CHEMICAL ECOLOGY

Comment on "Marine plastic debris emits a keystone infochemical for olfactory foraging seabirds" by Savoca *et al.*

Gaia Dell'Ariccia,[1]* Richard A. Phillips,[2] Jan A. van Franeker,[3] Nicolas Gaidet,[4,5] Paulo Catry,[6] José P. Granadeiro,[7] Peter G. Ryan,[8] Francesco Bonadonna[1]

In their recent paper, Savoca and collaborators (2016) showed that plastic debris in the ocean may acquire a dimethyl sulfide (DMS) signature from biofouling developing on their surface. According to them, DMS emission may represent an olfactory trap for foraging seabirds, which explains patterns of plastic ingestion among procellariiform seabirds. This hypothesis is appealing, but some of the data that Savoca *et al.* used to support their claim are questionable, resulting in a misclassification of species, as well as other decisions regarding the variables to include in their models. Furthermore, with their focus on a single lifestyle trait (nesting habit) of dubious relevance for explaining plastic ingestion, Savoca *et al.* neglect the opportunity to explore other factors that might provide better ecological insight. Finally, we are deeply concerned by the conservation policy recommendation proposed by Savoca *et al.*—to increase antifouling properties of consumer plastics—which constitutes a substantial environmental risk and delivers the wrong message to decision-makers. The reduction of plastic consumption, waste prevention, and proactive reuse through a circular economy should be at the heart of policy recommendations for future mitigation efforts.

In a recent paper published in *Science Advances*, Savoca and collaborators reported that plastic debris in the ocean may acquire a dimethyl sulfide (DMS) signature from biofouling developing on their surface (*1*). They described DMS as a "keystone infochemical" with wide implications because this volatile compound occurs particularly in productive habitats where there is intensive grazing by phytoplankton feeders and functions as an attractant for some seabirds (for example, some petrels and penguins), which probably use it as a cue to locate foraging patches (*2–5*). Savoca *et al.* (*1*) hypothesized that emission of DMS by biota on plastics may represent an olfactory trap for foraging seabirds and that it explained patterns of plastic ingestion among procellariiform seabirds. They tested this hypothesis by correlating the incidence of ingested plastic with DMS responsiveness in different seabird species, extracting data from the published literature. In addition, because nesting habit (burrow or surface) seems to correlate with DMS responsiveness (*6*), Savoca *et al.* extended their hypothesis to explore whether nest type also could serve as a predictor of plastic ingestion. They concluded the paper with various conservation policy recommendations—including increasing the antifouling properties of consumer plastics—to mitigate impacts of plastic debris on the marine environment.

The hypothesis that DMS emissions may explain plastic ingestion by procellariiform seabirds is appealing, but some of the data that Savoca *et al.* (*1*) used to support their claim are questionable. For several species, the results reported in the original papers on DMS responsiveness differ from those used in their analysis. The authors included three species among the DMS-responders (and non–DMS-responders, later in the text) that have been shown not to respond to DMS [*Pachyptila belcheri*, *Ardenna* (formerly *Puffinus*) *tenuirostris*, and *Ardenna grisea* (*7*, *8*)]. They also make assumptions about the responsiveness of nine other species whose responses to DMS have not been tested: Three prions (*Pachyptila* spp.) were included as DMS-responders, and six other petrels as non–DMS-responders, without any supporting data. The assumption that all prion species respond to DMS appears to be based on two studies that were unable to distinguish between prion species at sea (*2*, *9*); however, Savoca *et al.* (*1*) ignored a subsequent study showing that *P. belcheri* does not react to DMS (*7*). *Pachyptila desolata* is the only prion proven to respond to DMS (*10*). *A. tenuirostris* and *A. grisea* respond to fish oil and ammonia, but the abstract cited to support the claim that these species respond to DMS states, "responses to dimethyl sulphide and pyrazene were much less robust" (*8*), and gives no details on statistical analyses or results. Savoca *et al.* (*1*) also included among the non–DMS-responders several species that respond to other odors linked to foraging, but those, as far as we are aware, have not been tested for DMS [*Macronectes giganteus*, *Macronectes halli*, *Pelecanoides magellani*, *Pelecanoides georgicus*, *Pagodroma nivea*, and *Thalassoica antarctica* (*5*, *7*, *8*, *11*, *12*)]. The reclassification of all these species is likely to change the model results, including the statistical significance of some of the factors being tested. At a more fundamental level, odor responsiveness in procellariiform seabirds is not clear-cut [for a comprehensive review, see the study of Dell'Ariccia *et al.* (*5*)], and the binary classification of Savoca *et al.* (*1*) is an oversimplification of the complex ecology of these species in a heterogeneous marine environment that should have been at least considered in their discussion.

Other decisions by Savoca *et al.* (*1*) regarding the variables in their models are also questionable. To extend their analysis on the relationship with plastic ingestion to those species for which DMS responsiveness is unknown, they established "burrow-nesting habit as a proxy for DMS responsiveness," that is, they postulated that all burrow nesters are

[1]Centre d'Ecologie Fonctionnelle et Evolutive UMR 5175, CNRS - Université de Montpellier - Université Paul-Valéry Montpellier - EPHE - Montpellier, France. [2]British Antarctic Survey, Natural Environment Research Council, Cambridge, UK. [3]Wageningen Marine Research, Den Helder, Netherlands. [4]Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), UMR ASTRE, F-34398 Montpellier, France. [5]CIRAD, UPR GREEN, F-34398 Montpellier, France. [6]Marine and Environmental Sciences Centre, ISPA–Instituto Universitário, Lisbon, Portugal. [7]CESAM–Centro de Estudos do Ambiente e do Mar, Departamento de Biologia Animal, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal. [8]FitzPatrick Institute of African Ornithology, University of Cape Town, Cape Town, South Africa.
*Corresponding author. Email: gaiadellariccia@gmail.com

DMS-responsive and that all surface nesters are not. However, they excluded *Pelecanoides* spp. from the analysis "because diving petrels are burrow-nesting but not DMS-responsive." Using burrow-nesting habit as a proxy for DMS responsiveness relies on the premise that there is a tight and consistent relationship between these two traits. The lack of a consistent pattern, at least for some of the species for which DMS responsiveness has been tested experimentally, questions the validity of this assumption, and the exclusion of species that do not fit the rationale on which the proxy is based is inappropriate. As a consequence, the assertion that burrow nesters ingest plastic more frequently than surface nesters because of the greater behavioral attraction of the former to DMS is highly questionable. From this perspective, other predictors (diet, marine habitat preference, and other foraging characteristics) that have been shown in previous studies to correlate with variation in plastic ingestion rates (*13*) would have been more suitable. The authors justify the exclusion of these factors by the questionable arguments that prey "capture strategy does not align with 'species' among seabirds" and that "DMS tracking is an adaptation for foraging on crustaceans." However, on average, those Procellariiformes with the widest dietary niches ingest around double the amount of plastic than those that feed mainly on crustaceans or fish and almost four times than those that feed on cephalopods (*13*). Fulmarine petrels eat substantial proportions of krill (*14*, *15*) but do not respond to DMS (*8*), whereas *Calonectris borealis* is responsive to DMS (*5*) but hardly ever eats crustaceans (although it often preys on fish that graze on phytoplankton) (*16*). A more parsimonious explanation for the supposedly higher incidence of plastics in the stomach contents of DMS-sensitive species is that small plastic fragments are visually more similar to crustaceans than to other typical prey of seabirds (fish and cephalopods). In addition, all the surface nesters (with one exception) are either albatrosses (Diomedeidae) or in the Fulmarini clade of the Procellariidae, and thus, the comparison of surface and burrow nesters in Savoca *et al.* (*1*) is effectively a phylogenetic comparison between the Diomedeidae-Fulmarini and the other procellariiform seabirds (shearwaters, prions, storm petrels, and other petrels), which show key differences in morphology (and associated foraging and other lifestyle characteristics), as well as in nesting habit. One example of why phylogeny matters is that albatrosses have distinct gut morphologies from storm petrels and other petrels, which affects the propensity to retain ingested plastic (*17*). The incidence of plastic in stomach contents is a balance between the rate of ingestion and the retention period in the digestive tract, yet Savoca *et al.* (*1*) simply equate incidence with ingestion rate. The generalized linear mixed models tested by Savoca *et al.* (*1*) initially included family as a random variable, but this was dropped because of issues of multicollinearity with nesting behavior.

With their undue focus on a lifestyle trait (nesting habit) of dubious relevance for explaining plastic ingestion, Savoca *et al.* (*1*) neglected to explore other factors that might provide better ecological insight. One such potential predictor is body size. Only small to mid-sized procellariiform seabirds (up to the size of *Procellaria* petrels, at about 1300 g) nest in burrows, and small seabirds tend to eat smaller prey items; hence, the likelihood of encountering, and mistakenly ingesting, small plastics of similar size to prey may relate more to bird body mass than nesting habit. The reason why *Fulmarus glacialis*, *Daption capense*, and the two North Pacific albatrosses (*Phoebastria immutabilis* and *Phoebastria nigripes*) were notable exceptions in terms of plastic ingestion rates among the surface-nesting species [see Fig. 4 in the study of Savoca *et al.* (*1*)] would therefore be that the first two are relatively small (and hence frequently feed on small prey) and the last two also commonly eat small

prey—flying fish eggs—that occur in large strings attached to floating objects (*18*).

A second, neglected, predictor is plastic distribution over the oceans, which is not homogeneous and influences the amount of plastic found in seabirds (*17*). For example, the incidence of plastic ingestion in *F. glacialis* shows a strong regional pattern linked to the abundance of litter at sea (*19*). Savoca *et al.* (*1*) divided the oceans into nine study regions, which, based on the short descriptions, seem likely to have overlapping oceanographic and other characteristics (but no details were provided beyond broad geographic categories). However, each species was given a single plastic ingestion value, which was probably averaged across studies conducted over large spatial ranges. Given the limited sample size in terms of number of species, the division of the global ocean into nine regions seems likely to have severely reduced statistical power and would explain why the variable "region" was non-significant in the model. Given the large differences in oceanography and food web structure (and plastic abundance) in different latitudes or water masses, a more meaningful spatial classification might have produced some insights. Savoca *et al.* (*1*) also pooled data on plastic ingestion collected across five decades, further obscuring biologically meaningful patterns among taxa. When compared from the same region and sampling period, the prions provide an informative case study of plastic ingestion, with an inverse relationship between the degree of specialization in filter feeding and the incidence of ingested plastic from *P. belcheri* (no filtering lamellae, 69%) through *P. desolata* (the least specialized of the filtering species, 59%), *Pachyptila salvini* (52%), and *Pachyptila vittata* (the most specialized filter feeder, 30%) (*13*). This strongly suggests that plastic ingestion in this genus is stimulated mainly by visual cues. All petrels show strong color selection in the types of plastics ingested (*13*), irrespective of whether they respond to DMS, again indicating that visual rather than scent cues trigger plastic ingestion. This is in accordance with previous accounts that olfactory cues, such as DMS, may operate on a large scale by alerting seabirds to areas where prey is likely to be found. A change in the olfactory landscape may then trigger a behavioral switch aimed at locating specific prey, which probably involves a combination of visual, olfactory, and other cues (*9*, *20*). Plastics and zooplankton tend to aggregate in much the same places (frontal systems, eddies, and upwellings) as a consequence of ocean currents; hence, foraging seabirds that seek these high prey densities may ingest plastics because of spatial co-occurrence (*13*) rather than a misdirected attraction to a chemical signature.

Finally, we believe that the conservation policy recommendation proposed by Savoca *et al.* (*1*)—to increase antifouling properties of consumer plastics as a way to mitigate the environmental impact of marine plastic debris—constitutes a substantial environmental risk and delivers the wrong message to decision-makers. Biocidal antifouling components in plastics are a serious environmental problem due to their high persistence in the marine environment and their toxicity to nontarget aquatic organisms [for example, (*21*)]. How the scientific community represents an environmental problem can have a profound impact on the design and implementation of a policy response (*22*). Supposedly, evidence-based policy recommendations built on apparent cause-and-effect relationships—such as DMS emissions by marine-seasoned plastic causing plastic ingestion by procellariiform seabirds—can be an appealing prospect for policy-makers trying to mitigate the environmental impact of human actions. However, such recommendations point to particular causes and remediation strategies while obscuring responsibilities for the real root of the problem: the near-systemic inability of human societies to control the release of vast quantities of plastic

pollution into the oceans. The latter is the core issue, not the fact that marine-seasoned plastic is a substrate for DMS-producing biota. The challenge of marine plastic pollution is so profound and complex that a more responsible policy is required at national and global levels. The reduction of plastic consumption, waste prevention, and proactive reuse through a circular economy should be at the heart of policy recommendations for future mitigation efforts. For example, a number of European, African, and Asian countries have adopted legislative measures to ban disposable plastic bags and dishes, and we believe that these are much more appropriate policy responses.

We still have limited knowledge of the role of DMS (and other odors) in attracting seabirds and other marine predators; postulating a binary response is an oversimplification, given natural variation in foraging strategies according to environmental conditions, nutritional status, reproductive constraints, etc., as is the case for most of the biological responses in nature. Certainly, the conclusion that plastic may acquire a DMS signature by Savoca et al. (1) is an important result that may have implications for wildlife, but in our opinion, the question of whether this influences the rate of plastic ingestion requires a more critical reappraisal and interpretation of their results, taking into account other factors likely to influence the incidence of plastic ingestion. We hope that the points made above contribute to an important scientific discussion that should be continued. However, we consider that recommending the addition of antifouling properties to consumer plastics is poorly conceived and potentially harmful if implemented and ignores the fundamental issue for marine conservation: to vastly reduce plastic input into the oceans.

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