050 (0.925)	23 (46)	606	0.481	-0.382 (0.976)	15 (22)	75	0.098
	PA	0.197 (1.232)	39 (74)	1482	0.613	0.670 (0.962)	2 (10)	44	0.106
	AG	0.218 (0.818)	12 (23)	150	0.731	–	–	–	–
Dispersal trait	PF	-0.304 (0.815)	14 (17)	39	**0.080**	–	–	–	–
	DF	-0.134 (0.934)	27 (41)	304	0.103	0.109 (0.916)	3 (8)	19	0.945
	SF	-0.210 (1.082)	27 (46)	399	0.124	-0.367 (0.941)	11 (22)	96	0.337
	PA	0.196 (1.204)	27 (74)	1627	**0.198**	0.580 (0.950)	3 (10)	46	**0.064**
	AG	0.883 (1.030)	4 (23)	246	<0.001	–	–	–	–

Table S10 Comparison of raw *FDis* in disturbed habitats relative to primary forest for insectivore and frugivore communities (all species), with analyses run separately for individual functional traits. Analyses are two-tailed Wilcoxon tests (i.e. testing whether observed values are significantly different from the null expectation in either direction). Bold denotes significant differences. Analyses were run separately for individual functional traits in different land-uses: PF (Primary forest), DF (Disturbed primary forest), SF (Secondary forest), PA (Pasture), AG (Agriculture).

Functional trait	Land cover comparison	Insectivores		Frugivores	
		V	Wilcoxon *P*	*V*	Wilcoxon *P*
Body size	PF vs DF	3347	0.452	3469	0.710
	PF vs SF	3680	0.003	4131	**<0.001**
	PF vs PA	3913	0.313	6250	**<0.001**
	PF vs AG	1261	0.531	1109	**<0.001**
	DF vs SF	2892	**0.001**	3216	**<0.001**
	DF vs PA	3153	0.112	4803	**<0.001**
	DF vs AG	974	0.480	853	**<0.001**
	SF vs PA	1775	0.065	3353	**<0.001**
	SF vs AG	713	0.964	638	**<0.001**
	PA vs AG	923	0.776	625	**0.005**
Trophic traits	PF vs DF	4059	0.143	3157	0.179
	PF vs SF	4408	**<0.001**	3867	**<0.001**
	PF vs PA	5474	**<0.001**	4410	**<0.001**
	PF vs AG	1484	**0.038**	970	**<0.001**
	DF vs SF	3189	**<0.001**	3143	**<0.001**
	DF vs PA	3961	**<0.001**	3566	**<0.001**
	DF vs AG	1086	0.103	754	**<0.001**
	SF vs PA	2006	0.424	2417	0.068
	SF vs AG	666	0.677	590	**<0.001**
	PA vs AG	889	0.997	610	0.009
Locomotory traits	PF vs DF	3768	0.578	3979	0.225
	PF vs SF	3315	0.098	3050	0.492
	PF vs PA	2467	**<0.001**	5716	**<0.001**
	PF vs AG	641	**0.001**	1115	**<0.001**
	DF vs SF	2464	0.204	2134	0.826
	DF vs PA	1745	**<0.001**	4188	**<0.001**
	DF vs AG	454	**<0.001**	840	**<0.001**
	SF vs PA	1297	**<0.001**	3373	**<0.001**
	SF vs AG	349	**<0.001**	667	**<0.001**
	PA vs AG	780	0.375	643	**0.002**
Dispersal traits	PF vs DF	3020	0.076	4104	0.109
	PF vs SF	3214	0.198	3909	**<0.001**
	PF vs PA	1130	**<0.001**	4641	**<0.001**
	PF vs AG	202	**<0.001**	1084	**<0.001**
	DF vs SF	2653	**0.033**	2559	**0.089**
	DF vs PA	1193	**<0.001**	3288	**0.003**
	DF vs AG	197	**<0.001**	824	**<0.001**
	SF vs PA	860	**<0.001**	2413	**0.071**
	SF vs AG	139	**<0.001**	649	**<0.001**
	PA vs AG	520	**0.002**	683	**<0.001**

Table S11 Comparison of raw *FDis* in disturbed habitats relative to primary forest for insectivore and frugivore communities (forest-dependent species), with analyses run separately for individual functional traits. Analyses are two-tailed Wilcoxon tests (i.e. testing whether observed values are significantly different from the null expectation in either direction). Bold denotes significant differences. Land-cover categories: PF (Primary forest), DF (Disturbed primary forest), SF (Secondary forest), PA (Pasture), AG (Agriculture).

		Insectivores		Frugivores	
Functional trait	Land cover comparison	*V*	Wilcoxon *P*	*V*	Wilcoxon *P*
Body size	PF vs DF	3454	0.675	3365	0.486
	PF vs SF	3632	**0.005**	3930	**<0.001**
	PF vs PA	5763	**<0.001**	5975	**<0.001**
	PF vs AG	1646	**<0.001**	1109	**<0.001**
	DF vs SF	2776	**0.007**	3124	**<0.001**
	DF vs PA	4401	**<0.001**	4634	**<0.001**
	DF vs AG	1252	**<0.001**	857	**<0.001**
	SF vs PA	3299	**<0.001**	3218	**<0.001**
	SF vs AG	979	**<0.001**	646	**<0.001**
	PA vs AG	904	**<0.001**	615	**0.003**
Trophic traits	PF vs DF	3933	0.284	3028	0.081
	PF vs SF	4695	**<0.001**	3637	**0.005**
	PF vs PA	6554	**<0.001**	4091	**0.005**
	PF vs AG	1649	**<0.001**	971	**<0.001**
	DF vs SF	3468	**<0.001**	2994	**<0.001**
	DF vs PA	4956	**<0.001**	3348	**<0.001**
	DF vs AG	1258	**<0.001**	756	**<0.001**
	SF vs PA	3404	**<0.001**	2333	0.082
	SF vs AG	994	**<0.001**	590	**<0.001**
	PA vs AG	946	**<0.001**	596	**0.008**
Locomotory traits	PF vs DF	3492	0.764	4361	**0.016**
	PF vs SF	2895	0.904	3482	**0.023**
	PF vs PA	5147	**<0.001**	5768	**<0.001**
	PF vs AG	1649	**<0.001**	1112	**<0.001**
	DF vs SF	2250	0.763	2364	0.415
	DF vs PA	3932	**<0.001**	4129	**<0.001**
	DF vs AG	1258	**<0.001**	831	**<0.001**
	SF vs PA	3160	**<0.001**	3080	**<0.001**
	SF vs AG	1003	**<0.001**	645	**<0.001**
	PA vs AG	958	**<0.001**	614	**0.004**
Dispersal trait	PF vs DF	2904	**0.033**	4210	0.053
	PF vs SF	2845	0.953	3922	**<0.001**
	PF vs PA	2601	**0.010**	5038	**<0.001**
	PF vs AG	1358	**<0.001**	1085	**<0.001**
	DF vs SF	2410	0.305	2566	**0.084**
	DF vs PA	2106	0.053	3553	**<0.001**
	DF vs AG	1054	**<0.001**	819	**<0.001**
	SF vs PA	1885	0.395	2619	**0.002**
	SF vs AG	862	**<0.001**	644	**<0.001**
	PA vs AG	916	**<0.001**	649	**<0.001**

Table S12 Comparison of raw *FDis* in disturbed habitats relative to primary forest for insectivore and frugivore communities (non-forest species), with analyses run separately for individual functional traits. Analyses are two-tailed Wilcoxon tests (i.e. testing whether observed values are significantly different from the null expectation in either direction). Bold denotes significant differences. Land-cover categories: PF (Primary forest), DF (Disturbed primary forest), SF (Secondary forest), PA (Pasture), AG (Agriculture).

		Insectivores		Frugivores	
Functional trait	Land-cover comparison	*V*	Wilcoxon *P*	*V*	Wilcoxon *P*
Body size	PF vs DF	762	**<0.001**	126	0.049
	PF vs SF	600	**<0.001**	144	**0.004**
	PF vs PA	389	**<0.001**	138	**0.036**
	PF vs AG	170	**<0.001**	–	–
	DF vs SF	1548	0.918	546	0.137
	DF vs PA	1475	**0.002**	462	0.772
	DF vs AG	489	**0.034**	–	–
	SF vs PA	1136	**<0.001**	864	0.242
	SF vs AG	470	0.054	–	–
	PA vs AG	906	0.885	–	–
Trophic traits	PF vs DF	834	**0.002**	126	0.049
	PF vs SF	521	**<0.001**	144	**0.004**
	PF vs PA	452	**<0.001**	138	**0.036**
	PF vs AG	179	**<0.001**	–	–
	DF vs SF	1098	**0.006**	540	0.118
	DF vs PA	1317	**<0.001**	460	0.745
	DF vs AG	417	**0.004**	–	–
	SF vs PA	1929	0.741	855	0.285
	SF vs AG	567	0.383	–	–
	PA vs AG	896	0.951	–	–
Locomotory traits	PF vs DF	871	**0.004**	126	0.049
	PF vs SF	603	**<0.001**	144	**0.004**
	PF vs PA	430	**<0.001**	138	**0.036**
	PF vs AG	168	**<0.001**	–	–
	DF vs SF	1180	**0.024**	553	0.161
	DF vs PA	753	**<0.001**	469	0.867
	DF vs AG	302	**<0.001**	–	–
	SF vs PA	1106	**<0.001**	867	0.229
	SF vs AG	369	**0.003**	–	–
	PA vs AG	839	0.689	–	–
Dispersal trait	PF vs DF	815	**0.001**	126	0.049
	PF vs SF	561	**<0.001**	144	**0.004**
	PF vs PA	282	**<0.001**	138	**0.036**
	PF vs AG	84	**<0.001**	–	–
	DF vs SF	1298	**<0.001**	547	0.140
	DF vs PA	763	**<0.001**	450	0.616
	DF vs AG	223	**<0.001**	–	–
	SF vs PA	946	**<0.001**	818	0.513
	SF vs AG	244	**<0.001**	–	–
	PA vs AG	563	**0.007**	–	–

Table S13 The effect of habitat disturbance on functional traits in insectivorous and frugivorous birds in Amazonia. Separate analyses are conducted on forest and non-forest species. Results are from a Generalised Linear Model, with the final model chosen based upon the lowest AIC value. The initial 'global' model included a quadratic explanatory variable (Environmental^2). Guilds: IN = insectivores; FR = frugivores.

Community type	Guild	Functional trait	Explanatory variable	Estimate (S.E.)	*t*	*P*
Forest	IN	Body size	Environmental	0.099 (0.015)	6.384	**<0.001**
		Dispersal	Environmental	-0.103 (0.006)	-17.762	**<0.001**
			Environmental^2	0.048 (0.006)	8.139	**<0.001**
		Trophic	Environmental	0.115 (0.006)	20.264	**<0.001**
			Environmental^2	-0.035 (0.006)	-5.944	**<0.001**
		Locomotory	Environmental	0.155 (0.009)	16.360	**<0.001**
			Environmental^2	-0.075 (0.010)	-7.840	**<0.001**
	FR	Dispersal	Environmental	-0.008 (0.003)	-1.058	**0.010**
		Trophic	Environmental	0.086 (0.010)	8.796	**<0.001**
		Body size	Environmental	0.153 (0.022)	6.968	**<0.001**
		Locomotory	Environmental	-0.009 (0.003)	-2.710	**0.007**
Non-Forest	IN	Dispersal	Environmental	0.191 (0.412)	1.706	0.089
			Environmental^2	0.553 (0.441)	4.600	**<0.001**
		Trophic	Environmental	0.037 (0.016)	2.327	**0.021**
		Body size	Environmental	0.237 (0.052)	4.537	**<0.001**
			Environmental^2	0.162 (0.056)	2.904	**0.003**
		Locomotory	Environmental	-0.026 (0.016)	-1.622	0.106
	FR	Dispersal	Environmental	-0.078 (0.015)	-5.238	**<0.001**
		Trophic	Environmental	0.043 (0.015)	2.903	**0.004**
		Body size	Environmental	-0.037 (0.040)	-0.928	0.356
			Environmental^2	0.135 (0.036)	3.711	**<0.001**
		Locomotory	Environmental	0.192 (0.025)	7.680	**<0.001**