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RESEARCH ARTICLE

Positive forest cover effects on coffee yields are consistent across regions

Adrian González-Chaves[1] | Luísa G. Carvalheiro[2,3] | Lucas A. Garibaldi[4,5] | Jean Paul Metzger[1]

[1]Departamento de Ecologia, Instituto de Biociência, Universidade de São Paulo, São Paulo, Brazil

[2]Departamento de Ecologia, Universidade Federal de Goias (UFG), Goiânia, Brazil

[3]Faculdade de Ciencias, Centre for Ecology, Evolution and Environmental Changes (CE3C), Universidade de Lisboa, Lisboa, Portugal

[4]Universidad Nacional de Río Negro, Instituto de Investigaciones en Recursos Naturales, Agroecología y Desarrollo Rural, San Carlos de Bariloche, Argentina

[5]Consejo Nacional de Investigaciones Científicas y Técnicas, Instituto de Investigaciones en Recursos Naturales, Agroecología y Desarrollo Rural, San Carlos de Bariloche, Argentina

Correspondence
Adrian González-Chaves
Email: adgonzalez86@ib.usp.br

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Abstract

1. Enhancing biodiversity-based ecosystem services can generate win–win opportunities for conservation and agricultural production. Pollination and pest control are two essential agricultural services provided by mobile organisms, many depending on native vegetation networks beyond the farm scale. Many studies have evaluated the effects of landscape changes on such services at small scales. However, several landscape management policies (e.g. selection of conservation sites) and associated funding allocation occur at much larger spatial scales (e.g. state or regional level). Therefore, it is essential to understand whether the links between landscape, ecosystem services and crop yields are robust across broad and heterogeneous regional conditions.
2. Here, we used data from 610 Brazilian municipalities within the Atlantic Forest region (~50 Mha) and show that forest is a crucial factor affecting coffee yields, regardless of regional variations in soil, climate and management practices. We found forest cover surrounding coffee fields was better at predicting coffee yields than forest cover at the municipality level. Moreover, the positive effect of forest cover on coffee yields was stronger for *Coffea canephora*, the species with higher pollinator dependence, than for *Coffea arabica*. Overall, coffee yields were highest when they were near to forest fragments, mostly in landscapes with intermediate to high forest cover (>20%), above the biodiversity extinction threshold.
3. Coffee cover was the most relevant management practice associated with coffee yield prediction. An increase in crop area was associated with a higher yield, but mostly in high forest covers municipalities. Other localized management practices like irrigation, pesticide use, organic manure and honeybee density had little importance in predicting coffee yields than landscape structure parameters. Neither the climatic or topographic variables were as relevant as forest cover at predicting coffee yields.
4. *Synthesis and application*. Our work provides evidence that landscape relationships with ecosystem service provision are consistent across regions with different agricultural practices and environmental conditions. These results provide a way in which landscape management can articulate small landscape management with regional conservation goals. Policies directed towards increasing landscape

interspersion of coffee fields with forest remnants favour spillover process, and can thus benefit the provision of biodiversity-based ecosystem services, increasing agricultural productivity. Such interventions can generate win–win situations favouring biodiversity conservation and increased crop yields across large regions.

KEYWORDS

coffee production, ecosystem service supply and demand, forest cover, landscape configuration, multi-scale analysis, pest control, pollination service, Stingless bees

1 | INTRODUCTION

The increase in agricultural production, mainly through conventional intensification and continuous transformation of native vegetation into cropland while relying on the use of external inputs (fertilizers, pesticides, irrigation and tillage), continues to be the current major threat to biodiversity (Curtis et al., 2018; Hunter et al., 2017; Ramankutty et al., 2018; Tilman et al., 2011). The imbalance between achieving higher productivity and conserving biodiversity could be solved by enhancing local biodiversity contributions in agricultural landscapes (Garibaldi et al., 2019). In this sense, robust evidence shows that wild mobile organisms, which directly support crop production through pollination and pest control, depend on the extent of the native vegetation and its proximity to productive areas (Dainese et al., 2019). Unfortunately, along with biodiversity decline, evidence indicates that services are also being eroded globally (Brauman et al., 2020). Thus, it is crucial to align local and regional targets that contribute to increased crop yield through ecosystem service provision and biodiversity conservation (Isbell et al., 2017; Senapathi et al., 2015).

The capacity of a given patch of natural habitat to supply mobile organisms that provided services depends on the overall habitat amount at larger landscape scales (Batáry et al., 2011; Fahrig, 2013). Hence enhancing biodiversity in specific cropland depends on the remaining natural vegetation in the landscape that should be above the extinction threshold (Banks-Leite et al., 2014; Boesing et al., 2018). Simultaneously, the agricultural landscapes' heterogeneity will affect biodiversity and consequently service provision (Dainese et al., 2019; Sirami et al., 2019). For instance, increasing the amount of a specific crop cover will determine the ecosystem service demand while affecting organism mobility's permeability (Holzschuh et al., 2016; Rusch et al., 2016). Therefore, landscape features directly affect ecosystem service supply and demand and the flow between those areas (Metzger et al., 2020; Mitchell et al., 2015).

Improving our understanding on the effects of land-use changes on ecosystem service and crop yield, especially across larger spatial regions, it is essential to better inform policy and conservation practitioners (Isbell et al., 2017). For instance, researchers advocate for establishing ambitious goals, proposing to restore or conserve landscape or even the entire globe with more than 40% of natural habitat (Arroyo-Rodríguez et al., 2020; Watson & Venter, 2017). Nonetheless, Earth's biome has already been heavily transformed, and environmental policies commonly require no more than 5% of the agricultural landscape to be preserved for most countries, despite the evidence that a regional increase in native vegetation up to 30% could reduce biodiversity extinction risk by 50% (Garibaldi et al., 2020; Hannah et al., 2020). Such policies are primarily established for conservation proposes only, which might constrain farmers' acceptance. In Brazil, for example, there have been considerable efforts to soften those laws, further threatening biodiversity (Metzger et al., 2019). Hence, there is a need to frame such conservation policies together with societies' benefits drawn from them to engage synergies (Fischer et al., 2017).

Evidence showing that the positive landscape effects on biodiversity and ecosystem service cascade down to crop yields has recently started to emerge (Dainese et al., 2019). Nonetheless, most come from studies executed at small scales, generally smaller than 2 km radius circular landscapes (Chaplin-Kramer et al., 2011; Motzke et al., 2016). The few studies that evaluate pest control and pollination at larger regional scales estimate the proportion of regional production that can be attributed to these regulating services, by assuming that mobile organisms are either fully present or absent in crop fields across large regions (Breeze et al., 2016; Losey & Vaughn, 2006; Naranjo et al., 2015). Hence, there is an urge to assess whether we can predict regional or national yields using the habitat amount around crop fields. Moreover, such assessment across large regions would allow understanding whether landscape context can replace, complement or interact with localized agricultural management practices to predict regional yields, as ecosystem effects on yield depend on management practices (Gagic et al., 2017; Liere et al., 2017).

Brazilian coffee production more than doubled between 1996 and 2010 through conventional intensification, with only a 12% increase in coffee area (Jha et al., 2014), which indicates that land productivity per unit area increased. Yet, since coffee production benefits from pest control and pollination services (Chain-Guadarrama et al., 2019), it is likely that land productivity is below its potential. Brazil is the primary producer of the two most traded coffee species—*Coffea arabica* and *Coffea canephora*. Consequently, the reduction or suppression of native vegetation should result in lower crop yield (Karp et al., 2013), especially for the high pollinator-dependent coffee species (*C. canephora*) when compared to *C. arabica*, which modesty benefits from pollination services (Klein et al., 2003). Here we use land cover maps to test if 20% of the world coffee production associates with forest cover around the coffee fields. We intend to assess the potential of using landscape spatial management in agriculture by testing whether the landscape context surrounding coffee fields is more relevant than management practices across large variety of environmental conditions.

Using open data sources (from government and NGOs) from Brazil, we can assess which scale does forest cover most contributes to increasing municipality productivity across the whole Atlantic Forest Biome (Objective 1). We incorporated biological information of coffee species dependency on pollination to evaluate if forest contribution varies accordingly to pollinators demand (Objective 2). Moreover, by comparing management practices, climatic and topographic information, we were able to test the relevancy of landscape structure parameters at predicting coffee yields (Objective 3). We expect that small-scale forest cover (at the surrounding coffee fields), which are known to affect biodiversity-based ecosystem services like pest control and pollination, are best at predicting coffee yield than the amount of forest cover in the municipality. We expect that municipalities with higher pollination dependency would be more affected by forest cover changes, as natives bees (the main coffee pollinator) are known to respond to forest cover changes. Finally, we expect that landscape parameters (forest and coffee cover) are equally relevant to climatic variables and management practices crucial for achieving high productivity, as the spatial relationship between areas that supply and demand service determines biodiversity contribution to productivity.

2 | MATERIALS AND METHODS

2.1 | Study area and focal crop species

Coffee production is distributed widely across the tropics, and within Brazil, it ranges from subtropics nearly to the Equator, presenting broad environmental plasticity. Nonetheless, each of the two coffee species produced occupies a different niche. Arabica coffee (*C. arabica*) is mainly produced in the south-east Brazilian region, where mean annual temperatures range from 18 to 23°C. In contrast, Robusta coffee (*C. canephora*) is mainly cultivated in the lowlands of the states of Espírito Santo and Rondônia, where the annual mean temperature is higher than that in the south-eastern Brazil (22 to 26°C, Bunn et al., 2015).

For this study, we gathered information from 1.3 Mha destined for coffee production from the 610 municipalities that planted more than 50 ha of coffee each year between 2006 and 2012 (Figure 1). In the Atlantic biome, the production is concentrated in five states, Bahia ($n = 37$), Espírito Santo ($n = 64$), Minas Gerais ($n = 264$), Paraná ($n = 146$) and Sao Paulo state ($n = 99$). Using data from the Brazilian Institute of Geography and Statistics (IBGE, https://sidra.ibge.gov.br/pesquisa/pam/tabelas), we calculated coffee yield (productivity) for each year per municipality by dividing the total production (tons) by the total coffee area (ha) planted per municipality per year. Mean coffee yields were calculated from 3 consecutive years for each municipality. The years considered for each municipality depended on data availability of the coffee fields' maps, which were different for each state (see Table S1). The 3-year window selected for yield data corresponded to the year that coffee fields were mapped plus the year before and after. Little spatial variation within the 3-year window is expected, as coffee is a perennial crop that might be thinned every 7–8 years. We transformed the yield (kg/ha) values to the number of coffee bags (of 60 kg) per hectare, a frequently used unit among coffee farmers and trade agencies.

2.2 | Pollination service demand

To evaluate if the effect of forest cover on coffee yields varies with the animal pollination demand, we calculated the pollinator demand per municipality according to the proportion of the area planted with each coffee species. Using the IBGE dataset, we calculated the pollinator demand (PD) of the coffee produced in each municipality using the following equation:

$$\mathrm{PD} = \left(\frac{\mathrm{Area}_{\mathrm{arabica}}}{\mathrm{Area}_{\mathrm{coffee}}} \times 0.3\right) + \left(\frac{\mathrm{Area}_{\mathrm{canephora}}}{\mathrm{Area}_{\mathrm{coffee}}} \times 1\right),$$

$\mathrm{Area}_{\mathrm{arabica}}$ corresponds to the municipality area planted with *C. arabica*, $\mathrm{Area}_{\mathrm{canephora}}$, the area planted with *C. canephora*, and $\mathrm{Area}_{\mathrm{coffee}}$, the total area planted with coffee in the municipality. The coefficients 0.3 and 1 correspond to the level of pollinators' contributions associated with each crop species. *C. canephora* dependence ratio is equal to 1, while the modest pollinator-dependent *C. arabica* has a ratio equal to 0.3 (Klein et al., 2003). The municipality *pollinator demand* varies between 0.3 and 1.0 according to the area destined to each coffee species; a municipality with half of the planted area of each coffee species had values equal to 0.65. The majority of the municipalities (91%) planted one species only (44 municipalities with *C. canephora* and 509 with *C. arabica*).

2.3 | Landscape structure parameters

To determine forest cover surrounding coffee plantations, we used coffee maps from the National Company of supply (CONAB, http://www.conab.gov.br/), which compiled maps from the five leading coffee-producing states within the Atlantic Forest. Additionally, we used annual forest remnant maps from MapBiomas (Project of annual mapping of land use and land cover of Brazil, http://mapbiomas.org/), both with a resolution of 30 × 30 m. The year of forest cover maps was selected according to the coffee field maps, matching the coffee yield data years. For each coffee pixel (30 × 30 m), we calculated forest and coffee cover in circular areas at different scales (2 km, 1 km and 500 m radius), as the scales of effects have been shown to vary according to the mobile organism functional characteristics (Chaplin-Kramer et al., 2011; Greenleaf et al., 2007). We calculated the mean values of forest and coffee cover surrounding coffee fields per municipality for each scale.

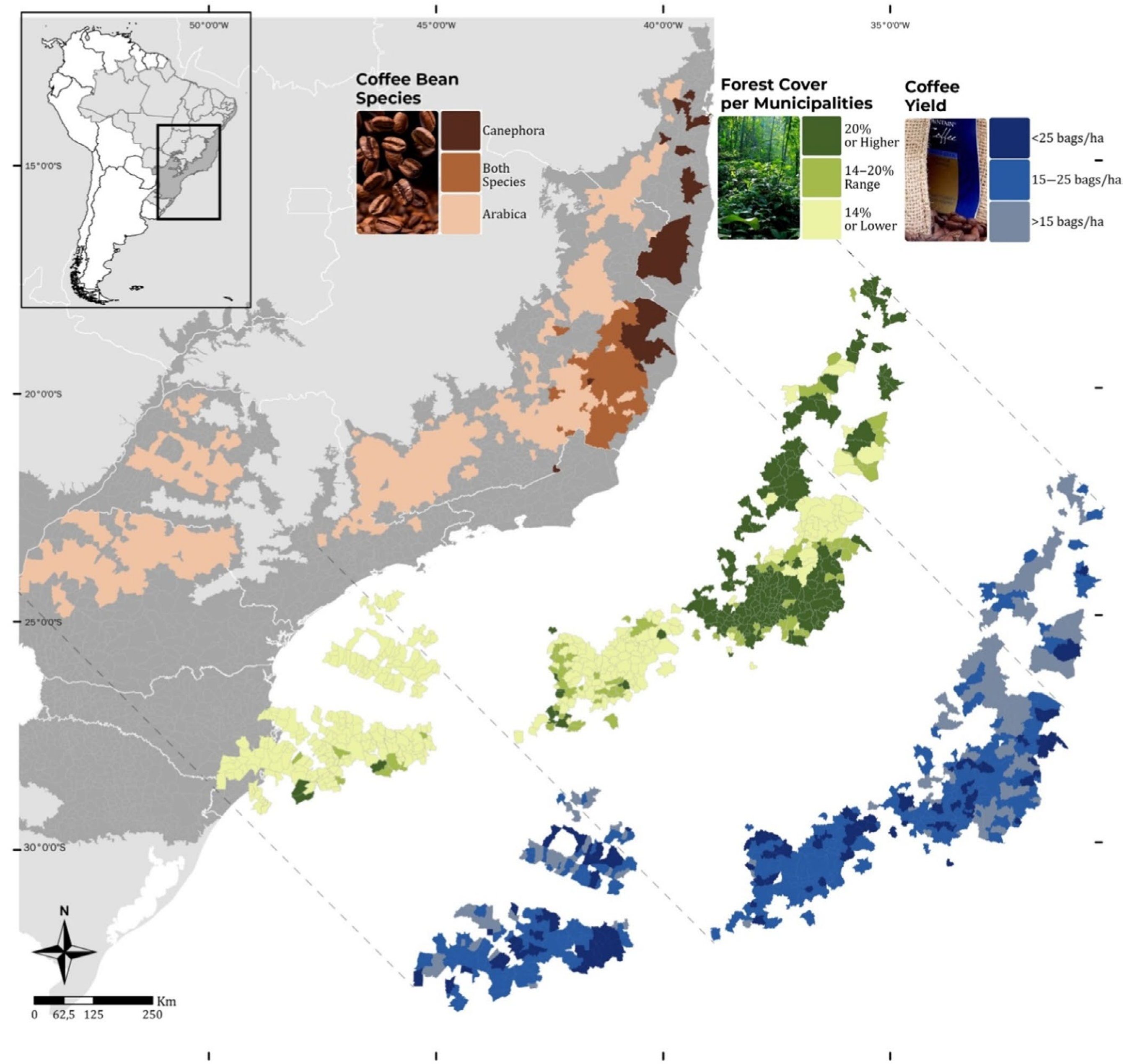

FIGURE 1 Study region within the Atlantic Forest, the different shades of brown indicate the species planted in the municipality. Average forest cover surrounding coffee fields within 2 km radius per municipality are in green and subdivided into three categories: (1) In dark green municipalities with more than 20% surrounding coffee fields within 2 km radius, (2) in green municipalities with forest cover between 14% and 20% and (3) in light green municipalities with <14%. Those forest cover categories are associated with restoration success probability (see Crouzeilles & Curran, 2016). Blue colour indicates the productivity levels of each municipality, also subdivided into three levels

Moreover, we calculated the amount of forest and coffee cover at the municipality level to compare with the means obtained with the circular buffers (around focal coffee pixels). Forest cover (at all scales) was calculated for each of the 3 consecutive years, and mean values were calculated accordingly to the year of coffee maps. We obtained the mean distance of coffee fields to the nearest forest fragment, by measuring the minimum distance pixel of coffee and forest and then obtaining the coffee fields' mean distance per municipality. We calculated the number and density of forest fragments and forest edge density per municipality, with the forest remnant maps. Similarly, we measured coffee cover (at different scales) and the number and density of coffee patches in the municipality.

2.4 | Environmental and farm management factors

Temperature, humidity and soil condition are known to affect coffee yields (DaMatta, 2004). Moreover, management practices and socio-economic characteristics also influence yield outcomes (Hipólito et al., 2016). Therefore to assess the relative impact that forest cover can have on coffee yield, we gathered 19 bioclimatic variables (source: www.chelsa-climate.org) from the same year of coffee production considered in the analyses, 12 soil properties variables (physical and chemical) based on 2017 model (www.soilgrids.org) and nine farm management variables. Environmental variables were extracted using the coffee fields' shapefiles, and we calculated mean values for each municipality. The management factors resulted from mean values between the data available from the closest annual data obtainable from national survey carried twice by IBGE (2006 and 2017) which contains municipalities' data (see Appendix S1).

2.5 | Statistical analysis

First, we tested whether the spatial structure contributed significantly to the variation in coffee yield (log-transformed) by incorporating the centroid's coordinate of every municipality in the models. We used linear mixed models (LMM) to compare the full model with and without the residual spatial correlation structure, linear and different equations function were considered as suggested in the statistic literature (Crawley, 2007; Zuur et al., 2009; Figure S6; Table S5). The exponential spatial correlation was considered in all the following model comparisons. Two model comparisons were made, one to select the scale for forest and coffee cover that best explained coffee yields (Table S2), and a second comparison to select the bests fixed structure among the landscape, management and climatic variables. We included municipalities' mesoregions nested within the state as a random structure in all models, allowing the intercept to vary according to the geopolitical mesoregions within the state that each municipality belongs to. This nested structure is essential because there is an inherent variation in the socio-economic and agronomic practices that affect coffee productivity across the main producing regions within each state of Brazil (Bliska et al., 2009).

We selected which landscape variable of forest and coffee cover at 500 m, 2 km radius, or at the municipality level best predicted coffee yields by creating 15 models, in which only additive effects were considered between coffee and forest at each scale (Table S2). Forest and coffee covers were not correlated, but forest cover at different scales were correlated (as well as coffee covers), reason why we avoid including the same variable at different scales in the same model. We compared all combinations using a multi-model inference approach based on information theory using Akaike information criterion (AIC; Burnham & Anderson, 2002). Forest cover at smaller scales were consistently better, so we maintained the 2 km scale for the rest of the analysis (Table S2), as local scales are known to affect biodiversity and ecosystem services. We considered the 2 km scale for coffee and forest to create the full models to test our hypothesis.

To test whether (a) forest cover predicts coffee productivity (yield) better than management practices or climatic variables, and (b) whether forest contribution to coffee productivity varies accordingly to the pollination dependency of the crops, we created a full model with 16 fixed-effect variables, considering only two-way interactions between either forest or PD and each one of the other fixed-effect variables (Table 1; Figure 1c). The 16 fixed-effect variables considered in the full model are a subset of all 60 variables

TABLE 1 The predictive variables included in the full model, with a short description, average and range values. Data were collected from different sources, we calculated the variables using data from: +1 MapBiomas and; +2 CONAB; +3 variables came from IBGE database; and +4 and +5 from WorldClim and soil Grid respectively

Factor	Variable	Description	Average	Range
Landscape	Forest Cover*	Mean value of the forest cover at 2 km surrounding each coffee pixel (%)+1	16	0.6–81
	Forest Patch Density	Density of forest patches divided by the total area of the municipality (n° patches/hectares × 10^6)+1	2.2	0.25–4.9
	Coffee Cover	Mean value of coffee cover at 2 km surrounding each coffee pixel (%) per municipality+2	9	0.02–49.3
	Land-use diversity	Shannon index of agricultural land uses considering the area of each crop+3	1.1	0.08–2.2
	Mean coffee field size	Coffee area divided by the number of coffee farms (ha)+3	16	0.7–268
Infrastructure	GDP	Gross domestic product (R$ × 1,000,000)+3	355	14.8–36,688
	Honey production	Total honey production in kilograms+3	3,832	0–108,193
Management	Family agriculture	Family coffee farms (%) of the total of coffee farms+3	74	0–100
	Irrigation	Coffee farms that use irrigation (%) of the total of coffee farms+3	6.6	0–100
	Organic fertilizer	Coffee farms that use organic manure (%) of the total of coffee farms+3	8.3	0–66.7
	Use of Agrochemicals	Coffee farms that use agrochemicals (%) of the total of coffee farms+3	36	0–100
Climatic	Precipitation	Mean annual precipitation (mm)+4	1,339	748–1,823
	Precipitation of the driest month	Precipitation of the driest month (mm)+4	34	6.3–117
	Wind	Wind speed (m/s)+4	1.9	1–2.6
Soil	Coarse fraction	Soil volumetric coarse fraction (%)+5	1.1	0–10.4

gathered, selected after checking for correlation to avoid multicollinearity, by excluding variables with Pearson correlation coefficient higher than 0.4 (Figure S1, see Appendix S1 for more information on the data gathered).

We compared all possible combinations derived from the full model, including a model without fixed effects (null model), using a multi-model inference approach based on information theory using AIC (Burnham & Anderson, 2002). For defining the scale, we also used LMM with Gaussian error distribution to predict the variability of coffee yield (60 bags per hectare; log-transformed). The best models (all with $\Delta AIC < 2$) were selected from comparing all the possible combinations of the full model (Figure 2c) using the 'dredge' function of the MuMIn package in R (Barton, 2015). For the best-fitting models (i.e. lowest AIC), we tested the Gaussian and homoscedasticity assumptions for the standardized residuals. To calculate each variable's importance at predicting coffee productivity, we used the sum model weights of all models, including each explanatory variable (Barton, 2015). For example, variables presented in all best models have relative importance close to 100%. We assess the strength of effect among the best-fitting model's selected variables by comparing the standardized estimate.

3 | RESULTS

On average, the Atlantic Forest biome produced 28.5 million coffee bags (60 kg bags) per year in 1.3 Mha, representing ~60% of all coffee produced in Brazil (Figure 1; Figure S5). For one third of

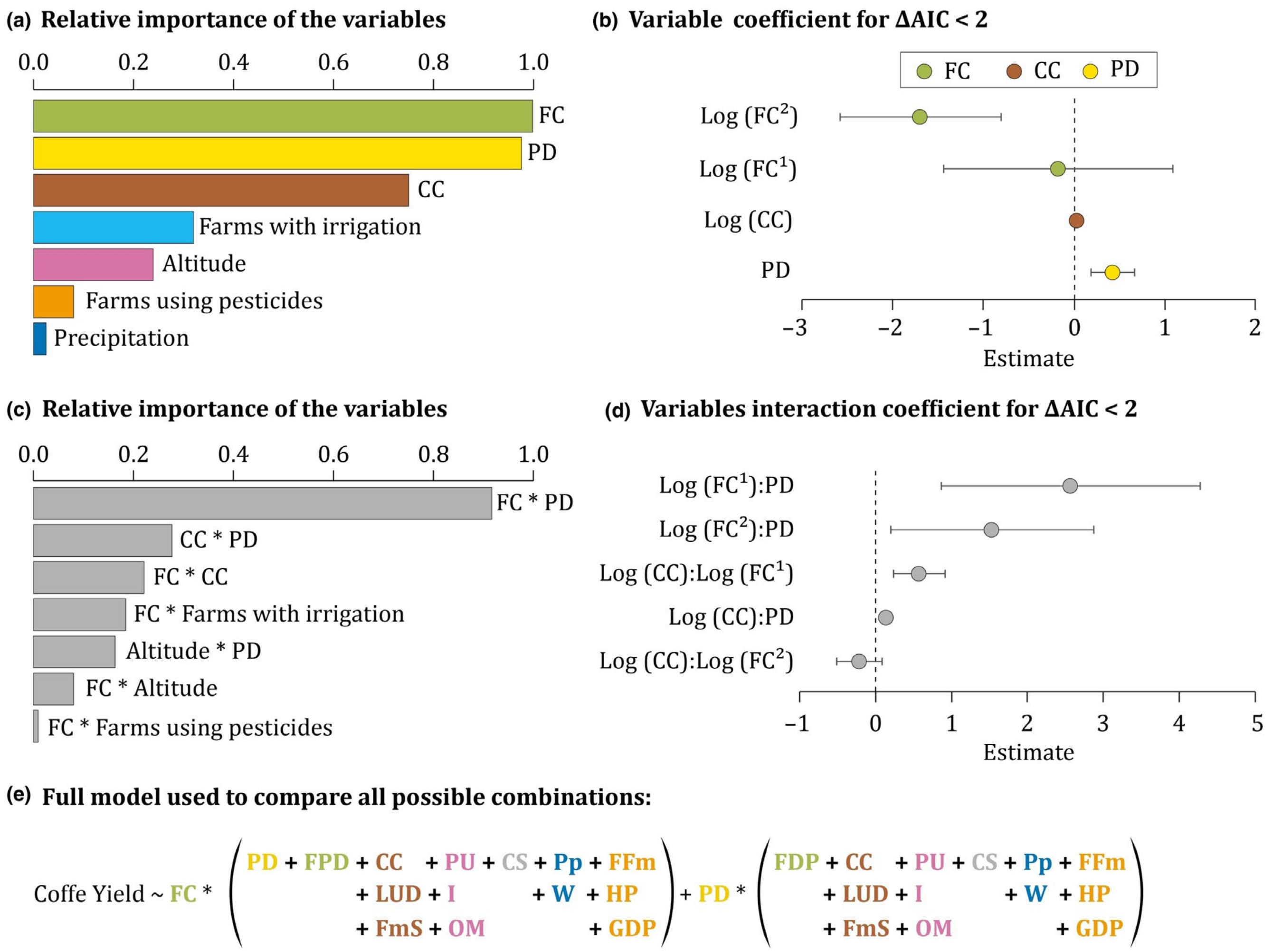

FIGURE 2 (a) Relative importance of the single variables based on the AIC weight considering all the possible fixed-effects combinations resulting from the full model to predict coffee yield per municipality. (b) Variables coefficient estimated and their standard error from all the models with ΔAIC lower than 2. (c) Relative importance of the interactions between the variables considered. (d) The coefficient estimated for each of the two-way interaction of the models with ΔAIC lower than 2. (e) The full model for which we tested all possible combinations. The variables are listed in Table 1, and are abbreviated as follows: FC = forest cover at 2 km scale; PD = pollinator dependency; CC = coffee cover at 2 km scale; LUD = land-use diversity; FmS = mean farm size; PU = pesticide use; I = irrigation; OM = organic manure; CS = Soil Coarse Fraction(%); Pp = mean annual precipitation; W = mean wind speed; FFm = family farms; HP = honey production; GDP = gross domestic product. See supplementary material (Table S4) for the first 20 model rank according to AIC, only the first four models presented ΔAIC lower than 2 the coffee municipalities, coffee plantations represented more than 10% of the land, with coffee cover extending up to 21,600 ha in total. On average, forest cover surrounding coffee fields (within 2 km circular landscapes) ranged from 0.6% to 81% (Table 1). The average forest cover for municipalities that produce either *C. arabica* or *C. canephora* was 14% and 30% respectively. Nonetheless, most of the coffee fields of the species that rely entirely on pollinators (*C. canephora*) have <20% of the forest in their surroundings. Most coffee production occurs in family farms (74% of the municipalities' farms), with the mean coffee fields size close to 16 ha.

The best-fitting models explained 81% of the variation in coffee yields, with forest effects at smaller scales (average cover at 2 km or 500 m radius around the coffee fields) predicting better than total cover at the municipality level (Table S2). Forest cover at smaller scales (from here forth forest cover) was the most important variable predicting coffee yields, with an overall positive effect (Figure 2). Moreover, forest cover effects were higher in the municipalities that planted more *C. canephora*, which is fully dependent on pollinators, but for *C. arabica*, yields tend to stabilize above ~16% of forest cover (Figure 3). Increasing coffee cover had a positive effect on yields, but only for *C. canephora* and when forest cover was intermediate or high (>20%; Figure 4). None of the management practices or the climatic variables were among the best-fitting models (Figure 2; Figure S4).

The landscapes that benefited most from the presence of forest cover were those with a more interspersed configuration between forest fragments and coffee fields (Figure S1a; Figure S1b). The forest and coffee cover increments in the municipalities are related to higher fragmentation and closer proximity between forest patches and coffee fields, as forest fragmentation was highest at

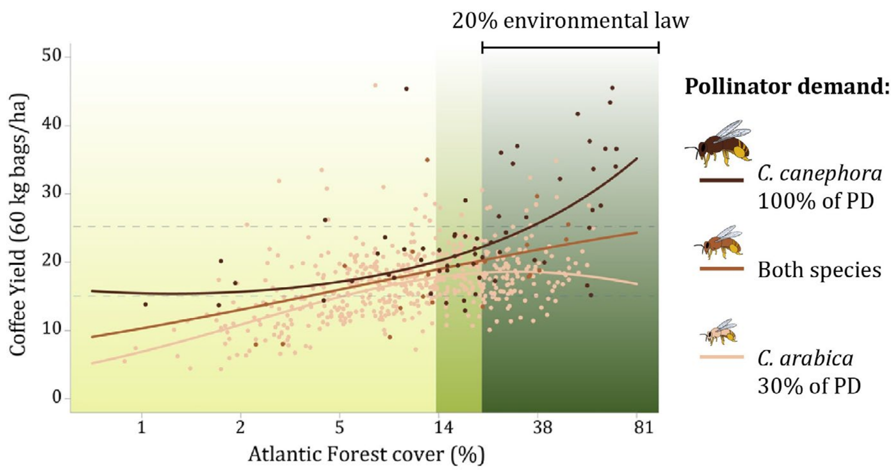

FIGURE 3 Relation between coffee yields (bags/ha) and forest cover (2 km radius) across the Brazilian Atlantic Forest. Light brown dots represent municipalities that produce *Coffea arabica* (30% of pollinator demand), and dark brown dots correspond to municipalities that produce *Coffea canephora* (100% of pollinator demand), brown dots represent municipalities that produce both coffee species. The symbol of the bees' size represents the percentage of bee contribution to coffee productivity for each species. The continuous lines represent the predicted relationship according to the selected model. Dark green shade represents the 20% threshold that environmental law in Brazil requires farmers to preserve within their farm, lighter green shade is associated with the categories from Figure 1

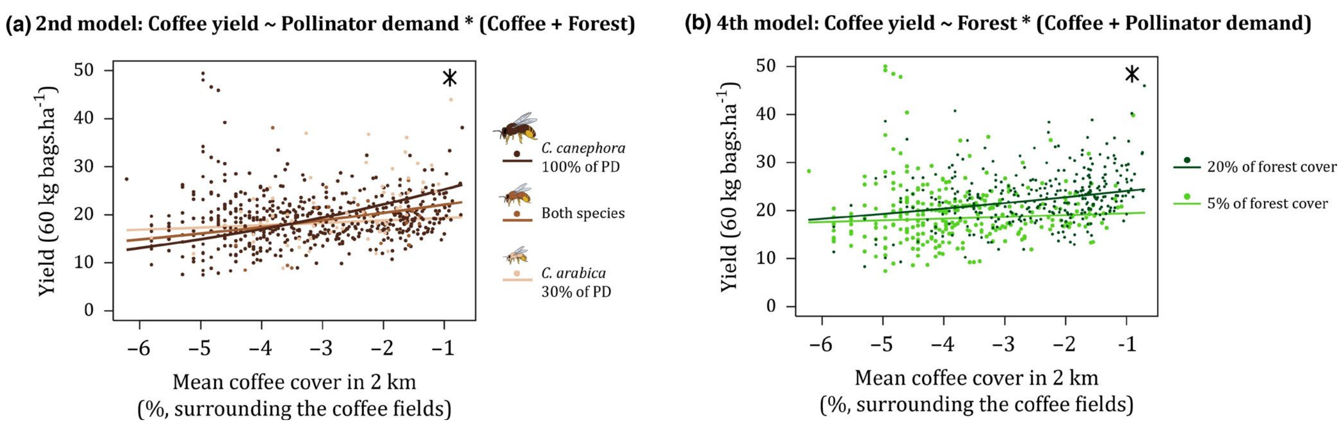

FIGURE 4 The relation between coffee cover, and coffee yields depending on: (a) the pollinator dependency of the coffee planted in the municipality (brown = fully *dependent*, red = intermediate and yellow = modest benefited); and (b) depending on the amount of forest cover in the landscape (low forest cover = light green – 5% and intermediate forest cover = dark green – 20%), model predicted was plotted considering the effect on the fully dependent coffee species. Each graph is the result of the model selected in which coffee effect interacts with another variable (Table S4)

intermediate forest cover (20%–40%; Figure S2). The coffee field's spatial arrangement was more fragmented as coffee cover increased (up to 50%; Figure S3). In such landscapes dominated by coffee fields and forest, where coffee productivity was higher, coffee was closer than 200 m from any forest fragment (Figure S3).

4 | DISCUSSION

Conservation and agriculture policy decisions occur at large scales (i.e. municipality or state levels), where governments are interested in stimulating and implementing practices that enhance the gross internal product while complying with environmental legislation (Metzger et al., 2019). To date, it was unclear whether the benefits previously detected at smaller landscape scales would also be evident at larger scales since regional differences in climate, soil type or even agricultural practices could alter the relationship obtained at the landscape scale. Here we detected that the amount of forest in the surrounding coffee fields was a major predictor of coffee productivity throughout the whole Atlantic Forest region, representing 20% of the world's coffee production. Forest cover was a more relevant predictor than management practices (i.e. agrochemicals, irrigation) and environmental conditions (i.e. rain, altitude), which affect coffee production. Our results suggest that the benefits crop production draws from natural vegetation are mediated by changes in ecosystem service provision (Martin et al., 2019; Sirami et al., 2019) and thus indirectly by biodiversity, as yields are higher in landscapes known to enhance functional and taxonomic biodiversity (Boesing et al., 2018). Especially pollination service seems to be an essential ecosystem service enhancing productivity. Increments in forest cover had more substantial productivity effects on the coffee species with the highest PD (*C. canephora*).

4.1 | Ecosystem services contribute to regional coffee yields

Each coffee species' different responses to the amount of forest cover were under our expectations related to different levels of pollinator dependence (*C. canephora* is highly dependent; Klein et al., 2003). Forest cover contributes to higher coffee fruit set by enhancing bee visitations (González-Chaves et al., 2020; Hipólito et al., 2018; Saturni et al., 2016), and we have found that municipalities with coffee fields surrounded by 20% of forest or more were more productive, especially for the coffee species which entirely rely on animal pollination. Together our findings reinforce that loss of biodiversity results in lower coffee yields, as landscapes with <20% of forest cover tend to present an abrupt loss of species richness in coffee landscapes (Banks-Leite et al., 2014; Boesing et al., 2018). Although we did not assess direct evidence of pollination services, literature shows that pollination dependency is a crucial feature to predict pollen limitation related to yield stability at a national level across the world (Deguines et al., 2014; Garibaldi et al., 2011).

Alternatively, the effect of pollination dependency in our model could be due to differences in each species' productivity not necessarily associated with pollination service. For instance, *C. canephora* is more resistant to disease, higher temperatures and water scarcity than *C. arabica* (DaMatta, 2004). Although we found that each coffee species responded differently to other variables (coffee cover, irrigation, altitude and pesticide use; Figure S4), none of the variables were more robust than forest cover. Hence, our results further reinforce that the difference between coffee species is not related to pest resistance or climatic variables but instead due to pollination service. Nonetheless, our results do not rule out that forest cover contributes to coffee production through other biodiversity-mediated ecosystem services. For instance, local landscapes with more than 20% of forest cover are known to favour spillover of birds, bats, and invertebrates that contribute with reducing pest incidence (e.g. coffee berry borer and leaf miners) and thus help increasing coffee yields (Aristizábal & Metzger, 2019; Boesing et al., 2018; Librán-Embid et al., 2017). Moreover, forests are known to contribute to water availability, probably reducing landscape temperature and enhancing evapotranspiration and moisture, therefore, the need for irrigation (Ellison et al., 2017; Mendes & Prevedello, 2020).

4.2 | Landscape features that favour pollinators's and pest enemy's spillover

Landscape simplification negatively affects biodiversity and ecosystem service provision (Dainese et al., 2019; Sirami et al., 2019). On the other hand, landscapes with more interspersed configuration between coffee fields and forest fragments were proven, at a smaller scales, to have higher bee diversity and crop pest control, which contribute to coffee yields (Aristizábal & Metzger, 2019; Hipólito et al., 2018; Librán-Embid et al., 2017; Medeiros et al., 2019; Saturni et al., 2016). Our work shows that such relationships can be upscale to the municipality level and across large regions, as it seems that the amount of forest in the municipality reflects the amount of forest surrounding the coffee fields. Moreover, we found that in the Atlantic Forest, coffee plantations are located on average at <200 m from a forest patch in landscapes with more than 20% of forest, distance above which pollination is highly restricted (González-Chaves et al., 2020). Furthermore, distances >1 km are reported to reduce biodiversity by half (Ricketts et al., 2008). Together, all this evidence reinforces that coffee landscape arrangement in relationship to forest patches can enhance biodiversity-based ecosystem services and that the negative effects of landscape simplification occurs across large regional areas (Dainese et al., 2019; Martin et al., 2019; Sirami et al., 2019).

4.3 | Implications for local and regional policies

Increasing tropical forest cover is a goal for the 2020–2030 decade, but it might still be unappealing for farmers (Brancalion et al., 2019;

Burton et al., 2008). Here we present strong evidence that managing cropland configuration within landscapes with intermediate habitat can enhance farmers' revenue and national income, specifically for coffee fields located nearby forest remnants. By doing a cross-regional study, we were able to compare the effects of landscape variables, agricultural practices and environmental variables like soil and climatic factors to directly estimate the relative importance of landscape parameters on crop yields, which generally is done through controlled experiments (Liere et al., 2017) or by inferring effects on yields (Chaplin-Kramer et al., 2011; Letourneau & Bothwell, 2008). Hence, we suggest tying together restoration/conservation goals with regional agricultural productivity by integrating governmental yield and management data with forest remnants' spatial information at different scales (from farm to municipalities), following recommendations that landscape should be managed at multiple spatial scales (Ekroos et al., 2016). After all, we reinforce the positive economic revenue for farmers that would result from landscape restoration initiatives (Morandin et al., 2016), which depend on incorporating natives plants (Albrecht et al., 2020; Carvalheiro et al., 2012). Municipality forest cover and coffee cover in the surrounding coffee field should guide restoration efforts within the Atlantic Forest by providing landscape strategies for coffee producers, which can potentiate their productivity by enhancing biodiversity-based ecosystem services.

Our results suggest that maintaining at least 20% of forest cover at the municipality level, preferentially with an interspersed configuration of forest fragments with coffee fields, could increase national income associated with coffee production. Currently, less than a third of municipalities ($n = 170$) are above the 20% threshold. Hence, our model predicts that restoration of up to 20%, targeted at maintaining proximity between forest fragments and coffee fields, would result in an annual increase of 50 thousand tons of coffee (842 thousand bags), which could be equivalent to 84 million dollars. Nonetheless, it is noteworthy that 39% of the coffee produced in the Atlantic Forest is undoubtedly benefiting from ecosystem service, as the few municipalities with forest cover above the 20% threshold concentrate the majority of the coffee production (Figure S5a). Moreover, municipalities that produce *C. canephora* have a higher potential to benefit from forest restoration, as the majority (79%) of the fields from this highly pollinator-dependent coffee species has low forest cover in their surroundings (Figure 1; Figure S5).

Currently, Brazilian environmental law requires medium and large farms to set aside 20% of their farms for conservation as native vegetation and restores the land if the necessary area was deforested in the past. Alternatively, the equivalent area can be compensated elsewhere (e.g. buying from landowners with forest surplus). Consequently, those farmers who chose to compensate elsewhere are least prone to benefit from ecosystem service. The same might occur with small farmers without forest, who are not required to set aside land for conservation, at least when they do not have riparian buffer zones or mountain tops. These law features do not embrace coffee farmers to benefit from conservation and ecosystem service, hence missing the opportunity to achieve higher productivity, especially for small farmers for whom pollination has the most significant impact (Brancalion et al., 2019; Garibaldi et al., 2016; Metzger et al., 2019).

4.4 | Final remarks

We present evidence that it is possible to coordinate local landscape efforts with regional planning, for instance, by identifying municipalities in which restoration efforts could enhance productivity. Therefore, cross-scale management of the restored areas and coffee fields' spatial arrangement can favour local landowners to comply with the law while benefitting through increments in crop productivity. Furthermore, we present evidence that by monitoring forest cover over large regions, we can also predict ecosystem service provision, as local landscape effects of native vegetation on service provision are consistent across larger regions, regardless of environmental and social variations. Therefore, managing landscape for conservation purposes across biomes can be coordinated with agricultural goals, facilitating the generation of win–win scenarios for economic development and species conservation.

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CONFLICT OF INTEREST

We declare there are no conflicts of interest.

AUTHORS' CONTRIBUTIONS

A.G.-C., L.G.C., L.A.G. and J.P.M. conceived the project and wrote the manuscript; A.G.-C. and J.P.M. obtained funding; A.G.-C. collected the data; A.G.-C. and L.A.G. analysed the data; A.G.-C. wrote the first draft of the manuscript.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.612jm644g (González-Chaves et al., 2021).

ORCID

Adrian González-Chaves https://orcid.org/0000-0002-5233-8957
Luísa G. Carvalheiro https://orcid.org/0000-0001-7655-979X
Lucas A. Garibaldi https://orcid.org/0000-0003-0725-4049
Jean Paul Metzger https://orcid.org/0000-0002-0087-5240

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SUPPORTING INFORMATION

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