Environmental Pollution 251 (2019) 717–722

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Life in a polluted world: A global review of anthropogenic materials in bird nests★

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A R T I C L E I N F O

Article history:
Received 25 November 2018
Received in revised form
1 May 2019
Accepted 6 May 2019
Available online 7 May 2019

Keywords:
Human footprint index
Bird
Nest construction
Debris
Plastic

A B S T R A C T

Human pressure exerts a significant influence on animals and the environment. One of its consequences, plastic pollution is considered one of the major threats to fauna as well as a significant conservation issue. In this research, we examined the global pattern of one example of avian behavior in response to pollution—namely, the incorporation of anthropogenic materials into nests—as well as the existing knowledge on this subject. Based on 25 articles, we studied 51 populations, involving 24 bird species, and checked 10,790 nests; as a result, we found that incorporation of debris is correlated with increasing human influence on the environment, measured as the Human Footprint Index. Moreover, the probability of debris incorporation is higher in terrestrial than in marine species. We also identified knowledge bias in favor of marine as opposed to terrestrial species: namely, marine species attract more scientific attention than terrestrial. Furthermore, research approaches to these two ecosystems differ. Undeniably, the factors which influence debris incorporation by birds, the scale of this behavior, and particular forms of use of debris in bird nests are aspects which require long-term standardized research. This is the first global review paper on debris incorporation by birds to demonstrate a close link to human pressure as a driver.

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1. Introduction

Every day, three million tons of waste are discarded worldwide. It has been estimated that this figure will increase to six million tons per day by 2025 (Hoornweg & Bhada-Tata, 2012; Hoornweg et al., 2013). Overproduction of waste and plastic pollution, which currently constitutes 54% of produced waste (Hoellein et al., 2014), impacts all ecosystems and ecotypes worldwide and ultimately influences wildlife (Plaza & Lambertucci, 2017; Windsor et al., 2019). The 2014 edition of the United Nations Environment Programme (UNEP, 2014) reported that plastic contamination had been listed as a critical environmental problem and constituted one of the major threats to marine fauna (Provencher et al., 2017) as well as to several terrestrial animals (Plaza & Lambertucci, 2017). Plastic pollution impacts the behavior, physiology, and survival of invertebrates and vertebrates (e.g., Ryan and Ryan, 1987; Richardson et al., 2011; Lavers et al., 2014; Setälä et al., 2014). Nevertheless, many aspects of animal ecology in terms of waste pollution have not yet been fully described, particularly given that increasing waste production is one of many effects of human pressure on earth. Human impact can be measured by the Global Human Footprint Index (hereafter HFI), which takes several components, including human population density, anthropogenic land transformation, and human access, into account. HFI was designed to indicate the areas of the earth under the greatest anthropogenic pressure (Sanderson et al., 2002).

Anthropogenic materials (hereafter debris), such as foil, plastic strings, and pieces of clothing, are incorporated into nests of many birds (Wang et al., 2009; Antczak et al., 2010; Avery-Gomm et al., 2012; Townsend and Barker, 2014; Carbó-Ramírez et al., 2015; Tavares et al., 2016; O'Hanlon et al., 2017). The approach of research to this behavior differs between the marine and terrestrial environment. Most research on marine birds has focused on behavioral patterns (Young et al., 2009), physical properties of debris (Verlis et al., 2014; Tavares et al., 2016), and negative consequences – like plastic entanglement and ingestion (Montevecchi, 1991; Huin & Croxall, 1996) to individuals, rather than on issues such as

★ This paper has been recommended for acceptance by Dr. Da Chen.

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https://doi.org/10.1016/j.envpol.2019.05.028
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effects and long-term consequences, which are the concerns of research on terrestrial birds (e.g., Antczak et al., 2010; Sergio et al., 2011; Suárez-Rodríguez et al., 2013; Townsend and Barker, 2014; Jagiello et al., 2018). Heretofore, several published papers have described various approaches to the incorporation of debris in bird nests. Birds use debris for different purposes: 1) as a replacement for unavailable natural nest material, due to the availability of debris in the environment; e.g., in an urban environment the availability of natural nest materials is reduced (Wang et al., 2009; Lee et al., 2015); 2) to strengthen the nest structure with plastic strings (Antczak et al., 2010); 3) to increase their chances for successful mating via the use of plastic decorations (Borgia, 1985); 4) to signal the current quality of individuals and the occupation of the territory (Sergio et al., 2011); or 5) to repel ectoparasites (Suárez-Rodríguez et al., 2013). However, no paper has demonstrated a more general pattern for this behavior, or included any comprehensive review of the literature.

In the current study we focused on debris as a nesting material used by birds worldwide as a lining or a structural component (McCabe, 1965; Norman et al., 1995; Surgey et al., 2012). We analyzed the literature on debris incorporation by birds and the frequency of debris incorporation in the studied populations, as well as the localization and type of environment. Accordingly, we advanced the following hypotheses: 1) marine and terrestrial birds differ in the frequency of incorporation of debris into their nests; 2) incorporation of debris into nests is driven by its availability in the surrounding environment (as indirectly expressed by the Human Footprint Index); 3) synanthropic birds incorporate more debris into their nests than non-synanthropic birds. We suggested which factors determine this behavior globally, summarized the present situation, and assessed the role of debris incorporation in worldwide avian biology.

2. Materials and methods

We carried out a comprehensive bibliographic search of publications, using the Scopus database to search for articles using the following keywords: *nest*debris*, *nest*plastic*, *nest*man-made material*, *nest*anthropogenic* until March 2018. Subsequently, we searched the references in each article we had found for published papers which might contain data useful for testing our hypotheses. We used only publications which reported numbers of studied nests and numbers of nests with debris in the analysis. We used only literature in English. The literature covered the period 1965–2018. In total, we used 25 articles in which numbers of nests investigated were provided, concerning 34 marine and 17 terrestrial populations, which examined the incorporation of debris in nests, thus fulfilling our requirements. In total, our survey covered 10,790 bird nests. We collected basic information about the species (scientific name, synanthropic status) and where the research was conducted (longitude and latitude, type of environment, i.e., marine or terrestrial, where it was performed). We noted the number of nests with debris and the overall number of nests in the study and the role of debris, e.g., as nesting material (Votier et al., 2011) or ectoparasite repellent (Suárez-Rodríguez et al., 2013). We also recorded cases of entanglement and ingestion. We noted whether the presence of anthropogenic materials in nests could be used as an indicator of plastic pollution. We divided research into types: observational report, observational report with experiment, study reporting some measurements of debris in nest, review, or synthesis paper (based on Provencher et al., 2017). Moreover, we considered collection techniques: after the breeding season, during the breeding season, with no breeding data, during breeding season with breeding data. As well, we noted whether the research indicated any influence of debris contamination on the environment surrounding the nest and the effect of this contamination on the amount and type of nest debris.

Using open source QGIS (version 2.18.15) software, we calculated the Human Footprint Index (hereafter, HFI) extracted from the NASA Socioeconomic Data and Applications Center website (http://sedac.ciesin.columbia.edu/data/set/wildareas-v2-human-footprint-geographic/data-download) for the exact coordinates from papers, using a zonal statistics plug-in. HFIs were calculated with an accuracy of 1 km^2. As the nesting territories of mostly solitary and colonial birds are larger than 1 km^2, we assumed that buffers with 5-km radii would match the average nesting territories of checked individuals more precisely.

3. Statistical analyses

To test for the relationship between the probability of debris incorporation in bird nests, HFI, environmental type (terrestrial or marine), and the synanthropization of a species (synanthropic or non-synanthropic), we used generalized linear mixed model (GLMM). We used the Z Score Transformation to standardize the explanatory variable (HFI). We used logit links and binomial family error terms and included population and study ID with a block as random effects. We employed the information-theoretic approach (Burnham & Anderson, 2002) to identify the most parsimonious models explaining variation in all dependent variables. Based on the full model, in each analysis, we constructed a set of candidate models that included different combinations of the predictors, in which we also included the null model (random effects only) (Zuur et al., 2009). For model selection, we used the Akaike Information Criterion, adjusted for small sample sizes (AICc). We used the best model with the lowest AICc. In our models, we used model validation graphs and confirmed the assumptions of homogeneity and overdispersion according to Zuur et al. (2009). We carried out all analyses in R 3.4.2 (R Core Team, 2017), the GLMM using the lme4 package (Bates et al., 2015). We accomplished the model selection using the MuMIn package (Bartoń, 2016). We visualized results and generated maps out in the ggplot2 (Wickham, 2009)

4. Results

4.1. General results

In this survey, we studied 51 populations of 24 bird species which incorporate debris into their nests. We took 17 terrestrial populations from 14 species and 34 marine populations from 10 species into account. Articles on marine birds included a significantly larger number of checked nests. Most of the studies were carried out in North America and Europe (both 32%) and Australia and South America (both 12%), the fewest in Africa (8%) and Asia (4%).

4.2. Role of debris and impact on avifauna

The most common role of debris is its practical use in nest building, as a constructional or/and padding material (84%). Debris also occurs in nests as food leftovers as a result of being mistaken for food, or following regurgitation (20%). Another role for debris incorporation is a signal to conspecifics, mostly during mating (a better-decorated nest signals the higher quality of the individual) (Sergio et al., 2011). Also, one study showed that debris can act as an ectoparasite repellent (Suárez-Rodríguez et al., 2013). Some authors noted more than one purpose for debris in nests.

Negative consequences of debris incorporation were also noted: entanglement (36%), ingestion (20%), and, in some cases, both (12%). In 44% of articles, the authors implied that the investigated species might serve as an indicator of plastic pollution in the environment.

4.3. Type of study

The most common type of research was a study reporting specific measurements of debris in the nest (56%), followed by observational reports (32%) and observational reports with an experiment (12%). There were no reviews or synthesis papers. We also considered the collection technique: after breeding season (44%), during the breeding season without breeding data (28%), during breeding season with breeding data (24%), during breeding season with breeding data collected but not reported in the study (4%).

Moreover, in 44% of studies, the surrounding environment was also surveyed (mostly using the linear transect method) during fieldwork, and its effect on the amount and type of debris in the nest tested.

4.4. Human Footprint Index

We obtained the Human Footprint Index (HFI) for all studied species from each continent (36 populations, 19 species). There were no data for 11 marine populations of five bird species, because the research area comprised mainly remote islands, e.g., South Georgia (Huin & Croxall, 1996), which were not included in the index, as HFI does not cover the entire surface of the earth (Sanderson et al., 2002). The model including HFI, environment type, synanthropic species, and interaction between HFI and the environmental type was the best (AIC = 6498.5, Table 1). GLMM showed that all tested explanatory variables and interaction were significant ($p < 0.05$, Table 2). The probability of occurrence of debris in bird nests was significantly higher in terrestrial than in marine environments (mean ± sd 0.47 ± 0.30, 0.38 ± 0.22, respectively, Fig. 2) and in non-synanthropic compared to synanthropic species (0.45 ± 0.27, 0.37 ± 0.24, respectively, Fig. 3). The probability of occurrence of debris in nests was positively correlated with HFI for both environments (Fig. 4).

5. Discussion

This review provides new information about the global pattern of the use of debris by birds during the nesting period. We considered several species from both marine and terrestrial environments.

5.1. General patterns

We found that debris incorporation in nests is correlated with increasing human influence on the environment, as measured by the Human Footprint Index. Undeniably, humans have a strong influence on all of the earth's ecosystems (Vitousek et al., 1997). Many aspects of nature that operate on a global scale are drastically affected by environmental changes caused by human activity, such as land use and land-cover changes (Noble et al., 2000; Goldewijk, 2001; Kalnay & Cai, 2003; Verheyen et al., 2003), climate change (Walther et al., 2002; Kalnay & Cai, 2003), the spread of alien species (Lowe et al., 2000), disturbance of ecosystems (Coleman & Williams, 2002; Führer, 2000; Magbanua et al., 2010), and, nowadays, environmental pollution, particularly due to waste production (Thompson et al., 2009). Life in a polluted and transformed world induces a behavioral response on the part of organisms. Animals must adapt to new conditions by means of evolutionary processes (Tuomainen & Candolin, 2011). Our findings imply that the use of plastic debris in nest construction is one of the responses of birds to plastic pollution. Changes in the natural, especially terrestrial, environment, may result in reduced availability of natural nesting materials, forcing individual birds to seek replacements. Shrikes commonly incorporate plastic string in nests, probably due to a lack of horse and cow hair (Antczak et al., 2010). In one previous study on the white stork, we found that the amount of debris incorporated into nests was correlated with the amount of waste in the surrounding area (Jagiello et al., 2018). This is consistent with the correlation between the number of anthropogenic materials used in nest building and human pressure on the landscape. In the case of critically endangered black-faced spoonbills (which breed in greatly transformed habitats), following the experimental provision of natural nest materials, the number of items of debris used in nest construction decreased (Lee et al., 2015). As this behavior is changing over time (Supplementary Table 1), long-term monitoring and standardization of methods, according to the classification proposed by Provencher et al. (2017), are highly necessary. Improved knowledge could enable better understanding of the use of debris as a novel (or additional structural) component of bird nests. Moreover, this behavior may be used as an environmental pollution indicator through observation of the birds' incorporation of waste into their nests (Borgia, 1985; Hartwig et al., 2007; Wang et al., 2009; Townsend & Barker, 2014; Jagiello et al., 2018).

Table 2
The estimates of predictors of GLMM's with binomial error structure describing the relationship between occurrence of debris in birds nest and HFI - Human Footprint Index, Environ. – the type of environment (in this case, reference category: marine), Synan. – whether the species is known as a synanthropic or not (reference category: no synanthrope), and interactions between the factors.

Variable	Estimate±se	Z-value	P
HFI	−0.61 ± 0.11	−5.71	<0.01
Environ. = terrestrial	7.65 ± 2.99	2.55	<0.05
Synan. = synanthrope	1.31 ± 0.51	2.59	0.01
HFI × Environ. = terrestrial	−1.80 ± 0.26	−6.81	<0.01

Table 1
The GLMM's with binomial error structure describing the relationship between occurrence of debris in birds nest and HFI (Human Footprint Index), Environ. – the type of environment (marine or terrestrial), Synan. – whether the species is known as a synanthropic or not, and interactions between the factors.

Model	df	Log likelihood	AIC	delta	weight
HFI + Environ. + Synan. + HFI × Environ.	8	−3241.23	6498.5	0.00	0.625
HFI + Environ. + Synan.+ HFI × Environ. + Environ. × Synan.	9	−3240.92	6499.9	1.40	0.31
HFI + Environ. + HFI × Environ.	7	−3244.50	6503.0	4.53	0.07
HFI + Environ.	6	−3264.81	6541.6	43.16	0
HFI	5	−3266.81	6543.6	45.15	0
HFI + Synan.	6	−3266.30	6544.6	46.13	0
Null model (random effect only)	4	−3311.46	6630.9	132.45	0
Synan.	5	−3311.44	6632.9	134.42	0

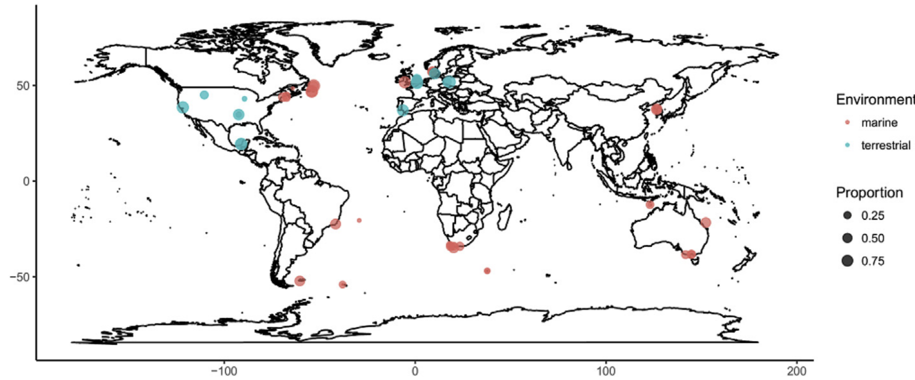

Fig. 1. Map of distribution of studies which reported a proportion of debris incorporation in bird's nests.

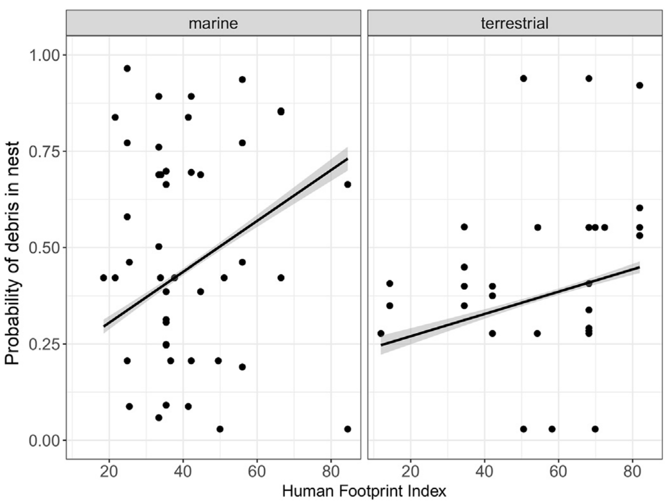

Fig. 2. A relationship between probability of occurrence of debris in bird's nests and the value of Human Footprint Index.

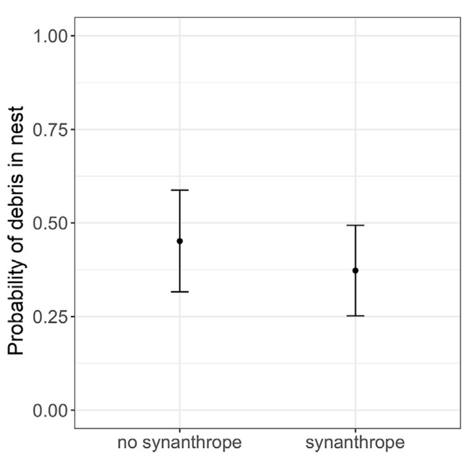

Fig. 3. Differences in probability of debris incorporation in bird's nests between non-synanthropic and synanthropic species.

5.2. Environmental impact

We also found that the probability of the occurrence of debris in bird nests differed significantly between terrestrial and marine ecosystems and between synanthropic and non-synanthropic

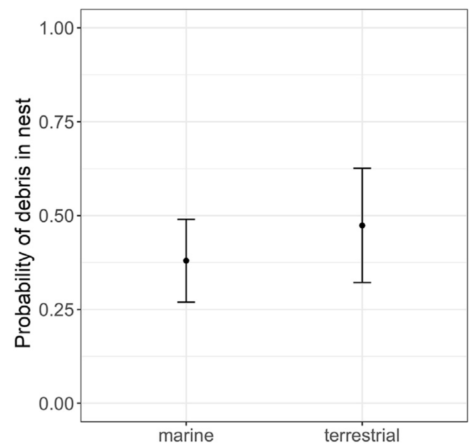

Fig. 4. Differences in probability of debris incorporation in bird's nests between marine and terrestrial species.

species. What is more, we found a significant bias concerning marine and terrestrial studies as well as scientific approaches within these two research groups. Studies of the terrestrial environment have attracted much less attention. Most previous reviews and research papers discussing the effects of waste pollution on wildlife concentrated on plastic pollution in a marine environment (e.g., Votier et al., 2011; Bond et al., 2012; Schuyler et al., 2014, 2016; Gall & Thompson, 2015; Lee et al., 2015; Provencher et al., 2017), as evidenced by the number of scientific papers on this topic. Moreover, the prevalent concerns of these studies were quantitative and qualitative reports of the occurrence of debris in nests of birds (e.g., Votier et al., 2011; Bond et al., 2012; Lee et al., 2015), ingestion (Henry et al., 2011), or general summaries and descriptions of the implications of this phenomenon for nature conservation (Gall & Thompson, 2015; Provencher et al., 2017). Most studies investigating marine debris focus on individuals or local populations, whereas studies from terrestrial environments focus on temporal changes (Antczak et al., 2010; Møller, 2017) and sometimes on spatial analyses (Henry et al., 2011). However, the number of bird species studied under this assumption is insufficient. Our synthesis reported that the probability of the occurrence of debris in the nests of terrestrial birds was significantly higher than in those of marine birds. This is probably because waste is produced on land, where it is spread widely throughout the landscape, whereas in marine ecosystems it forms aggregations (Schuyler et al., 2016). However, evidence of debris in relation to terrestrial wildlife is scarce, which creates a global challenge concerning bias in our knowledge of pollution. Maps of plastic pollution are available for marine environments (Eriksen et al., 2014), but not for terrestrial habitats.

In developed countries, particularly in the Northern Hemisphere, the production of waste is at a high level (Barnes et al., 2009). The majority of studies of the occurrence of debris in nests of terrestrial species have been conducted in North America and Europe, and thus in human-affected environments. However, in reports on nest building or nest composition, quantitative information about debris is seldom included. Moreover, there is a considerable gap in studies of this issue from highly populated areas and biodiversity hotspots, e.g., the Caribbean, the Pacific coast of South America, the Mediterranean Basin, the Caucasus, the Eastern Arc Mountains and Coastal Forests of Tanzania and Kenya, the West African Forests, India, Sri Lanka, and Indo-Burma (cf. Fig. 1 and Cincotta et al., 2000), as well as from densely populated areas where HFI is high. Again, more evidence from various regions of the globe is needed.

HFI covers only continents; marine environments are not immediately impacted by, e.g., land transformation and population density, to name two examples of direct measures used in HFI. However, our results show that marine environments are subject to a lower level of human pressure. Nevertheless, the marine environment is highly polluted with plastic (Eriksen et al., 2014; Schuyler et al., 2016), which demonstrates that marine species also respond to human activities. The map created by Eriksen et al. (2014) showing plastic pollution in the ocean and indicating areas where floating plastic elements accumulate due to sea currents reflects our findings concerning marine birds and their use of debris in nests (Fig. 1). Locations where the proportion of debris materials in the nests of marine birds is higher are associated with points of plastic concentration (Barnes et al., 2009).

In this paper, we found that the nests of non-synanthropic birds were characterized by a higher probability of the presence of debris than those of synanthropic species. Assuming that most of the marine birds discussed in this review are non-synanthropic, and that they live in environments where nesting material is not readily available, we may be observing evidence of the disproportionate attention of researchers to marine over terrestrial birds concerning the issue of debris in nests.

6. Conclusion

In conclusion, the global pattern of debris incorporation in nests by birds reflects human pressure on earth. As plastic pollution increases, its negative consequences and potential ecological risk may continue into the future; therefore monitoring of all interactions between pollution and organisms is necessary. Incorporation of debris in nests by birds has gained some scientific attention, but a gap in our knowledge of drivers, patterns, and long-term effects persists. Moreover, standardized methods to measure such traits are lacking.

Acknowledgements

We are grateful to Marcin Dyderski for critical comments on an earlier version of the manuscript. This paper is a contribution to the project CGL2017-85637-P of the Spanish Ministry of Economy and Competitiveness.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.05.028.

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