Variable relationships between trait diversity and avian ecological functions in agroecosystems

Electronic Supplementary Material

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Appendix 1. Study system and sampling methodologies

Figure S1.1. Map of the Iberian peninsula indicating the region of study (A) (Asturias province in dark grey), and the location of the two types of Cantabrian agroecosystems studied (B), woodland pastures (within red box) and apple orchards (within green box). Dots represented plots studied (N=50).

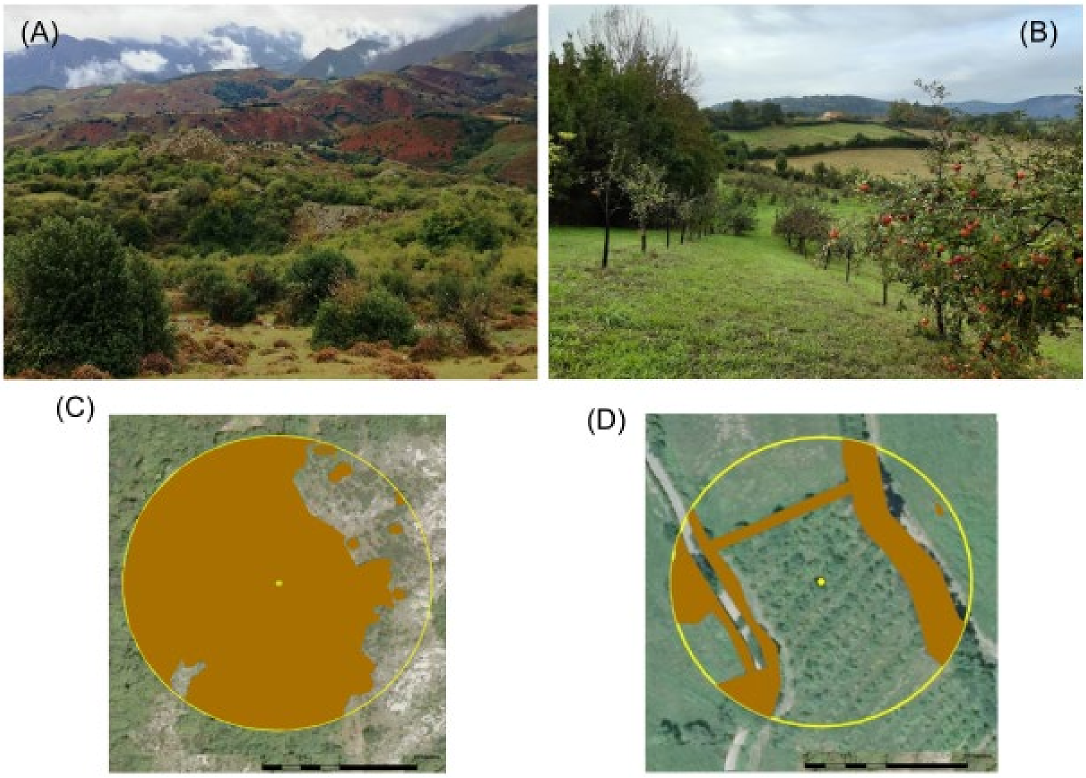

Figure S1.2. Landscape view showing the structure of vegetation and habitat physiognomy of the two types of agroecosystems in the Cantabrian range (N Asturias) that were studied, woodland pastures and apple orchards. Woodland pastures (A) show high habitat heterogeneity with forest patches, remnant trees, pastures, heathland and rocky outcrops. In apple orchards (B), apple trees are embedded in a highly variegated landscape, typically surrounded, either totally or partially, by natural woody vegetation in the form of hedgerows, composed of shrubs (*Crataegus monogyna*, *Prunus spinosa*, *Rhamnus alaternus*), scrub (*Rubus* spp., *Rosa* spp.) and tree species of varying size (e.g., *Quercus robur*, *Fraxinus excelsior*, *Corylus avellana*). Aerial photographs of a study plot in woodland pastures (C) and an apple orchard (D) depicting the delimitation of the 50m radius plots (yellow circles) around a single sampling station (yellow dot); also shown is the layer showing the extensive forest cover (mustard patches) within each plot.

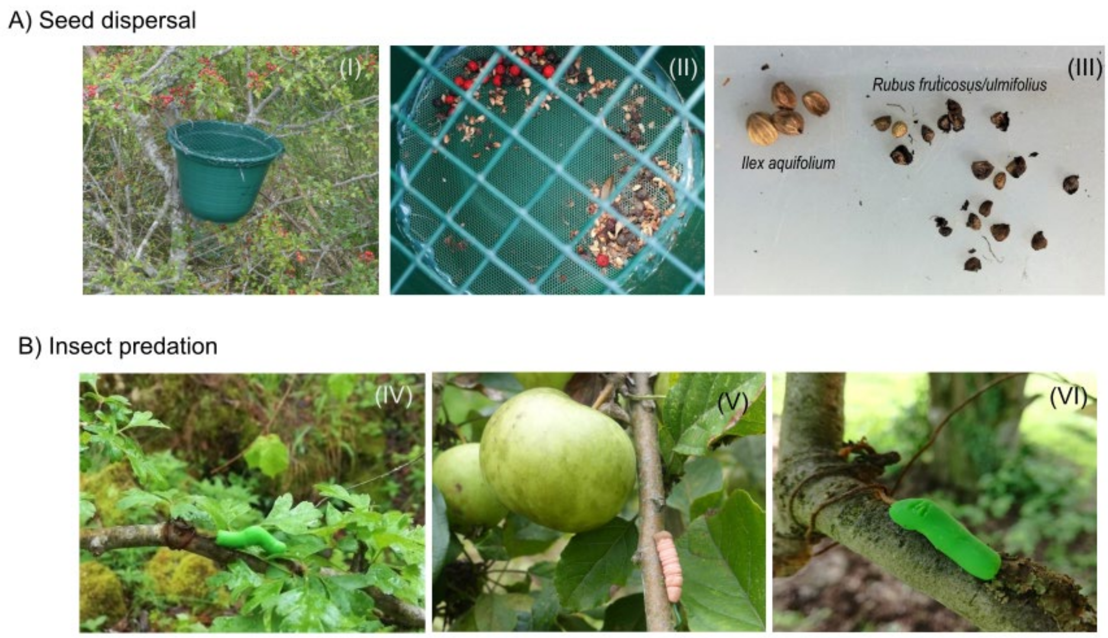

Figure S1.3 Sampling of seed dispersal (A) using seedtraps (I) that consisted of a hanging plastic pot with a surface area of 0.07 m^2. These were designed with holes to allow the drainage of rainwater, and covered by a wire mesh to protect seeds from predation by small mammals (II). Seed species were identified from external morphology considering only intact seeds (III). Sampling of insect predation function (B) using plasticene caterpillar models (15 mm long and 3 mm in diameter) that imitated common species present in each agroecosystem: *Aporia crataegi* (Lepidoptera: Pieridae) in woodland pastures (IV) and *Cydia pomonella* (Lepidoptera: Tortricidae) in apple orchards (V). Each model was presented to birds, in a posture imitating natural movement on a branch, pierced through its longitudinal axis with a green wire to attach it to the branch. Example of plasticine model with beak marks after bird attack (VI).

Appendix 2. Morphological traits and functional guild of bird species.

Table S2. Average values of morphological traits and functional guild of bird species under study.

Scientific name	Acronym	Bill length	Bill width	Kipp's distance	Tarsus length	Tail length	Body mass	Functional guild	Agroecosystem
Aegithalos caudatus	aegcau	8.12	5.35	0.23	16.67	87.25	8.60	Frugivore/insectivore	woodland pastures/apple orchards
Anthus trivialis	anttri	16.63	7.77	0.31	20.26	58.75	23.33	Insectivore	woodland pastures
Certhia brachydactyla	cerbra	19.90	6.60	0.19	15.22	60.13	8.20	Insectivore	woodland pastures/apple orchards
Cettia cetti	cetcet	14.90	5.78	0.15	18.92	56.00	13.22	Insectivore	woodland pastures
Coccothraustes coccothraustes	coccoc	21.09	15.37	0.32	20.60	56.93	56.63	Frugivore	woodland pastures
Columba palumbus	colpal	28.74	12.42	0.41	33.53	158.38	490.00	Frugivore	woodland pastures/apple orchards
Cuculus canorus	cuccan	28.34	19.36	0.49	24.92	162.75	111.36	Insectivore	woodland pastures
Cyanistes caeruleus	cyacae	8.84	5.01	0.22	14.93	51.88	13.30	Frugivore/insectivore	woodland pastures/apple orchards
Dendrocopos major	denmaj	30.08	12.31	0.30	22.86	86.25	74.94	Insectivore	woodland pastures/apple orchards
Erithacus rubecula	erirub	15.70	7.28	0.22	24.75	58.88	17.70	Frugivore/insectivore	woodland pastures/apple orchards
Ficedula hypoleuca	fichyp	13.83	7.25	0.31	16.99	53.20	13.79	Insectivore	apple orchards
Fringilla coelebs	fricoe	14.35	7.51	0.28	17.58	66.00	23.81	Frugivore/insectivore	woodland pastures/apple orchards
Garrulus glandarius	gargla	34.27	17.60	0.19	40.23	153.75	159.46	Frugivore/insectivore	woodland pastures/apple orchards
Lanius collurio	lancol	19.78	12.86	0.32	23.31	79.00	28.44	Insectivore	apple orchards
Locustella naevia	locnae	16.06	6.12	0.28	20.22	57.83	13.30	Insectivore	apple orchards
Lophophanes cristatus	lopcri	12.35	5.01	0.22	17.55	52.38	11.04	Frugivore/insectivore	woodland pastures/apple orchards
Muscicapa striata	musstr	17.13	8.85	0.30	14.20	60.56	15.90	Frugivore/insectivore	woodland pastures/apple orchards
Nannus troglodytes	trotro	14.40	5.18	0.16	16.60	31.00	9.74	Insectivore	woodland pastures/apple orchards
Oriolus oriolus	oriori	29.95	14.13	0.39	21.12	87.00	79.00	Insectivore	apple orchards
Parus major	parmaj	12.71	6.30	0.19	18.38	66.50	16.25	Frugivore/insectivore	woodland pastures/apple orchards
Periparus ater	perate	11.24	5.86	0.22	14.70	48.88	9.20	Frugivore/insectivore	woodland pastures/apple orchards

Phoenicurus ochruros	phooch	15.13	6.95	0.23	23.04	60.33	16.50	Insectivore	woodland pastures/apple orchards
Phoenicurus phoenicurus	phopho	14.10	6.88	0.26	21.75	57.00	14.59	Insectivore	woodland pastures/apple orchards
Phylloscopus collybita	phycol	13.23	4.93	0.20	19.75	48.38	8.30	Frugivore/insectivore	woodland pastures/apple orchards
Phylloscopus ibericus	phyibe	13.25	4.61	0.22	19.56	46.83	8.30	Frugivore/insectivore	woodland pastures
Picus sherpei	picshe	44.98	13.75	0.24	27.16	100.50	176.00	Frugivore/insectivore	woodland pastures/apple orchards
Poecile palustris	poepal	9.38	4.83	0.18	15.38	52.88	11.14	Frugivore/insectivore	woodland pastures/apple orchards
Prunella modularis	prumod	14.15	8.03	0.21	20.25	60.13	20.24	Insectivore	woodland pastures/apple orchards
Pyrrhula pyrrhula	pyrpyr	12.68	11.55	0.25	17.38	67.25	24.26	Frugivore/insectivore	woodland pastures
Regulus ignicapilla	regign	11.73	4.67	0.22	16.36	39.58	5.60	Insectivore	woodland pastures/apple orchards
Regulus regulus	regreg	12.66	4.38	0.23	14.06	42.75	5.54	Insectivore	apple orchards
Sitta europaea	siteur	22.28	6.81	0.24	19.56	44.75	20.37	Insectivore	woodland pastures/apple orchards
Sylvia atricapilla	sylatr	15.76	7.75	0.26	20.88	61.75	16.70	Frugivore/insectivore	woodland pastures/apple orchards
Sylvia borin	sylbor	15.16	8.25	0.31	19.50	54.20	18.20	Frugivore/insectivore	woodland pastures/apple orchards
Sylvia communis	sylcom	14.43	6.96	0.25	21.37	63.74	15.10	Frugivore/insectivore	woodland pastures/apple orchards
Sylvia melanocephala	sylmel	14.67	6.16	0.19	20.75	59.75	11.70	Frugivore/insectivore	apple orchards
Sylvia undata	sylund	14.57	5.24	0.13	18.52	64.63	10.80	Frugivore/insectivore	woodland pastures
Turdus iliacus	turili	24.64	11.28	0.32	27.90	80.88	61.20	Frugivore/insectivore	woodland pastures/apple orchards
Turdus merula	turmer	28.83	12.50	0.23	30.65	107.13	102.73	Frugivore/insectivore	woodland pastures/apple orchards
Turdus philomelos	turphi	25.41	12.24	0.31	31.48	82.63	67.74	Frugivore/insectivore	woodland pastures/apple orchards
Turdus pilaris	turpil	27.48	12.90	0.33	33.89	119.13	106.00	Frugivore/insectivore	woodland pastures
Turdus torquatus	turtor	28.19	13.37	0.30	32.21	111.30	109.00	Frugivore/insectivore	woodland pastures
Turdus viscivorus	turvis	27.25	13.39	0.36	32.70	111.00	117.37	Frugivore/insectivore	woodland pastures/apple orchards

Appendix S3. Phylogenetic relationships of forest-dwelling birds in the Cantabrian mountains (northern Iberian Peninsula).

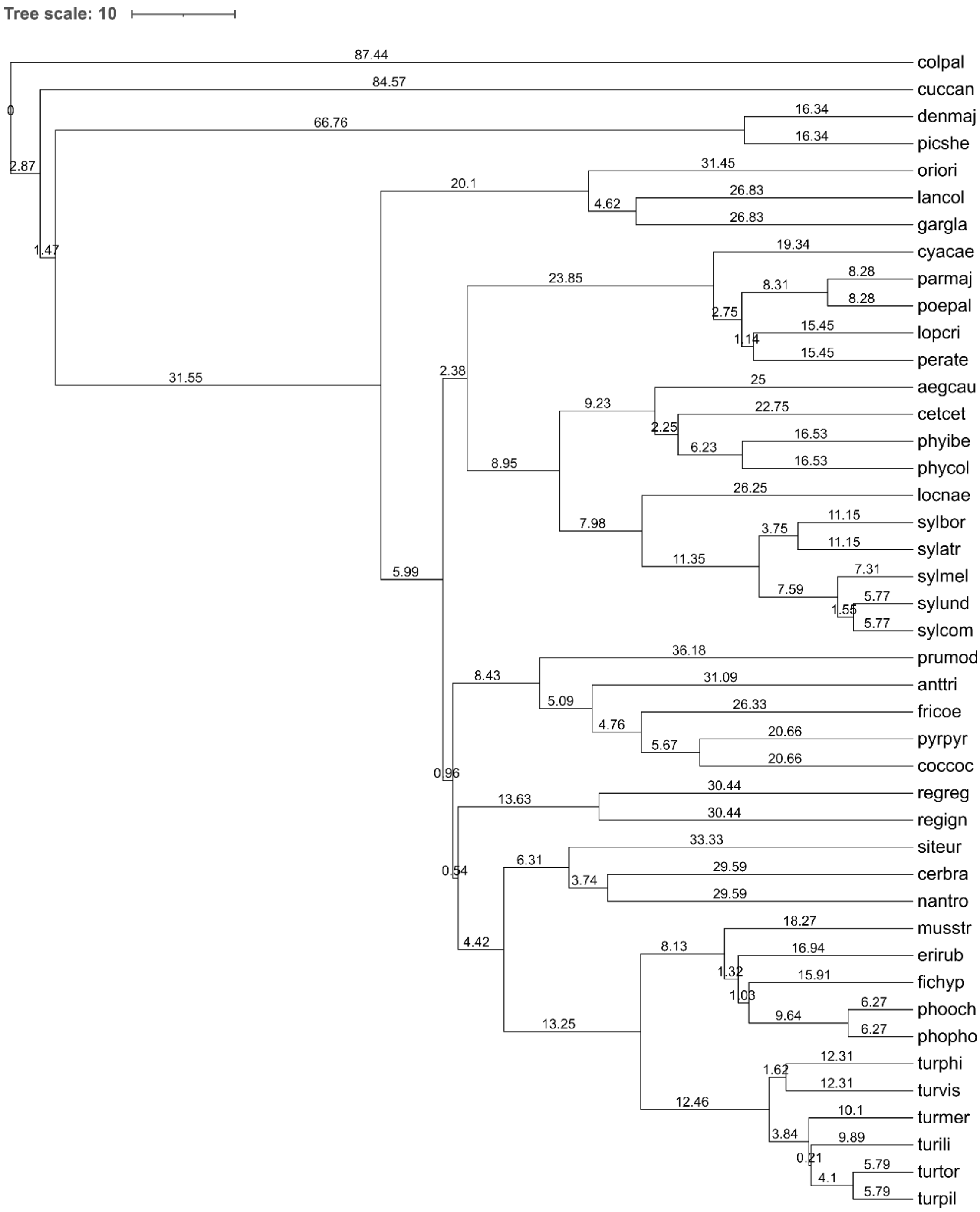

Fig. S3 Phylogenetic relationships of forest-dwelling birds in the Cantabrian mountains (N Spain). Trees based on published phylogenies (Jetz et al., 2012), and branch length is shown (myr). Bird species are indicated by their acronyms (Table S2).

References:

Jetz, W., G. H. Thomas, J. B. Joy, K. Hartmann, and A. O. Mooers. 2012. The global diversity of birds in space and time. Nature 491:444–448.

Appendix 4. Environmental factors and biodiversity components of frugivorous and insectivorous birds in two Cantabrian agroecosystems in Asturias (N Spain)

Table S4.1 Mean, minimum and maximum values of biodiversity component estimates of frugivores and insectivores in Cantabrian agroecosystems.

Agroecosystem		**Woodland pastures**						**Apple orchards**	
Avian guild		**Frugivores**			**Insectivores**			**Insectivores**	
estimates	**Min**	**Max**	**mean +SD**	**Min**	**Max**	**mean +SD**	**Min**	**Max**	**mean +SD**
Species richness	5	18	12 ± 2	6	21	14 ± 3	9	22	15 ± 2
FDis	-2.55	2.53	-0.42 ± 0.98	-2.62	2.27	-0.28 ± 1.00	-1.7	1.5	0.09± 0.82
Bird abundance	19	173	88 ± 32	47	136	96 ± 20	41	248	139 ± 59
MPD	-3.5	3.61	-0.25 ± 1.41	-4.63	2.74	-0.1 ± 1.44	-2.3	2.39	0.15 ± 0.96

Table S4.2 Minimum, maximum and mean values of environmental factors, such as forest cover and resource availability of Cantabrian agroecosystems for seed dispersal (i.e., fruit abundance, measured as number of fruits/plot) and insect predation (i.e., arthropod abundance measured as biomass(g)/plot).

Agroecosystem		**Woodland pastures**						**Apple orchards**	
Function		**Seed dispersal**			**Insect predation**			**Insect predation**	
Environmental variables	**Min**	**Max**	**mean +SD**	**Min**	**Max**	**mean +SD**	**Min**	**Max**	**mean +SD**
Forest cover (%)	6	77	33.77 ± 22.40	6	77	33.77 ± 22.40	0	38	0.16 ± 0.08
Resource abundance	638	1.15×10^6	$2.5 \times 10^5 \pm 2.2 \times 10^5$	0.02	0.14	0.04 ± 0.03	0.13	1.21	0.53 ± 0.26

Appendix 5. Piecewise structural equation modelling

Data analyses

The piecewise Structural Equation Modelling (pSEM) approach is a form of path analysis that deals with complex multivariate relationships between a set of interrelated variables, and thus allows the sum of causal direct and indirect interactions among variables to be considered (Grace, 2006). In addition, pSEM allows relationships between variables (i.e., links) to be parameterized through mixed effects models that take into account non-Gaussian error distribution in the response variables, as well as it accounting for random effects (Lefcheck, 2016). pSEMs are represented by path diagrams i.e., the variables and effect pathways (e.g., Fig. 1b). Every path in the pSEM is described as a fixed effect, allowing for interactive effects between multiple variables (e.g., environmental variables, biodiversity components and ecological functions), and the partitioning of correlation between variables into direct and indirect effects. Direct effects are represented by links between consecutive variables (e.g., the green arrows between environmental factors and biodiversity components in Fig. 1b) and are measured by regression coefficients. Furthermore, the pSEM approach also permits the inclusion of correlated errors between variables, which reflect the situation where the relationship between two variables is not presumed to be causal and unidirectional (e.g., the relationship between biodiversity components represented by grey double headed arrows in Fig.1b), but rather that both could be driven by some underlying driver and therefore might appear to be correlated (Lefcheck, 2016).

Specifically, in our study, we hypothesized different causal links distinguishing three hierarchical levels, represented by the conceptual model in Figure 1.b (see Methods). In particular, we expected that the magnitude of a given ecological function would be determined by the direct and indirect (biodiversity-mediated) effects of environmental gradients (forest cover and resource availability), and by the direct effects of different biodiversity components (trait diversity, abundance and phylogenetic diversity) on ecological functions. As we were interested in comparing the same biological hypotheses across function and agroecosystem, we performed the same pSEM for seed dispersal and insect predation in woodland pastures to enable comparisons between functions, and also for insect predation in two different types of agroecosystems, i.e., woodland pastures and apple orchards. Each pSEM were represented by a list of models that considered different variables as response variables (e.g., resource abundance, biodiversity components and ecological function). These effects among variables were described by generalized linear-mixed effects models (GLMM) using the lme function (Gaussian error distribution) of the nlme package and glmer of the lme4 (Poisson or binomial error distribution). Fixed correlated errors are specified using the operator %~~% within the psem function (see Rcode of our conceptual scheme below).

Model reduction:

We fitted each pSEM by initially including all causal relationships between variables (i.e., those represented in the conceptual scheme, Fig.1b), from which we removed all non-significant paths sequentially, until the best-fit model determined by the Akaike's and Bayesian's Information Criteria (lowest AIC and BIC) was achieved (Fig. S5.1, S5.2 and S5.3).

In the interest of parsimony, we did not control for year (2017/2018 in woodland pastures) or sampling season (spring-summer/fall-winter in apple orchards) in the models as their inclusion did not qualitatively change our findings (see backward simplification modelling of pSEMs in Fig. S5.1, S5.2 and S5.3).

Rcode of the conceptual scheme (Fig. 1b)

```
 pSEM <- psem (
-    lme ( Resources ~  forest_cover,
       random= ~ 1|plot , na.action = na.exclude, data),
-    lme (MPD ~  forest_cover + resources,
      random= ~ 1|plot , na.action = na.exclude, , data),
-    lme (FDis ~  forest_cover + resources ,
      random= ~ 1|plot , na.action = na.exclude, , data),
-    lme (Abundance ~  forest_cover + resources,
      random= ~ 1|plot ,na.action = na.exclude, , data),
-    glmer (FUNCTION ~  forest_cover + resources + MPD + FDis + Abundance
       + (1|plot), na.action = na.exclude, , data),  family =# poisson (link = "log") # binomial  ("logit") ),
  MPD%~~%FDis,
  MPD%~~%Abundance,
  FDis%~~%Abundance,
  data)
```

References:

Grace, J. B. (2006). Structural EquationModeling andNatural Systems. Cambridge: Cambridge University Press.

Lefcheck, J. S. (2016). piecewiseSEM: Piecewise structural equation modelling in r for ecology, evolution, and systematics. *Methods in Ecology and Evolution*, *7*(5), 573–579. doi:10.1111/2041-210X.12512

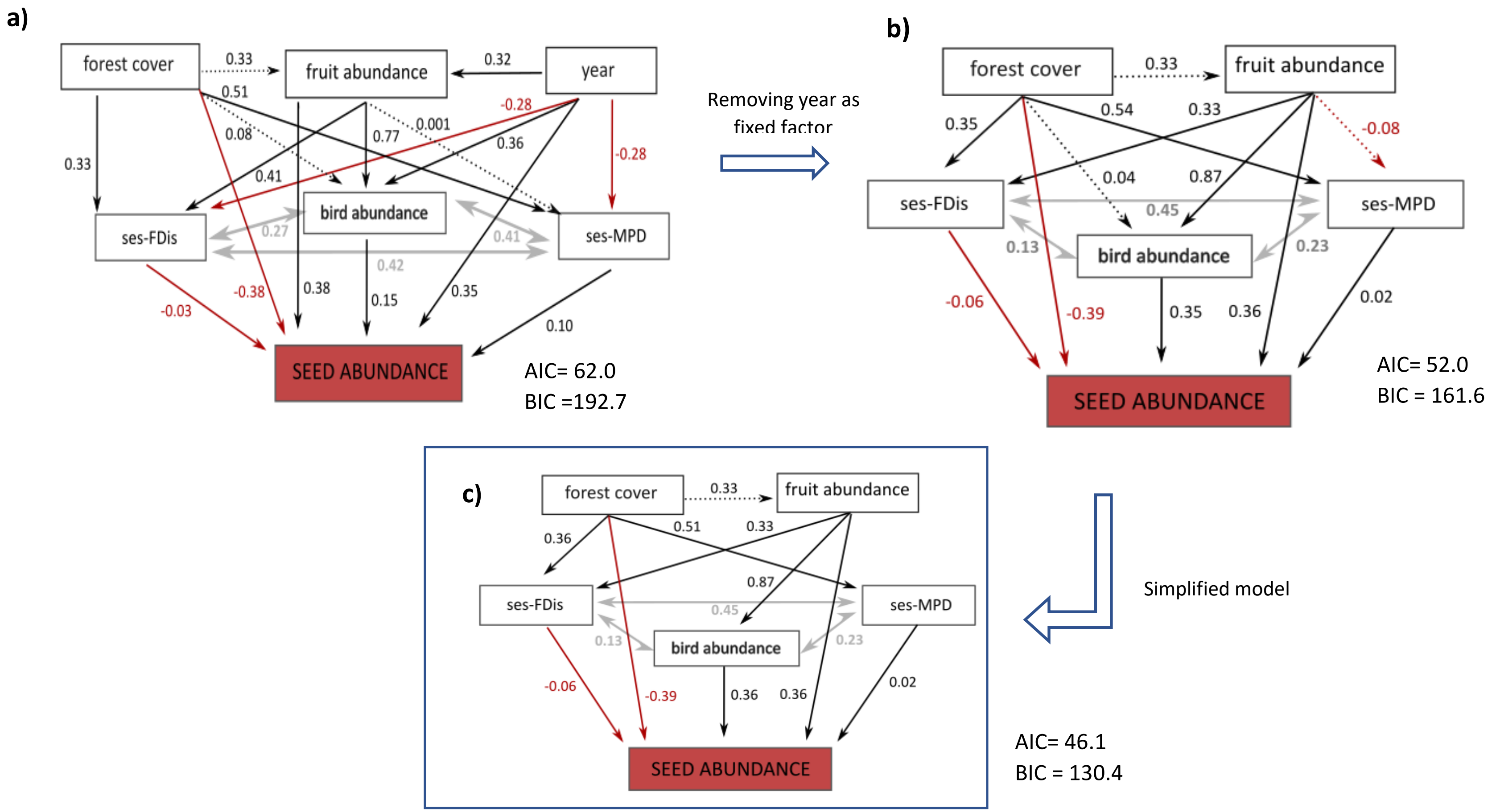

Figure S5.1 Structural Equation Model (pSEM) showing all predicted relationships between environmental gradients (forest cover and resource abundance), biodiversity components (trait diversity (ses-FDis), bird abundance, and phylogenetic diversity (ses-MPD)) and seed dispersal function (seed abundance), including year as fixed factor (a); pSEM including all links of the conceptual scheme (b) (Fig. 1b); and, the optimized model (according AIC and BIC) excluding all non significant paths (c). Standardized path coefficients are given next to each path, where positive effects are shown in black and negative effects in red. Non-significant effects are represented by dashed arrows (p > 0.05). Grey double headed arrows show correlated errors between biodiversity components. Values of Akaike's and Bayesian's Information Criteria (i.e., AIC and BIC, respectively) are shown for each model. FDis and MPD represent standardized effect size (ses) values (see Methods).

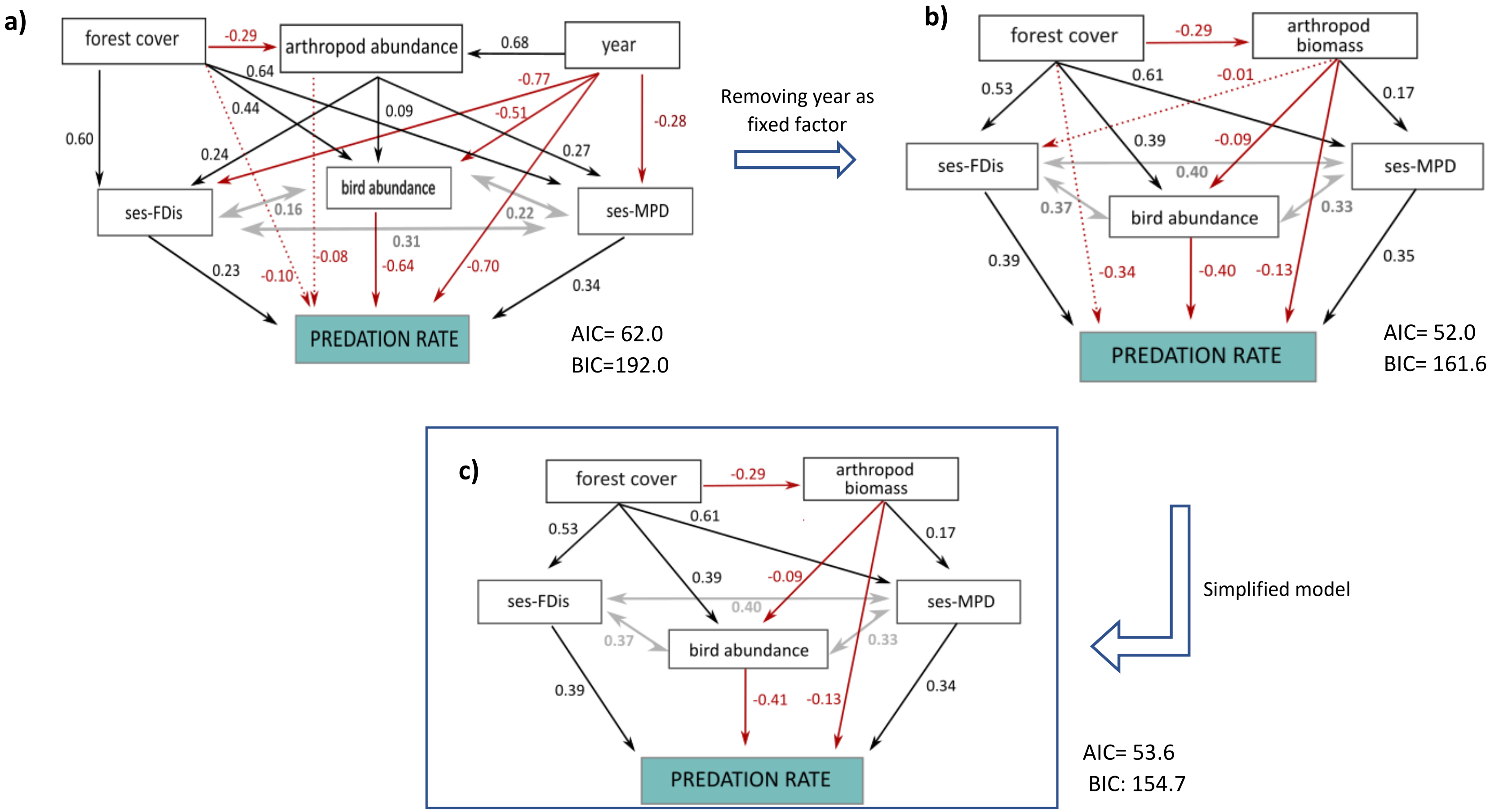

Figure S5.2 Structural Equation Model (pSEM) showing all predicted relationships between environmental gradients (forest cover and resource abundance), biodiversity components (trait diversity (ses-FDis), bird abundance, and phylogenetic diversity (ses-MPD)) and insect predation function (predation rate) in woodland pastures including year as fixed factor (a); pSEM including all links of the conceptual scheme (b) (Fig. 1b); and, the optimized model (according to AIC and BIC) excluding all non significant paths (c). Standardized path coefficients are given next to each path, where positive effects are shown in black and negative effects in red. Non-significant effects are represented by dashed arrows ($p > 0.05$). Grey double headed arrows show correlated errors between biodiversity components. Values of Akaike's and Bayesian's Information Criteria (i.e., AIC and BIC, respectively) are shown for each model. FDis and MPD represent standardized effect size (ses) values (see Methods).

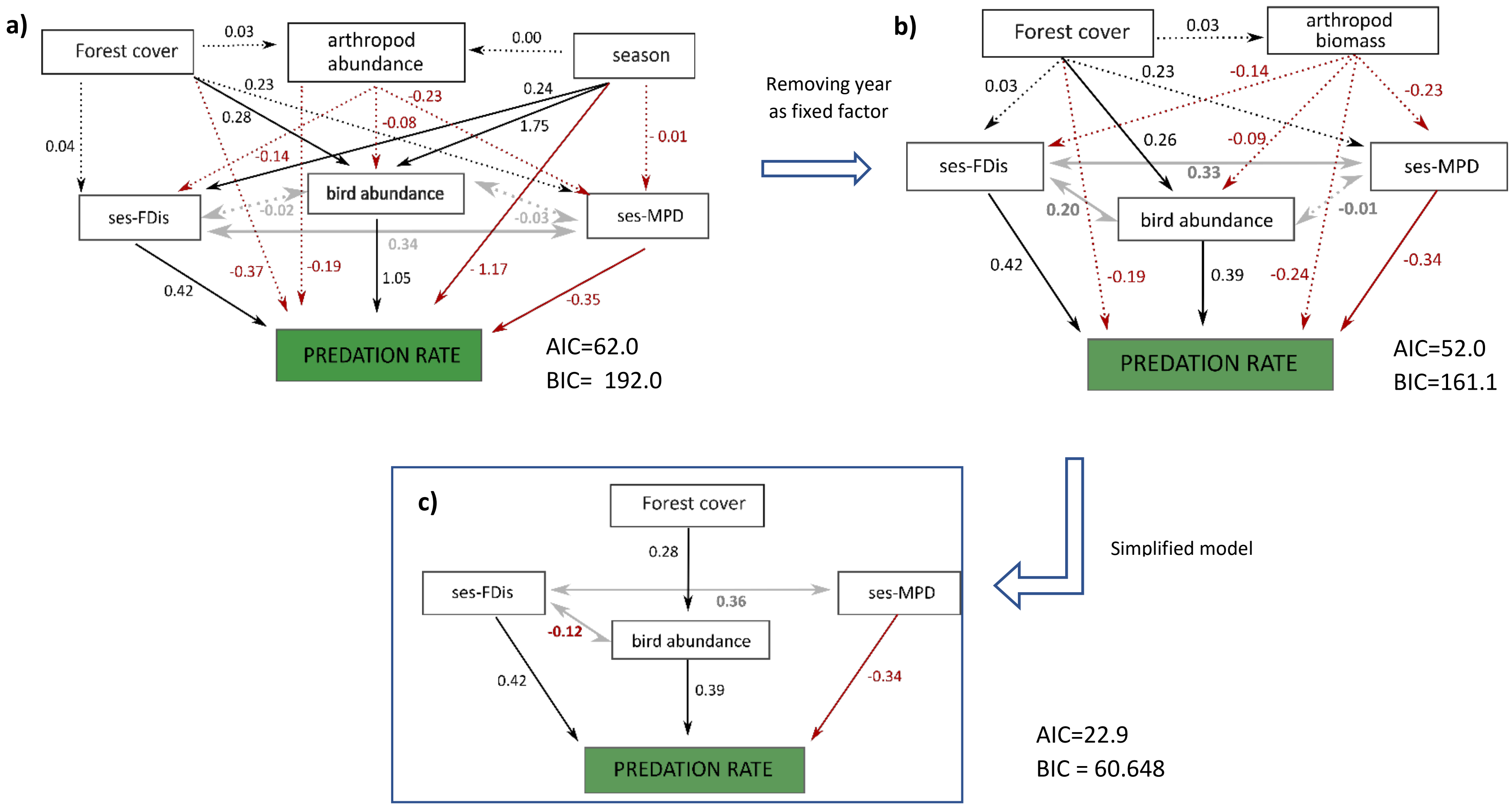

Figure S5.3 Structural Equation Model (pSEMs) showing all predicted relationships between environmental gradients (forest cover and resource abundance), biodiversity components (trait diversity (ses-FDis), bird abundance, and phylogenetic diversity (ses-MPD)) and insect predation function (predation rate) in apple orchards including season as fixed factor (a); pSEM including all links of the conceptual scheme (b) (Fig. 1b); and, the optimized model (according to AIC and BIC) excluding all non-significant paths (c). Standardized path coefficients are given next to each path, where positive effects are shown in black and negative effects in red. Non-significant effects are represented by dashed arrows ($p > 0.05$). Grey double headed arrows show correlated errors between biodiversity components. Values of Akaike's and Bayesian's Information Criteria (i.e., AIC and BIC, respectively) are shown for each model. FDis and MPD represent standardized effect size (ses) values (see Methods).

Table S5.1 Piecewise SEM (pSEM) model specifications including distributions for response variables and R-squared values. Model types include generalized linear mixed models (GLMM). In the three independent pSEMs (Fig. 4), we specified correlated error structures between biodiversity components (FDis, MPD, and bird abundance).

Function & Agroecosystem	Partial model	Response variable	Model	Distribution	Predictors	Random effects	Marginal R^2	Conditional R^2
Seed dispersal (woodland	1	FDis	GLMM	normal	Forest cover + fruit abundance	Plot	0.30	0.65
pastures)	2	MPD	GLMM	normal	Forest cover	Plot	0.25	0.70
	3	Bird abundance	GLMM	normal	Fruit abundance	Plot	0.64	0.87
	4	Seed dispersal	GLMM	poisson	Forest cover + fruit abundance + FDis + MPD + bird abundance	Plot	0.72	1.00
Insect predation	1	Arthropod abundance	GLMM	normal	Forest cover	Plot	0.08	0.49
(woodland	2	FDis	GLMM	normal	Forest cover	Plot	0.27	0.53
pastures)	3	MPD	GLMM	normal	Forest cover + arthropod abundance	Plot	0.31	0.82
	4	Bird abundance	GLMM	normal	Forest cover + arthropod abundance	Plot	0.17	0.79
	5	Insect predation	GLMM	binomial	arthropod abundance + FDis + MPD + bird abundance	Plot	0.06	0.19
Insect predation (apple orchards)	1	Bird abundance	GLMM	normal	Forest cover	Plot	0.08	0.18
	2	Insect predation	GLMM	binomial	FDis + MPD + bird abundance	Plot	0.05	0.47

Table S5.2. Summary of the direct (D), indirect (I), and total (Total) effects of predictors (rows) on response variables (columns) in the simplified (best) fit piecewise SEM for seed dispersal and insect predation functions in two Cantabrian agroecosystems: woodland pastures and apple orchards. FDis and MPD represent standardized effect size values. All parameters were scaled to zero mean and unit of variance prior to analysis. Dashed lines in cells represent relationships not included in the best-fit model.

Agroecosystem	**Woodland pastures**						**Apple orchards**		
Function	**Seed dispersal**			**Insect predation**			**Insect predation**		
Response variable	*seed deposition*			*insectivory rate*			*insectivory rate*		
Predictor effect	*D*	*I*	*Total*	*D*	*I*	*Total*	*D*	*I*	*Total*
Habitat structure	-0.39	-0.01	-0.40	--	0.22	0.22	--	0.11	0.11
Resources	0.36	0.29	0.65	-0.13	0.09	-0.04	--	--	--
FDis	-0.06	--	-0.06	0.39		0.39	0.42	--	0.42
MPD	0.02	--	0.02	0.34		0.34	-0.34	--	-0.34
Bird abundance	0.36	--	0.36	-0.41		-0.41	0.39	--	0.39

Appendix 6. Spatial correlation tests

Table S6.1. Values of the Moran´s I test for the occurrence of spatial auto-correlation in the values of the components of biodiversity of frugivorous birds (i.e., trait diversity (FDis), phylogenetic diversity (MPD) and bird abundance (Abundance)) in woodland pastures for each sampling year (i.e., 2017 and 2018). Spatial auto-correlation was tested on the raw data and also on the residuals of models, considering components of biodiversity as response variables in the context of the fitting of a pSEM for seed dispersal in woodland pastures (Fig.4a). Values in bold represent significant Moran's I values ($p < 0.05$). Euclidean distances between sampling points (25 plots separated from each other by at least 200 m) were estimated from a Geographic Information System based on UTM coordinates.

		raw data		pSEM residuals	
Year	**Frugivores**	Moran's I	p	Moran's I	p
2017	FDis	-0.097	0.333	0.012	0.352
	MPD	**0.130**	**0.003**	-0.126	0.140
	Abundance	-0.074	0.574	-0.020	0.707
2018	FDis	-0.054	0.821	0.022	0.271
	MPD	-0.051	0.869	-0.133	0.117
	Abundance	-0.009	0.571	-0.022	0.732

Table S6.2 Values of the Moran´s I test for the occurrence of spatial auto-correlation in the values of the components of biodiversity of insectivorous birds (i.e., trait diversity (FDis), phylogenetic diversity (MPD) and bird abundance (Abundance)) in woodland pastures for each sampling year (i.e., 2017 and 2018). Spatial auto-correlation was tested on the raw data and also on the residuals of models, considering components of biodiversity as response variables in the context of the fitting of a pSEM for insect predation in woodland pastures (Fig.4a). All values showed non-significant Moran's I values ($p > 0.05$). Euclidean distances between sampling points (25 plots separated from each other by at least 200 m) were estimated from a Geographic Information System based on UTM coordinates.

		raw data		pSEM residuals	
Year	**Insectivores**	Moran's I	p	Moran's I value	p
2017	FDis	-0.022	0.738	-0.106	0.269
	MPD	-0.031	0.849	-0.023	0.737
	Abundance	0.021	0.275	-0.045	0.957
2018	FDis	-0.074	0.576	-0.098	0.336
	MPD	-0.014	0.627	-0.023	0.743
	Abundance	0.044	0.133	-0.044	0.960