When does agriculture enter into conflict with wildlife? A global assessment of parrot–agriculture conflicts and their conservation effects

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Abstract

Aim: No human activity has changed natural habitat availability and ecosystem functioning more than agriculture. As a consequence, species may be forced to use croplands as foraging habitat, resulting in potential conflicts with farmers. To assess the causes and consequences of wildlife–agriculture interactions, we investigated the underlying associations among species traits, climate and landscapes factors that determine parrot species to use croplands, and related them to their conservation status.

Location: Global.

Methods: We used parrots as a model due to their global distribution, high behavioural plasticity, high proportion of species using croplands (43%) and threatened species (26%). Within the distribution range of the 398 extant parrot species, we calculated annual averages and seasonality of ecosystem productivity, climate conditions and land-use patterns from satellite data. We then categorized species conservation status using information provided by IUCN.

Results: We found that habitat degradation, where biodiversity is low and primary productivity is low and intermittent, together with the plasticity of species to use different habitats, is key interrelated conditions that increase the likelihood of species to use croplands worldwide. The persecution of parrots as crop pests varied among regions, being higher for large-bodied species, those with small distributions, and in highly human-impacted areas. Moreover, persecution is contributing to the global population decline and extinction risk of parrots, especially in those species with small distribution ranges.

Main conclusions: Parrot–agriculture conflicts may affect both the conservation of parrot species and their key ecological functions. Our results highlight the importance of using multi-specific and multi-source information to understand and predict where and why human–wildlife conflicts may arise, as their main drivers interact and are heterogeneous at large spatial scales. Further studies should evaluate the actual extent and economic impact of crop losses caused by wild species to help solve agriculture–wildlife conflicts.
1 | INTRODUCTION

Much of the Earth's terrestrial surface has undergone agricultural expansion, increase in infrastructure and development of urban areas in the last decades (Tilman, 1999; Venter et al., 2016; Zabel et al., 2019). But no human activity has changed the terrestrial surface more than agriculture (Ellis & Ramankutty, 2008). Agro-pastoral habitats constitute the most widespread anthropogenic biome, covering approximately 38% of Earth's ice-free land and accounting for more than 10% of the annual terrestrial net primary production (Monfreda et al., 2008). Consequently, habitat loss and changes in ecosystem functioning caused by agriculture expansion are the greatest global threats to biodiversity (Wright et al., 2012), especially in tropical regions (Phalan et al., 2013). Since agriculture also alters the temporal and spatial patterns of primary productivity, modifies the land-surface hydrology, and reshapes the biogeochemical cycles of carbon, nitrogen and phosphorous (Foley, 2005), agricultural expansion and intensification can disrupt evolutionary connections between wild animals and natural ecosystem functions. Although our understanding about the human impacts on the biosphere has increased, we still have an important lack of knowledge on how species traits and environmental conditions determine the adaptability of wild animals to anthropogenic biomes and how these factors determine the conservation status of species at a global scale.

As a consequence of the massive human pressure on ecosystems, species are disappearing at increasing rates (De Vos et al., 2015) and their likelihood of becoming extinct in the future is also rising (Di Marco et al., 2018). However, some species are still able to exploit human-dominated landscapes (e.g. degraded forests, croplands, urban areas) (BirdLife International, 2019). These novel habitats, in particular croplands, can deliver abundant and predictable anthropogenic food resources or subsidies (e.g. exotic fruits, corn) (Oro et al., 2013), allowing species to boost their intake rate of energy and nutrients over time (Wood et al., 2019). However, anthropogenic food subsidies (e.g. crop production or feeding stations) may create ecological traps because of their negative and paradoxical effects on populations (Oro et al., 2013). That is, in some cases, anthropogenic feeding areas can increase the risk of predation (Morris, 2005), rise exposure to high levels of pollution (Freemark & Boutin, 1995; Kale et al., 2013; White et al., 1983), increase mortality due to human infrastructures (Tella, Hernández-Brito, et al., 2020) or enhance intraspecific competition (Donáz et al., 2020). In other cases, farmers may perceive these species as pests when they potentially deteriorate the amount or quality of the crop production (Woodroffe et al., 2005), resulting on persecution and deterioration of the species conservation status (Berkusky et al., 2017; Di Marco et al., 2018).

In addition to describing the occurrence of particular cases of human–wildlife conflicts, we should also understand the general conditions (environment, landscape characteristics and animal behaviour) that motivate wild species to undertake the risk of foraging on croplands and what motivates farmers to persecute them (e.g. their income level, harsher environmental conditions to produce crops). This knowledge is necessary for identifying the drivers of species conservation risk and for prioritizing the actions and policies required to halt their way towards extinction. In rare cases, the reasons why a restricted group of animals cause agricultural or livestock damage are addressed (De Azevedo, 2008). However, this kind of monospecific and local-level approach limits the possibilities of knowing what species traits (i.e. body size, behavioural flexibility) and environmental conditions (i.e. ecosystem productivity, seasonality, level of habitat degradation) can induce the use of anthropogenic food resources by wild animals. Therefore, we still need to advance our knowledge on multi-specific and global-level approaches that evaluate the use of human-dominated landscapes by wild species to open new ways to identify and anticipate emerging human–wildlife conflicts. Such knowledge may be used as a tool in rural development management and planning with the aim of reducing conflicts with wild species.

The occurrence of wildlife–human conflicts and the proportion of threatened species are not evenly distributed among groups of species. For birds in particular, one in eight of all species is threatened with global extinction (BirdLife International, 2019). The order Psittaciformes (parrots) is one of the few bird groups that present a particularly high proportion of threatened species (26%) and, moreover, more than half (58%) of the species show global population declines (BirdLife International, 2019). Parrots show a worldwide distribution (BirdLife International, 2019) and are abundant in tropical regions, where land cover changes are mostly related to the expansion of agriculture (Laurance et al., 2014; Zabel et al., 2019). A global assessment based on information compiled by IUCN identified the loss of natural habitats by agriculture as the most important threat for parrots across the world (Olah et al., 2016). Nonetheless, some species could adapt to these changes, given that parrots include a large variety of plant structures and species in their diet (Blanco et al., 2018; Renton et al., 2015), and that their relative brain size, considered as a proxy of behavioural flexibility, is large compared to other taxa (Iwaniuk et al., 2005). Species with high behavioural and ecological plasticity may attain the highest benefits from novel anthropogenic habitats (Sol et al., 2005), which could explain why some species thrive in highly transformed habitats, including cities (Luna et al., 2018; Tella et al., 2014), or are successful invaders beyond their native ranges (Abellán et al., 2017; Cardador et al., 2016). All these facts suggest a high potential for the adaptability of parrots to use croplands as foraging habitats. However, such an adaptation could become a threat if farmers persecute and kill them as crop pests. In fact, Olah et al. (2016) identified hunting and trapping as the third

**KEYWORDS**

behavioural plasticity, climate, ecosystem functioning, human–wildlife conflicts, land-use change, NDVI
most frequent threat for parrots, although this threat category included persecution due to agriculture damage alongside trapping for the pet trade. Altogether, parrots constitute a good study model for multi-specific and global-level approaches on agriculture–wildlife conflicts and their conservation consequences.

Here, we conducted a global assessment of agriculture–parrot conflicts and their conservation effects on parrot species. In particular, we investigated underlying associations among parrot species traits, natural environment and anthropogenic factors to determine the occurrence of agriculture–parrot conflicts and deterioration of their conservation status. We tested the hypothesis that parrots with higher behavioural plasticity (Iwaniuk et al., 2005; Sol et al., 2005) are more likely to use croplands and consequently be involved in conflicts with farmers (e.g. persecution), which could contribute to their population decline and extinction risk (Bodrati et al., 2006). In addition, we expected a higher use of croplands by species with smaller distribution ranges because of higher potential restrictions on habitat availability and lower dispersal capacity within their restricted ranges (Gaston, 1996). Because the use of anthropogenic food resources is affected by environmental stochasticity and food availability (Oro et al., 2013), we expected that parrots are pushed to use croplands when biodiversity is low and climate conditions are unfavourable (low precipitation, high seasonality) within their distribution ranges, natural food resources are restricted

| TABLE 1 | Summary of the explanatory variables used in this study, their description, source data, main references and related groups of hypothesis (H1: Use of croplands, H2: Persecution, H3: Population decreasing, H4: Extinction risk) |
|----------------|--------------------------------------------------------------------------------|
| Abbreviation   | Variable description                                                                                                     |
| Range distribution | Native distribution range in km² (also defined as ‘extent of occurrence’ by IUCN)                                           |
| Number of habitats | Number of habitat types used by the species                                                                              |
| Body size       | Body length (cm)                                                                                                         |
| Body mass       | Animal weight (g)                                                                                                         |
| Relative brain size | Residuals obtained from the linear regression between body mass (g) and brain volume (ml)                                |
| Species richness | Average bird species richness within the distribution range, as a proxy of biodiversity                                  |
| % forest biomes | Proportion of the species distribution range covered by forest biomes                                                    |
| NDVI            | Annual average and SD of NDVI                                                                                             |
| Precipitation   | Annual accumulation (mm) and CV                                                                                            |
| Temperature     | Annual average (°C) and SD of the daytime temperature                                                                   |
| Human footprint | Human footprint index indicating human population pressure land use and infrastructure                                    |
| Land protection | Proportion of species distribution range located within environmentally protected areas                                  |
| GDP             | Average gross domestic product per capita within the species distribution range (human income level)                     |
| Crop area       | Proportion of the distribution range covered by croplands (agriculture)                                                  |
| Persecution     | Species are persecuted or controlled (“yes” or “no”)                                                                    |
| Region          | Distribution of the species: Neotropical, Afrotropical, Australasia, and Indo-Malaysia                                    |
| Island          | Indicates the exclusive presence of a species on islands smaller than 110,000 km² (“yes” or “no”)                         |
| Source          | IUCN (2019)                                                                                                              |
| Related hypothesis | H1, H2, H3, H4                                                               |
| Source          | IUCN (2019)                                                                                                              |
| Related hypothesis | H1, H3, H4                                                               |
| Source          | Forshaw (2006)                                                                                                          |
| Related hypothesis | H2, H3, H4                                                               |
| Source          | Forshaw (2006); Franklin et al. (2014); Iwaniuk et al. (2005); Schuck-Paim et al. (2008)                                |
| Related hypothesis | H2, H3, H4                                                               |
| Data for brain volume: Franklin et al. (2014); Iwaniuk et al. (2005); Schuck-Paim et al. (2008)                             |
| Related hypothesis | H1                                                                       |
| Data obtained from gridded maps (see detailed data processing description in Supplementary Material 1). |

Abbreviations: CHIRPS, Climate Hazards Group InfraRed Precipitation with Station data; CV, coefficient of variation; MODIS, Moderate Resolution Imaging Spectroradiometer; NDVI, normalized difference vegetation index; SD, standard deviation.

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(low environmental productivity), and human impact on landscape is high. Likewise, the consequences of persecution on population decrease and extinction risk may be higher in harsher environments and in human-dominated landscapes (Di Marco et al., 2018). Some species traits, such as large body size, make species more conspicuous and attract human attention (Frynta et al., 2010; Romero-Vidal et al., 2020), which we believe may also enhance their persecution by farmers. Finally, we expected higher risk of persecution and extinction for species with geographical ranges located in regions with low level of environmental protection (UNEP-WCMC & IUCN, 2019).

Building on the above hypotheses and predictions, we used a set of species-specific traits, environmental, climatic, anthropogenic and socio-economic variables (Table 1) for assessing factors driving species to forage on crops and thus entering into conflict with agriculture, which of these species are persecuted by farmers, and to what extent persecution contributes to their population declines and extinction risk. For such a purpose, we used the IUCN Red List (IUCN, 2019) as a homogenous source of information on the use of agriculture habitats, persecution, population declines and extinction risk for the parrots of the world.

2 | METHODS

2.1 | Datasets

2.1.1 | Habitat use and conservation status of parrots

Using IUCN Red List of Threatened Species database (IUCN, 2019), we classified all the 398 extant species of parrots on whether (a) they use agricultural land as foraging habitat ("use croplands", hereafter), (b) they are persecuted by humans, which involves harming or killing them because they are considered undesirable crop pests ("persecution"), (c) they show decreasing population trends ("population decreasing"), and (d) they have any level of extinction risk ("extinction risk"). We classified each parrot species into binary conditions ("yes" or "no") for each of the above-mentioned variables (i.e. use croplands, persecution, population decreasing, extinction risk).

These were our four response variables used to answer our questions on why species forage on croplands and how it may result in a conservation threat.

In particular, we classified the species as "yes" for "use croplands" when the IUCN database indicates the species use arable land, pastureland and plantations, indicating a potential use of crops as food resources. We considered all parrot species classified as "use croplands" (i.e. forage in agriculture habitat) as a potential source of agriculture–parrot conflicts. For "persecution", we classified the species as "yes" when the threat classification scheme of the IUCN recorded Persecuted or Control. Here, we assumed that persecution or control mainly occurs within an agriculture context, since parrots within their native distribution ranges are not usually persecuted due to reasons other than crop damage, and all parrot species under persecution use agricultural habitats. To determine "population decreasing", we classified as "yes" those species that show population decline ("Decreasing" in the IUCN database) and as "no" when the species show "Increasing" or "Stable" trends. We did not consider species with "Unknown" trend (n = 8) for analyses. Finally, species classified by the IUCN as "Vulnerable", "Endangered" or "Critically Endangered" were coded as "yes" for "extinction risk". For the last three response variables (persecution, population decreasing and extinction risk), we subset the parrot species to focus our analyses exclusively on the species that previously were classified as "yes" in "use croplands" (163 species).

2.1.2 | Drivers of parrot–agriculture conflicts

To understand the main drivers of parrots’ habitat use and potential conflicts with agriculture, we used three groups of explanatory variables: (a) parrot species traits (i.e. range distribution, number of habitats, body size, body mass, relative brain size); (b) natural environment (i.e. species richness, proportion of forest biomes, annual average and standard deviation of vegetation productivity/biomass using NDVI, annual precipitation, precipitation coefficient of variation, mean annual temperature, standard deviation of temperature); and (c) anthropogenic factors (i.e. human footprint, land protection, GDP, crop area, persecution). In total, these three groups included 18 explanatory variables used to test different hypotheses (see Table 1; Supplementary Material 1 for a complete description of each variable).

Some of these variables were obtained from gridded raster maps (e.g. temperature, precipitation, NDVI, human footprint). To calculate variables from these gridded raster maps, we spatially overlapped and filtered each gridded map with the range distribution map (BirdLife International & Handbook of the Birds of the World, 2019) of each parrot species and averaged all remaining pixels. For some variables, such as NDVI, precipitation and temperature, we also calculated the temporal average, standard deviation or coefficient of variation using datasets between the years of 2001 and 2015 (see additional detail of the data sources and processing in Table 1; Supplementary Material 1).

2.2 | Statistical analyses

Region of the world and whether a species is confined or not in islands may influence the conservation status of parrots (Berkunsky et al., 2017; Olah et al., 2016). Thus, we included the region and island factors (details in Table 1) of each species as covariates in the modelling procedure. We also used a Person $\chi^2$-squared test to describe the influence of these biogeographic factors (region and island, Table 1) in our response variables (use croplands, persecution, population decreasing, extinction risk).

We then used within-group generalized linear models (GLM) to evaluate the performance of the explanatory variable within their
corresponding groups (i.e. species traits, natural environment, anthropogenic drivers and covariates), independently, for explaining each response variable (use croplands, persecution, population decreasing, extinction risk). We used all extant parrot species (398 species) in the GLM model for “use croplands”. For the other three response variables (persecution, population decreasing and extinction risk), we restricted our analyses to those species that were previously identified as species that use croplands, resulting in 163 species. Explanatory variables were standardized to the same scale (i.e., they were transformed to have a mean of 0 and SD of 1). We used this within-group GLMs to exclude redundant or correlated variables and to previously select the most important variables within each group of explanatory variables (i.e. statistically significant). Therefore, some variables were excluded after this first modelling step. To do so, we calculated the variance inflation factor (VIF) to exclude correlated and redundant variables with high collinearity (variables with VIF higher than 5 were excluded) using the “car” R package (Fox & Weisberg, 2011). Subsequently, we estimated correlations (Pearson correlation) among the remaining explanatory variables to identify highly correlated ones. Since none were highly correlated ($r < .7$) after applying VIF, we used all the remaining variables in the following analyses.

In a second step, we ran a new GLM model for each response variable (use croplands, persecution, population decreasing, extinction risk), although now we included the remaining explanatory variables from all groups together (species traits, natural environment, anthropogenic factors, covariates) after filtering variables using the previous within-group GLM step. We fitted all possible combinations and subsets of the explanatory variables and covariates for each of the response variables. Here, we also calculated the variance inflation factor (VIF) to exclude correlated and redundant variables with high collinearity (variables with VIF higher than 5 were excluded). We selected the model with the lowest AICc, but we implemented a model-averaging function in the “MuMIn” R package (Barton, 2013) when obtaining models with a delta AICc $< 2$ relative to the best model. This function averages parameter estimates across all considered models for each response variable where the respective parameter appeared, weighted by the relative importance of each model. We used a binomial distribution for all GLMs. We also calculated the percentage of explained deviance (i.e. the amount of variability explained by the model) of the final models. All analyses were performed in R version 3.6.0 (R Core Team, 2019).

We used the statistically significant variables obtained from the previous step to perform a variation partitioning approach among the three groups of explanatory variables (species traits, natural environment and anthropogenic drivers) according to Bocard et al. (2011). We calculated the amount of variation explained by the unique and shared contribution of species traits, natural environment and anthropogenic variables and expressed this relative to the total amount of variation explained by the fixed factors in the global model (containing all three groups of explanatory variables and the covariates). We used the R package vegan to perform this analysis.

### RESULTS

Croplands cover an enormous extent of the original coverage of parrot habitats (approximately 25%; Figure 1), and 40% of the global cropland extent is located within the distribution range of all parrot species together. Consequently, 173 parrot species use cropland as habitat (43.5% of the species) in different regions of the world, and 24% of these species are persecuted. The use of croplands, persecution, population trends and vulnerability to extinction of the species seems to be unevenly distributed across the globe (Figure 2). We found differences in the proportion of species that use croplands ($\chi^2$-squared $= 19.49, p < .001$) over Indo-Malaysia (91% of 11 species present in this region), Afrotropical (54% of 26 species), Australasia (48.6% of 185 species) and Neotropical region (34% of 176 species). Regional differences were also observed for persecution ($\chi^2$-squared $= 29.63, p < .0001$), population decreasing ($\chi^2$-squared $= 8.0189, p = .045$) and extinction risk ($\chi^2$-squared $= 17.828, p < .001$). However, most of these regional differences disappeared when we fitted region together with all other variables (species traits, natural environment and anthropogenic factors) in our model selection approach (Table 2). Only persecution resulted significantly influenced by region, with 60% of the species that use cropland in Indo-Malaysia, 36% in Neotropical, 21% in Afrotropical and 13% in Australasia being persecuted (Table 2).

The probability of using croplands was related to natural and anthropogenic variables, as well as to species-specific traits (Table 2). We found lower richness of birds, higher percentage of forest biomes and crop area, higher variability of NDVI and higher human footprint within the distribution range of parrot species that use croplands than in those that do not use croplands (Table 2; Figure S1 of the Supplementary Material 2). We also found a higher likelihood of using croplands when the number of natural habitats used by a species is high, suggesting that species with higher habitat plasticity are more likely to use croplands.

Among those species that use croplands, we found larger body size, smaller range distribution, lower annual precipitation and higher human footprint within the distribution range for those species that are persecuted than for those that are not persecuted (Table 2; Figure S2 in Supplementary Material 2). Species are more likely to show decreasing population trends and higher extinction risks when they are persecuted and have small distribution ranges (Figures S3–S6 in Supplementary Material 2). Moreover, we found lower annual precipitation and lower temperature seasonality within the distribution range of parrot species showing decreasing populations than in those that are not decreasing (Table 2; Figure S3 in Supplementary Material 2).

Variation partitioning analyses allowed us to calculate the amount of variation explained by the pure and shared contributions of each group of variables (Figure 3; see the statistically significant explanatory variables from each group in Table 2). The shared contribution of natural environment and anthropogenic factors accounted for 48% of the variance explained by the model related to the question of why parrots use croplands (Figure 3a), although each group...
still showed relatively high independent levels of importance (21.6% for species traits, 14.5% for anthropogenic factors and 12% for natural environment). However, the persecution of parrot species was mostly explained by the pure effects of species traits (48%) and anthropogenic factors (12%), with little contribution of shared effects (Figure 3b). Although anthropogenic factors were also key to determine decreasing population trends (48%), it is also relevant the pure contribution of natural environment (15%), their shared contribution (17%), and the shared contribution between anthropogenic factors and species traits (10%; Figure 3c). Finally, extinction risk was mainly affected by the pure effects of species traits (64.5%) and, secondarily, by anthropogenic factors (21%) and their shared contribution (14.5%, Figure 3d).

4 | DISCUSSION

4.1 | Why do parrots forage on croplands?

At first sight, the use of croplands by parrots seemed to be heterogeneous across the globe, with the highest proportion of species using them in the Indo-Malaysia and the lowest one in the Neotropical regions. However, our modelling approach showed that these apparent biogeographical differences actually result from underlying factors that consistently drive species use of croplands worldwide.

In particular, we found that the combination of species traits, climate conditions, biome type, ecosystem productivity and landscape degradation determines whether or not a parrot species make use of croplands.

Our results supported the hypothesis that a high plasticity in habitat use increases the likelihood of parrots to supplement their range of habitats with croplands. That is, the higher the number of habitats originally used by a species the higher is the likelihood of this species to forage on agricultural lands. Parrots show a great dietary plasticity, which can determine their diversification on habitat use (Renton et al., 2015), and variability among species in dietary plasticity (Benavidez et al., 2018; Blanco et al., 2015) could contribute to explain this result. On the other hand, the relative brain size of birds has been shown to reflect behavioural flexibility (Sol et al., 2005) and inter-individual variability to colonize anthropogenic habitats like cities (Carrete & Tella, 2011). Although large brains could benefit parrots for adapting to new environments (Schuck-Paim et al., 2008), we did not find evidence for their role in using croplands.

Previous studies have suggested that habitat degradation and the consequent loss of natural food resources are important drivers of parrot habitat shift to agriculture (Downs, 2005; Martin et al., 2014). Indeed, we found that habitat degradation increases the likelihood of a parrot species to use croplands. However, this tendency mainly occurred in forested biomes (habitat type that most parrot species use) located in regions with low pool of biodiversity.
and intermittent availability of natural resources (measured here as avian diversity and primary productivity, respectively). Many natural forested habitats, such as dry forests, exhibit high temporal and spatial variability in plant productivity and availability of plant resources (Ting et al., 2008). As habitat degradation arises on these inconstant and harsher environments and the lack of food resources intensifies with intra- and inter-annual seasonality, animals are expected to shift habitat use and to exploit predictable anthropogenic food resources or subsidies (Oro et al., 2013). Moreover, parrot species living in these harsh environments may be more prone to shift habitat use because their evolutionary capacity to employ a combination of strategies of diet switching, habitat shifts and movements to track food resources (Renton et al., 2015).

We should consider, however, that our results explained a relatively low proportion of the variance in the models, probably because our global-scale approach cannot capture local sources of variability. For example, in addition to the global pattern suggesting that the depletion of natural food resources is driving parrots to forage on croplands, in some cases parrots might also make use of them, even in the absence of habitat loss, simply because croplands constitute an abundant, predictable and easy-to-obtain food resource. Therefore, croplands may replace or complement some natural sources of nutrients and key food resources necessary for specific moments of their life cycle (Khorozyan et al., 2015; Warburton & Perrin, 2006; Woodroffe et al., 2007).

Although our results reveal a consistent global pattern, they also illustrate how heterogeneous may be the reasons of why parrots use agricultural habitats. Therefore, further studies should evaluate in what cases the use of croplands is driven by a lack of key food resources due to habitat degradation, or by a diet shift mostly motivated by a scenario of easy-to-obtain food resources. Moreover, further local-scale studies should evaluate how important is the interaction between natural habitat degradation and the availability of food resources to determine parrot foraging behaviour in a specific period of the year or throughout the full annual cycle. These types of local-scale and species-specific studies can help to better design management strategies where conflicts between parrots and farmers are more frequent and harmful.

4.1.1 When do parrot-agriculture conflicts lead to persecution?

While 46% of the parrot species of the world enter in conflict with humans because of foraging on croplands, only 22.5% of them have been recorded in the IUCN Red List to be persecuted (IUCN, 2019). We found that persecution is mostly influenced by species traits (range distribution and body size), being higher in human-dominated landscapes (higher human footprint) and, contrary to the use of croplands, varying among biogeographic regions.
TABLE 2  Model coefficients of a model-averaging approach relating macroecological variables and species traits with the use of croplands by parrots, persecution by humans when foraging in croplands, their decreasing population trends and extinction risk

| Species traits | Use croplands | Persecution | Population decreasing | Extinction risk |
|----------------|---------------|-------------|-----------------------|----------------|
| Range distribution | -0.636* | -0.359+ | -1.742*** |
| Number of habitats | 0.561*** |
| Body size | 0.732** |
| Relative brain size | |
| Body mass | |

| Natural environment | Use croplands | Persecution | Population decreasing | Extinction risk |
|---------------------|---------------|-------------|-----------------------|----------------|
| Species richness | -0.441** | |
| % of forest biomes | 0.366* |
| NDVI SD | 0.357* |
| Mean annual NDVI | |
| Precipitation CV | |
| Annual precipitation | -0.490+ | -0.807** |
| Temperature SD | |
| Mean temperature | |

| Anthropogenic factors | Use croplands | Persecution | Population decreasing | Extinction risk |
|-----------------------|---------------|-------------|-----------------------|----------------|
| Human footprint | 0.542*** |
| Land protection | |
| GDP | |
| Crop area | 0.317* |
| Persecution | 2.111** |
| Extinction risk | 1.533** |

| Biogeographic | Use croplands | Persecution | Population decreasing | Extinction risk |
|---------------|---------------|-------------|-----------------------|----------------|
| Region | 2.310* |
| Island | |

| N | Use croplands | Persecution | Population decreasing | Extinction risk |
|---|---------------|-------------|-----------------------|----------------|
| 398 | 18% | 16% | 44% |
| 2.310* | 23% | 16% |
| Island | |

Note: Significant values are highlighted in bold. P-values as follow: ***p < .001, **p < .01, *p < .05, +p < .07. We also show the % of explained deviance of the model and the number of species included in the analyses (n).

Abbreviations: CV, coefficient of variation; GDP, gross domestic product; NDVI, normalized difference vegetation index; SD, standard deviation.

FIGURE 3  Proportion of pure and shared contributions of species traits, anthropogenic factors, and natural environment variables on parrot’ habitat use and conservation status (i.e. use of croplands, persecution, population decreasing trend and extinction risk). See model coefficients for each variable in Table 2. The amount of variation explained each group of variables was calculated as a percentage of the total variation explained by the fixed factors in the global model, and are represented by colours indicating the percentage of variation explained.
Our results did not support the hypothesis that the use of crop-lands is more frequent in parrots with small distribution ranges, but revealed that persecution is higher for them. However, the fact that species with large distribution ranges tend to be less persecuted might be an artefact resulting from the nature of the data used for this global approach. There is the possibility that localized persecution of some species with large distributions might not be regarded by experts as a threat for their global conservation and thus are not recorded as persecuted in the IUCN Red List. Moreover, and contrary to other easily detected threats, such as parrot poaching for the pet markets (e.g. Pires et al., 2016), parrot persecution may be largely overlooked as it is often performed by local communities in remote areas (Tella et al., 2013). In fact, through our large-scale field studies on the foraging ecology of parrots (e.g. Sebastián-González et al., 2019), we have recorded the persecution and killing of several Neotropical parrot species due to crop damages that are not recorded by IUCN (FH and JLT, unpub. data). This knowledge gap, probably at the global scale, surely made statistical noise and not recorded by IUCN (FH and JLT, unpub. data). This knowledge gap, probably at the global scale, surely made statistical noise and not recorded by IUCN (FH and JLT, unpub. data).

Persecution occurred more often towards larger-bodied species, as we expected because large species attract more attention from people (Frynta et al., 2010); they are more conspicuous and/or are perceived by farmers to produce greater damage to crops. However, to the best of our knowledge, there is no evidence supporting the belief that large parrot species cause more damage to croplands than small species. Contrarily, large-bodied species are usually less abundant in nature (Blackburn et al., 1993; White et al., 2007), and thus, their population-level effects on ecosystems, and similarly on croplands, can be lower than for small-sized species since the later usually show higher population-level biomass (see Blanco et al., 2015 for a community of parrot species). Therefore, a higher persecution of large parrot species may result from their higher detectability when foraging on crops and the misperception that large animals are causing more crop damages. Moreover, the persecution of large parrots as crop pests may be synergistically enhanced by other exploitation uses where size matters, such as their capture for their use as pets or hunting for food. Large parrot species, which usually are more attractive and better at imitating human speech, are preferred across cultures as pets (Romero-Vidal et al., 2020; Tella & Hiraldo, 2014). For example, red-fronted macaws (Ara rubrogenys) are killed as crop pests but also live-trapped in corn crops for the pet market in Bolivia (Tella et al., 2013), and vasa parrots (Coracopsis vaso) are heavily persecuted as crop pests, hunted for food and also captured for the caged bird trade in Madagascar (Martin et al., 2014).

Finally, persecution does not occur equally around the globe. Regional differences in persecution could be at least partially related to socio-cultural characteristics, including religious beliefs and taboos. As described by Baker et al. (2014), two Nigerian villages perceived crop pests differently according to their religion. On the other hand, the economic impact of crop losses could play a major role in encouraging persecution. Although at a global scale we did not find a direct link between GDP and persecution, further attention should be paid to how local-level farmer income may be related to persecution, since climate and pests can show higher impacts on crop production of smallholder farmers (Belay et al., 2017; Tambo & Abdoulaye, 2013). Consequently, local-level farmer income could have additional influence on how farmers perceive and face damage.

Unfortunately, little is known about actual crop damage by parrots. Studies addressing the amount of parrot damage on crop production were restricted to a few species and localities (Ahmad et al., 2012; Bomford & Sinclair, 2002; Long, 1985; Navarro et al., 1991; Sánchez et al., 2016; Warburton & Perrin, 2006), and even fewer studies addressed the actual economic losses caused (Barbosa & Tella, 2019; Long, 1985). These studies may reveal mismatches between the severity of crop damage, farmers’ perception and persecution, as illustrated by the burrowing parrot (Cyanoliseus patagonicus). While this species was considered a national crop pest and thus was legally killed by thousands in Argentina, its actual impact on agriculture is negligible (Sánchez et al., 2016). Much more research is thus needed to ascertain the actual economic impact of parrots on agriculture and how farmers with different income levels and cultures perceive them, for a better understanding and justification of persecution.

### 4.1.2 Consequences of parrot-agriculture interactions

All regional assessments, based on information compiled by IUCN (Olah et al., 2016, 2018), literature reviews (Martin et al., 2014) or expert knowledge (Berkunsky et al., 2017), ranked persecution, often mixed with hunting and trapping, within the five more frequent threats for parrots but did not assess its contribution on the conservation status of the species. We found that the persecution of parrots in the agricultural context, through methods such as shooting, trapping and poisoning (FH and JLT, unpubl. data), is strongly linked to the population decline and extinction risk of the species worldwide, while controlling for other environmental and anthropogenic factors and species traits that might influence their conservation status. These results suggest that the impact of persecution has been underestimated compared to other threats causing the removal of individuals from the wild. Contrary to live trapping for the pet market, which most often causes the removal of chicks from nests (Pain et al., 2006; Pires et al., 2016; Romero-Vidal et al., 2020; Wright et al., 2001), persecution causes the death of all age classes including adult breeders, thus impacting more strongly on the population dynamics of long-lived, slow-breeding species such as parrots (Young et al., 2012). Therefore, even slow rates of persecution may have caused long-term population declines and range contractions of several species, increasing their risk of extinction. In fact, it
was argued that the blue-winged macaw (*Anodorhynchus leari*), once considered as crop pest, became extinct in Argentina just after five decades of persecution by farmers (Bodrati et al., 2006) and that hunting by farmers contributed to the abrupt global extinction of the Carolina parakeet (*Conuropsis carolinensis*) in North America (Gelbert et al., 2020).

Some management actions, such as exclusion netting (Bomford & Sinclair, 2002) and the use of bioacoustic devices (Ribot et al., 2011), are effective in reducing crop damage by parrots and thus could help to avoid the persecution of some threatened species or populations. However, these methods may be economically unviable when dealing with very large agricultural areas and impoverished regions. Another possibility is changing the seasonality of crop productions to reduce their use by parrots (Mahli, 2000). However, measures aimed at avoiding parrots foraging on crops could be negative for the conservation of some species in places where natural food resources are scarce and cannot fulfill their requirements, as discussed above. When affordable, the compensation of economic losses caused by parrots to farmers can solve this conflict and avoid persecution. This is the case of the Lear’s macaw (*Anodorhynchus leari*), where a compensatory programme for corn losses did not totally avoid the shooting of macaws by farmers but may have contributed, together with other conservation actions, to the recent recovery of the species (Barbosa & Tella, 2019). Nonetheless, the negative consequences to parrots of feeding on croplands may also come from sub-lethal effects, such as the intoxication from pesticides (Tella et al., 2013). There is a widespread and increasing use of pesticides in agriculture around the globe (FAO, 2019), in which countries present different restriction levels of pesticide residue allowed (Donley, 2019) and smallholder farmers often perform unsafe practices when using pesticides (Mengistie et al., 2017; Pedlowski et al., 2012; Schreinemachers et al., 2017). As a consequence, pesticides are a very important threat to wildlife (IUCN, 2019), and recent non-invasive methodological approaches allowing inference of vulnerability to pesticides (Baos & Hiraldo, 2018; Monclús et al., 2018) should be applied to parrot species tied to agricultural resources.

In addition to the above-mentioned species-level consequences of the use of croplands by parrots, there are potential consequences for the ecosystems. Recent research has shown a variety of ecological functions for parrots, acting as seed dispersers, pollinators and facilitators of food and secondary seed dispersal for other species (Blanco et al., 2016, 2018, 2020; Gleiser et al., 2017; Sebastián-González et al., 2019; Tella et al., 2015), and thus playing a fundamental role in the structure, organization and functioning of ecosystems (Bahos-Villalba et al., 2017; Blanco et al., 2015; Montesinos-Navarro et al., 2017). Moreover, some parrot species may be the main long-distance seed dispersers of large and biomass-dominant woody plants (Blanco et al., 2019; Tella et al., 2019; Tella, Hiraldo, et al., 2020). As we partially lose these important ecological processes when parrots replace their natural food resources with crops, we consequently expect a critical cascade effect on ecosystem functioning. Moreover, persecution may have contributed to the population decline and range contraction of several species, which have caused the large-scale loss of some key plant–parrot mutualistic interactions (Tella et al., 2016; Tella, Hiraldo, et al., 2020).

### 5 | CONCLUSIONS

Due to the widespread occurrence of anthropogenic biomes in the globe, wild species have increasingly been reliant on human-made food resources (Oro et al., 2013). Our methodological approach shows the importance of using multi-specific and multi-source information to study the derived human–wildlife conflicts at a global scale. We provide evidence that habitat use plasticity in response to environmental conditions and habitat degradation are the main drivers for parrot species to use croplands across the globe. Because an expected increase in natural habitat degradation (Jantz et al., 2015; Powers & Jetz, 2019), an expected change in climatic seasonal cycles (DeSole et al., 2014; Santer et al., 2018) and the rapidly expanding agricultural areas encroach into the habitats of parrots (Vergara-Tabares et al., 2020), our results shed light on why and how parrot-agriculture conflicts may intensify in these prospective scenarios. Consequently, persecution will continue to erode their conservation status and ecosystem services provided. As we suggest, further local-scale research is needed to fully assess the extent of parrot-agriculture conflicts and to ameliorate the impacts of persecution through adequate management actions.

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### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in public repositories and all cited in Section 2.

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**BIOSKETCH**

Our research at the Department of Conservation Biology focuses on the adaptation of organisms to novel environments and the overlooked role of parrots as key multilinkers in the structure and functioning of tropical ecosystems.

Author contributions: All authors contributed to developing the ideas and collected the data; J.M.B. processed the spatial data and the statistical analyses. All authors contributed to the writing of the manuscript.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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