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Frugivores enhance potential carbon recovery in fragmented landscapes

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SUPPLEMENTAL MATERIAL

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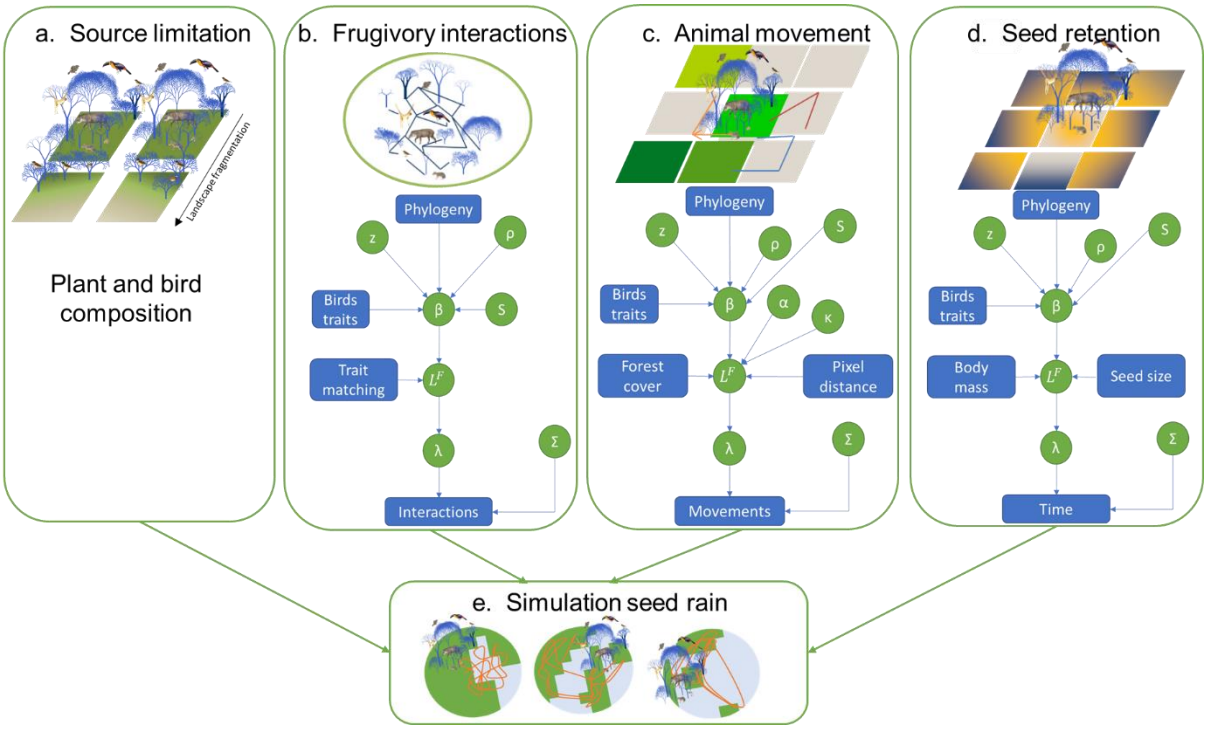

Extended Data Figure 1. Methodological diagram. The upper panel shows the structure of the models developed for each process: source limitation(a), frugivory interactions (b), animal movement (c), seed retention (d). In the model structure, blue squares represent the data and the green circles the parameters estimated by the model. We can observe a hierarchical structure of the models where phylogeny and traits indirectly influence the mean response of the species, while variables such as trait matching or cover type directly influence the processes. The parameters estimated in each model, and the plant and bird composition in each landscape, are intergraded in simulation of seed rainfall in each landscape cover (e). Illustrations of trees and animals – Copyright Pedro Jordano, authorized by the author)

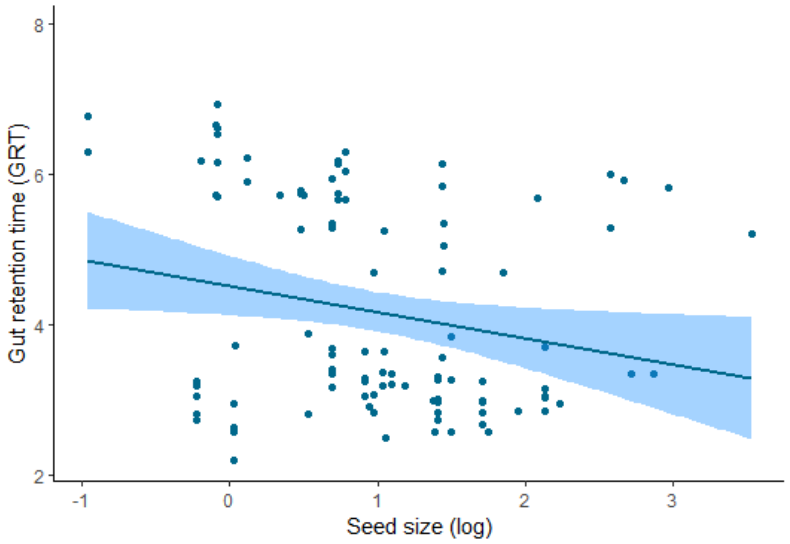

Figure S1. Exploratory analysis between seed size and gut retention time. We gather seed size information for 60% of the species in our database, and for cases where seed size data was unavailable, we imputed the genus mean. We conducted an exploratory analysis using phylogenetic generalized least squares (pgls) to mimic our Bayesian procedure, which also incorporates phylogeny. We observed a negative, albeit marginally significant relationship (β= -0.1418, p=0.051), between seed size and GPT. The model showed a slight improvement compared to the pgls model that only included body mass (Rseed2= 0.84, Rbody2 =0.82). Line represents fitted mean tendency and ribbon area (95% confidence intervals)

Table S1. Description of 10 landscapes used to simulate bird movement and seed deposition in open areas. Landscapes are ordered by the percentage of forest cover

Landscape	Forest cover	Number of patches	Mean forest isolation	N birds	Latitude	Longitude
ls01	9%	19	222.45	28	-22.928	-46.586
ls02	12%	17	155.24	29	-23. 072	-46.468
ls03	19%	37	108.53	29	-22.996	-46.494
ls04	22%	17	152.20	29	-22.996	-46.543
ls05	32%	31	89.20	27	-23.083	-46.692
ls06	39%	31	62.32	28	-23.236	-46.610
ls07	48%	8	106.57	22	-23.231	-46.296
ls08	55%	19	62.16	18	-23.064	-46.547
ls09	59%	23	69.37	18	-23.178	-46.494
ls10	61%	15	60.64	17	-23.150	-46.691

Table S2. Model coefficients. In columns the exploratory variables. In rows the respond variables. * represent significant variables with 90% and ** with 95% of confidence from a two-sided z-test.

		Forest cover		*Forest isolation*		*Body mass (log)*		*Gape size*		*Distance to forest edge (log)*	
		coef	**p-value**	**coef**	**p-value**	**coef**	**p-value**	**coef**	**p-value**	**coef**	**p-value**
Seed deposition	intercept	501.38	<0.001**	501.39	<0.001**	12.55	<0.001**	10.07	<0.001**	3329.14	<0.001**
	x	1662.87	<0.001**	-1595.2	<0.001**	-2.31	<0.001**	-0.54	<0.001**	-1598.9	<0.001**
	x^2	245.35	0.002**	559.9	<0.001**						
	x^3	554.06	<0.001**	-344.9	<0.001**						
	Pseudo-R2 conditional	0.83		0.79		0.21		0.25		0.75	

	Pseudo-R2 marginal					0.25		0.21		0.51	
Biomass potential	intercept	2.44	<0.001**	4.0	<0.001**	4.52	<0.001**	4.81	<0.001**	1.04	<0.001**
	x	2.29	<0.001**	-0.008	<0.001**	-0.02	0.09	-0.03	0.05*	-0.99	<0.001**
	x^2	-0.24	0.39								
	x^3	1.63	<0.001**								
	Pseudo-R2 conditional	0.55		0.62		0.10		0.078		0.557	
	Pseudo-R2 marginal					0.003		0.001		0.435	

Table S3. Inflection points for predicted models. Threshold values are in the same units as the co-variables.

Predicted variable	Co-variable	Threshold
Number of seeds	Forest cover	38%
Number of seeds	Forest isolation	133
Potential biomass	Forest cover	36%
Potential biomass	Forest isolation	112

Table S4. Random effects for fitted models for seed dispersal and biomass restoration against body mass and gape size. In bold we highly the change on tendency

Percentage forest cover	***Biomass***				***Seed dispersal***			
	Body mass		Gape size		Body mass		Gape size	
	(Intercept)	log(Body)	(Intercept)	Gape	(Intercept)	log(Body)	(Intercept)	Gape
0.09	2.02	-0.80	1.22	-0.19	-0.19	-0.15	-0.15	-0.05
0.121	1.98	-0.76	1.48	-0.21	0.51	-0.30	0.61	-0.11
0.185	0.47	-0.35	0.28	-0.10	-0.87	0.04	-0.56	-0.02
0.217	0.17	-0.25	0.48	-0.12	-1.40	0.20	-0.79	0.01
0.315	1.49	-0.60	0.80	-0.14	-0.36	-0.05	-0.21	-0.03
0.391	1.60	-0.61	0.97	-0.15	**0.07**	-0.15	0.11	-0.05
0.475	**-0.63**	**0.20**	**-0.22**	**0.03**	**0.87**	-0.10	1.07	-0.06
0.55	**-1.70**	**0.86**	**-1.51**	**0.28**	**0.86**	**0.06**	**0.24**	**0.08**
0.588	**-2.79**	**1.18**	**-2.11**	**0.34**	**0.02**	**0.30**	**-0.51**	**0.16**
0.61	**-2.60**	**1.12**	**-1.39**	**0.26**	**0.49**	**0.16**	**0.19**	**0.08**

Table S5. Convergence and model performance. Rhat<1.1 shows the percentage of chains converging at each model. Rturj only applied to binary variables

Model	Rhat<1.1	Waic	Rturj	R2 Gelma
Frugivory interactions	98.00%	1796.58	0.19	0.39
Gut passage time	80.00%	-131.23		0.93

Table S6. Average number of fruits consumed per bird species. References are in supplemental material S4

Species	Average Fruits/Visit	Number of individuals
Antilophia galeata	2.8	166

Ara manilata	7.0	8
Aratinga aurea	10.0	4
Aratinga leucophtalmus	4.6	
Arremon flavirostris	1.8	3
Arremon tacitumus	1.0	
Baryphtengus ruficapillus	2.9	17
Basileuterus culicivorus	15.0	1
Brotogeris chiriri	5.5	
Brotogeris tirica	12.0	
Brotogeris versicolurus	12.0	
Cacicus chrysopterus	2.0	28
Cacicus haemorrhous	4.8	
Camptostoma obsoletum	3.0	2
Capsiempis flaveola	3.0	
Carpornis cucullata	2.5	
Casiornis rufa	3.0	4
Catharus fuscenses	1.8	9
Celeus flavescens	5.8	
Ceratopipra rubrocapilla	2.1	
Chiroxiphia caudata	3.6	6
Cnemotriccus fuscatus	2.4	1
Coereba flaveola	2.8	29
Colaptes campestris	59.0	
Colaptes melanochloros	37.5	12
Colonia colonus	5.0	1
Conirostrum speciosum	1.6	
Conopias trivirgata	1.8	
Coryphospingus cucullatus	6.8	
Cyanerpes cyaneus	2.7	1
Cyanocorax caeruleus	3.0	
Cyanocorax chrysops	4.8	12
Cyanocorax cristatellus	8.1	25
Cyanocorax cyanopogon	1.0	
Cyclarhis gujanensis	2.4	3
Dacnis cayana	4.1	133
Diopsittaca nobilis	14.0	
Dixiphia pipra	2.6	
Dryocopus lineatus	66.7	9
Elaenia chiriquensis	3.2	77
Elaenia cristata	3.7	52
Elaenia flavogaster	3.2	58
Elaenia mesoleuca	2.4	26
Elaenia obscura	2.5	35
Elaenia spp.	1.2	
Empidonomus varius	2.4	37
Eucometis penicilatta	2.8	7
Euphonia chlorotica	10.2	34
Euphonia cyanocephala	220.1	5
Euphonia violacea	10.3	4
Forpus xanthopterygius	1.1	3
Geothlypis aequinoctalis	1.0	

Habia rubica	3.1	
Haplospiza unicolor	1.8	
Hemithraupis flavicollis	1.8	
Hemithraupis guira	5.3	66
Hemithraupis ruficapilla	5.0	
Hemitriccus margaritaceiventer	4.0	
Hylophilus amaurocephalus	3.0	
Hylophilus poicilotis	1.0	3
Icterus pyrrhopterus	2.7	
Ilicura militaris	5.9	
Knipolegus cyanirostris	1.0	
Lathrotriccus euleri	3.6	6
Legatus leucophaius	3.3	4
Leptopogon amaurocephalus	1.0	1
Leptotila rufaxilla	6.9	
Lipaugus lanioides	2.1	
Machaeropteris regulus	2.7	
Machetornis rixosus	1.0	
Manacus manacus	2.4	
Megarhynchus pitangua	4.0	11
Melanerpes candidus	3.3	
Mimus saturninus	7.4	48
Mionectes oleaginea	2.0	
Mionectes rufiventris	3.4	9
Molothrus bonariensis	1.9	1
Myiarchus ferox	2.8	9
Myiarchus swainsoni	3.7	8
Myiarchus tyrannulus	2.1	17
Myiodynastes maculatus	3.3	65
Myiopagis caniceps	1.0	1
Myiozetetes cayanensis	2.0	
Myiozetetes similis	2.6	6
Nemosia pileata	2.1	4
Neopelma pallescens	23.2	5
Orthogonys chloricterus	1.0	
Pachyramphus polychopterus	1.8	1
Pachyramphus validus	3.5	1
Parula pitiayumi	1.9	14
Patagioenas cayenensis	4.3	
Patagioenas picazuro	11.9	7
Patagioenas plumbea	22.9	38
Patagioenas speciosa	6.0	
Penelope obscura	9.0	
Penelope superciliaris	6.2	5
Phaeomyias murina	3.8	
Phyllomyias fasciatus	2.7	43
Phylloscartes ventralis	2.4	38
Piculus aurelentus	29.7	10
Pipile jacutinga	85.0	
Pipraeidea melanonota	2.9	1
Piranga flava	8.2	2

Pitangus sulphuratus	4.0	61
Poospiza thoracica	1.6	
Procnias nudicollis	4.1	
Pteroglossus bailloni	9.0	
Pyroderus scutatus	3.5	
Pyrrhura frontalis	71.4	9
Ramphastos dicolorus	3.5	1
Ramphastos toco	12.0	3
Ramphastos vitellinus	7.3	5
Ramphocelus bresilius	3.7	
Ramphocelus carbo	6.2	14
Saltator fuliginosus	1.4	
Saltator maximus	2.8	13
Saltator similis	3.7	128
Saltatriculla atricollis	9.0	1
Schiffornis virescens	4.5	4
Schistochlamys melanops	1.5	4
Schistochlamys ruficapillus	2.7	17
Selenidera maculirostris	7.3	
Serpophaga subcristata	1.1	10
Sporophila caerulescens	2.8	23
Sporophila nigricollis	7.1	14
Stephanophorus diadematus	1.8	
Synallaxis ruficapilla	2.3	3
Syristes sibilator	10.0	
Tachyphonus coronatus	3.9	1
Tachyphonus cristatus	2.8	
Tachyphonus rufus	3.2	43
Tamnophilus caerulescens	2.0	3
Tamnophilus doliatus	1.0	
Tamnophilus punctatus	1.0	
Tangara cayana	3.6	157
Tangara cyanocephala	3.3	
Tangara cyanoventris	1.5	
Tangara desmaresti	3.4	2
Tangara mexicana	2.0	
Tangara peruviana	7.2	
Tangara preciosa	10.5	45
Tersina viridis	6.9	52
Thlypopsis sordida	1.0	1
Thraupis bonariensis	7.5	3
Thraupis cyanoptera	1.2	
Thraupis palmarum	2.3	23
Thraupis sayaca	3.0	490
Tityra cayana	2.8	2
Tolmomyas flaviventris	1.0	
Tolmomyias sulphurescens	1.2	1
Trichothraupis melanops	4.2	8
Trogon surrucura	2.0	2
Trogon viridis	1.8	
Turdus albicollis	3.1	82

Turdus amaurochalinus	5.9	83
Turdus flavipes	2.5	
Turdus leucomelas	4.8	370
Turdus rufiventris	5.9	196
Turdus subalaris	2.9	35
Tyrannus albogularis	5.0	1
Tyrannus melancholicus	3.4	33
Tyrannus savanna	4.1	64
Veniliornis passerinus	1.7	5
Vireo olivaceus	3.0	56
Volatinia jacarina	8.0	8
Zonotrichia capensis	4.9	27

SM5. Fruit consumed references

We searched the databases Google Scholar, Scopus, and Web of Science using the terms “bird”, “avian”, “frugivory”, “seed dispersal”, and their Portuguese and Spanish equivalents for studies that reported the number of fruits removed in each feeding visit made by birds to focal fruiting plants in the Neotropical region. In general, the authors reported the mean number of fruits removed in complete bird visits (i.e., the complete period from the arrival of a bird to a fruiting plant to its departure).

Allenspach, N., and M. M. Dias. 2012. Frugivory by birds on Miconia albicans (Melastomataceae), in a fragment of cerrado in São Carlos, southeastern Brazil. Brazilian Journal of Biology 72:407-413.

Argel de Oliveira, M. M. 1999. Frugivoria por aves em um fragmento de floresta de restinga no Estado do Espírito Santo, Brasil. PhD Thesis. UNICAMP, Campinas, Brazil.

Athiê, S and M. M. Dias. 2010. Acnistus arborescens (L.) Schltdl. (Solanaceae) como recurso alimentar para as aves em projetos de recuperação de áreas degragadas. Atualidades Ornitológicas 142: 22-24.

Castro, E.R. 2003. Variação espaço-temporal na fenologia e frugivoria do palmito juçara Euterpe edulis Martius (Arecaceae) em três tipos de Floresta Atlântica. Master Dissertation, UNESP, Rio Claro, Brazil.

Cazetta, E., P. Rubim, V. O. Lunardi, M. R. Francisco, and M. Galetti. 2002. Frugivoria e dispersão de sementes de Talauma ovata (Magnoliaceae) no sudeste brasileiro. Ararajuba 10:199-206.

Colussi J., and N. P. Prestes. 2011. Frugivoria realizada por aves em Myrciaria trunciflora (Mart) O. Berg. (Myrtaceae), Eugenia uniflora L. (Myrtaceae) e Ilex paraguariensis St. Hil. no norte do estado do Rio Grande do Sul. Revista Brasileira de Ornitologia 19:48-55.

Correia, J. M. S. 1997. Utilização de espécies frutíferas da mata Atlântica na alimentação da avifauna da Reserva Biológica de Poços das Antas, RJ. Master Dissertation, Universidade de Brasília, Brasília, Brazil.

Côrtes, M. C. 2003. Frugivoria e dispersão de sementes de Euterpe edulis (Arecaceae) em três tipos florestais no Parque Estadual da Ilha do Cardoso – SP. Master Dissertation, UNESP, Rio Claro, Brazil.

Côrtes, M. C., E. Cazetta, V. G. Staggemeier, and M. Galetti. 2009. Linking frugivory activity to early recruitment of a bird dispersed tree, Eugenia umbelliflora (Myrtacease) in the Atlantic rainforest. Austral Ecology 34:249-258.

de Jesus, S., and E. L. A. Monteiro-Filho. 2007. Frugivoria por aves em Schinus terebinthifolius (Anacardiaceae) e Myrsine coriaceae (Myrsinaceae). Revista Brasileira de Ornitologia 15:585-591.

Francisco, M. R., and M. Galetti. 2001. Frugivoria e dispersão de sementes de Rapanea lancifolia (Myrsinaceae) por aves numa área de cerrado do Estado de São Paulo, sudeste do Brasil. Ararajuba 9:13-19.

Francisco, M. R. and M. Galetti. 2002. Aves como potenciais dispersoras de sementes de Ocotea pulchella Mart. (Lauraceae) numa área de vegetação de cerrado do sudeste brasileiro. Revista Brasileira de Botânica 25: 11-17.

Francisco, M. R., V. O. Lunardi, and M. Galetti. 2007. Características dos propágulos, atributos das aves e a dispersão das sementes de Pera glabrata Schott (Euphorbiaceae) numa área degradada de cerrado. Brazilian Journal of Biology 67:631-637.

Gondim, M. J. C. 1995. Dispersão de sementes de Trichilia spp. (Meliaceae) por aves em uma mata mesófila semidecídua no município de Rio Claro, SP. Master Dissertation. Instituto de Biociências, UNESP, Rio Claro, Brazil.

Gondim, M. J. C. 2002. A exploração de frutos por aves frugívoras em uma área de cerradão no Estado de São Paulo. PhD Thesis. Instituto de Biociências, UNESP, Rio Claro, Brazil.

Gridi-Papp, C. O., M. Gridi-Papp, and W. R. Silva. 2004. Differential fruit consumption of two Melastomataceae by birds in Serra da Mantiqueira, southeastern Brazil. Ararajuba 12:7-13.

Guerra, T. J., and M. Â. Marini. 2002. Bird frugivory on Struthantus concinnus (Loranthaceae) in southeastern Brazil. Ararajuba 10:187-192.

Guerta, R. S., L. G. Lucon, J. C. Motta-Jr., L. A. S. Vasconcellos, and R. A. de Figueiredo. 2011. Bird frugivory and seed germination of Myrsine umbellata and Myrsine lancifolia (Myrsinaceae) seeds in a cerrado fragment in southeastern Brazil. Biota Neotropica 11:59-65.

Guimarães, M. A. 2003. Frugivoria por aves em Tapirira guianensis (Anacardiaceae) na zona urbana do município de Araruama, estado do Rio de Janeiro, sudeste brasileiro. Atualidades Ornitológicas 116: 12.

Krügel, M. M., M. I. Burger, and M. A. Alves. 2006. Frugivoria por aves em Nectandra megapotamica (Lauraceae) em uma área de Floresta Estacional Decidual do Rio Grande do Sul, Brasil. Iheringia, Ser. Zool. 96: 7-24.

Lamberti, N.F., R. Y. Hashimoto, and B. G. Silva. 2012. Frugivoria por aves em Eugenia uniflora L. (Myrtaceae) em ambientes antropizados na região de Sorocaba-SP. Revista do Instituto Florestal 24:225-241.

Laps, R. R. 1996. Frugivoria e dispersão de sementes de palmiteiro (Euterpe edulis, Martius, Arecaceae) na Mata Atlântica, sul do estado de São Paulo. Master Dissertation, UNICAMP, Campinas, Brazil.

Lopes, R. F. 2000. Frugivoria e dispersão de sementes através da avifauna, em quatro espécies de vegetais na região de Botucatu – SP. Master Dissertation, ESALQ/USP, Piracicaba, Brazil.

Maruyama, P. K., Mendes-Rodrigues, C., Alves-Silva, E., and Cunha, A. F. 2012. Parasites in the neighbourhood: Interactions of the mistletoe Phoradendron affine (Viscaceae) with its dispersers and hosts in urban areas of Brazil. Flora 207:768-773.

Melo, C. and P. E. Oliveira. 2009. Frugivory in Lacistema hasslerianum Chodat (Lacistemaceae), gallery forest understory treelet in central Brazil. Brazilian Journal of Biology 69: 201-207

Melo, C., E. C. Bento, and P. E. Oliveira. 2003. Frugivory and dispersal of Faramea cyanea (Rubiaceae) in cerrado woody plant formations. Brazilian Journal Biology 63:75-82.

Motta-Júnior., J. C. 1991. A exploração de frutos como alimento por aves de mata ciliar numa região do Distrito Federal. Master Dissertation. Instituto de Biociências, UNESP, Rio Claro, Brazil.

Motta-Júnior, J. C. and J. A. Lombardi. 1990. Aves como agentes dispersores da Copaíba (Copaifera langsdorffii, Caesalpiniaceae) em São Carlos, estado de São Paulo. Ararajuba 1:105-106.

Navarro, A. 2016. Atratividade de aves por embaúba (Cecropia pachystachya Trécul) em uma paisagem fragmentada e agrícola. Bachelor Dissertation, ESALQ/USP, Piracicaba, Brazil.

Oliveira, A. P., C. G. Machado and M. R. Sigrist. 2013a. Matayba guianensis (Sapindaceae): frugivoria por aves em remanescente de cerrado do Centro-Oeste brasileiro. Sitientibus (série Ciências Biológicas) 13: 13-20.

Oliveira, D. S. F., A. G. Franchin and O. Marçal Jr. 2013b. Disponibilidade de frutos de Michelia champaca L. (Magnoliaceae) e seu consumo por aves na área urbana de Uberlândia, MG. Biosci. J. 29: 2053-2065

Pascotto, M. C. 2006. Avifauna dispersora de sementes de Alchornea glandulosa (Euphorbiaceae) em uma área de mata ciliar no estado de São Paulo. Revista Brasileira de Ornitologia 14:291-296.

Pascotto, M. C. 2007. Rapanea ferruginea (Ruiz & Pav.) Mez. (Myrsinaceae) como importante fonte alimentar para as aves em uma mata de galeria no interior do Estado de São Paulo. Revista Brasileira de Zoologia 24:735-741.

Pascotto, M. C., H. T. Caten and J. P. F. De Oliveira. 2012. Birds as potential seed dispersers of Curatella americana L. (Dilleniaceae) in the Brazilian Cerrado. Ornitología Neotropical 23: 585-595.

Silva, W. R. 1988. Ornitocoria em Cereus peruvianus (Cactaceae) na Serra do Japi, Estado de São Paulo. Revista Brasileira de Zoologia 48: 381-389.

Zimmermann, C. E. 1996. Observações preliminares sobre a frugivoria por aves em Alchornea glandulosa (Endl. & Poepp.) (Euphorbiaceae) em vegetação secundária. Revista Brasileira de Zoologia