An unusual source of essential carotenoids

A yellow-faced vulture includes ungulate faeces in its diet for cosmetic purposes.

The rare Egyptian vulture (*Neophron percnopterus*) stands out among the Old World vultures (Family *Accipitridae*) because of its brightly ornamented head[1], which is coloured yellow by carotenoid pigments, and its practice of feeding on faeces. Here we show that Egyptian vultures obtain these pigments from the excrement of ungulates. To our knowledge, this is the first demonstration that faeces can be used as a source of carotenoids by a vertebrate.

Coprophagy is uncommon in birds, apart from the consumption of nestlings' faeces by parents in songbird species[2]. The consumption of faeces is likely to be dangerous because they frequently contain high levels of parasites[3]. In addition, excrement is a poor source of the principal macronutrients (containing less than 5% protein and under 0.5% fat, according to our analyses). However, the faeces of ungulates contain large amounts of intact carotenoids (see below), which have a pigmentary function[4] and are also considered to be valuable micronutrients for vertebrates because of their antioxidant and immunostimulant properties[5]. Vertebrates are unable to synthesize essential carotenoids and must therefore obtain them by dietary means[4].

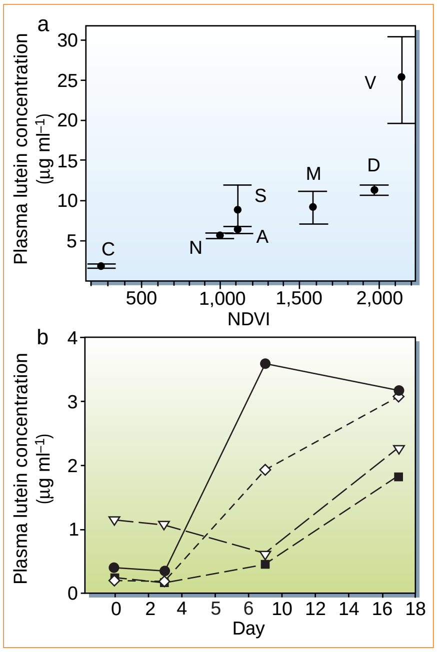

Figure 2 Plasma lutein concentrations in Egyptian vultures (*Neophron percnopterus*). **a,** Mean concentrations of lutein ± s.e.m. in the plasma of wild Egyptian vultures. Sampling areas (all in Spain; sample sizes in parentheses): C, Canary Islands (22); N, Navarra (72); A, Aragón (77); S, Segovia (4); M, Menorca (4); D, Andalucía (11); V, Vizcaya (6). Lutein concentrations were measured by spectrophotometry[12]. The mean lutein concentration in each population correlates with the local values of a vegetation index (NDVI), which is an indicator of photosynthetic production[13] ($r = 0.93$, $P < 0.01$, $n = 7$). **b,** Plasma lutein concentration (μg ml^{-1}) of four captive adult Egyptian vultures measured by high-performance liquid chromatography[6]. Before day 0, the birds were fed on cow meat. On days 0–9, they had access to cow dung only. From day 9 onwards, the birds were returned to the meat diet and no dung was available. Plasma lutein concentrations increased significantly over this time (repeated-measures ANOVA, $F_{3,9} = 4.799$, $P = 0.0298$).

Rotten flesh and bones, the typical diet of vultures, are poor sources of carotenoids. *N. percnopterus* may obtain these pigments from egg yolks or from insects, such as grasshoppers[1]. The excrement of ungulates, however, is the most readily available and reliable source of carotenoids in areas covered by *N. percnopterus*. These vultures are often seen pecking at cow dung and eating the droppings of goats and sheep.

We used high-performance liquid chromatography[6] to analyse the carotenoid content of ungulate faeces and to identify the carotenoids that are transported in the plasma and deposited in the yellow facial skin of *N. percnopterus* (Fig. 1). A single peak for lutein (which co-eluted with small quantities of zeaxanthin) was observed in all samples, accounting for over 95% of the total main carotenoid content. Lutein concentration in vulture skin (sampled from a freshly dead adult bird found in the wild) was 98 μg g^{-1}, and a mean concentration of 6.5 μg ml^{-1} was found in plasma (0.3–42.1 μg ml^{-1}, $n = 196$). Mean lutein concentrations in faeces were 35.7 μg g^{-1} in cow dung, 185.8 μg g^{-1} in sheep droppings, and 36.6 μg g^{-1} in goat droppings (two samples were analysed from each species of ungulate).

Additional evidence, albeit indirect, to support our idea that Egyptian vultures obtain carotenoids from faeces is provided by the fact that higher plasma carotenoid concentrations were evident in individual birds from areas with greener pastures, where free-grazing cattle are more abundant (Fig. 2a).

We confirmed that *N. percnopterus* obtains carotenoids from cow dung by conducting a food trial on four adult birds at Jerez Zoo, Spain. These birds had been fed a cow-meat diet for several months and only had traces of lutein (less than 1 μg ml^{-1}) in their plasma when the trial began. They were fed exclusively on an unlimited diet of fresh cow dung for 10 days, of which they consumed about 1.3 kg in total. All four birds showed significantly higher plasma lutein levels at the end of this trial than at the beginning (Fig. 2b).

The cow dung used in the food trial contained 4% semi-decomposed protein (determined using the Kjeldahl method[7]) and 0.38% fat (determined using the Soxhlet method[7]), and is therefore a poor source of major nutrients. However, the high concentrations of carotenoids in cow dung mean that the adoption of a coprophagous habit by *N. percnopterus* ensures the intake of an excess of dietary carotenoids, well above the levels needed for healthy physiological function.

Figure 1 The Egyptian vulture has earned the nickname in Spain of '*churretero*' or '*moñiguero*', meaning 'dung-eater'.

This excessive consumption of pigment suggests a possible evolutionary mechanism for the development of carotenoid-dependent ornaments in *N. percnopterus*. Surplus carotenoids would diffuse passively to the skin[8] and the resulting yellow coloration could have become a useful signal in mating displays[9], for advertising dominant status[10], or both.

For the signal to be reliable, however, it must be associated with costs that can only be met by high-quality individuals[11]. One potential cost of eating excrement is that it may expose the consumer to gastrointestinal parasites[3]; another is the time and effort involved in searching for food with negligible nutritional content.

J. J. Negro*, J. M. Grande*, J. L. Tella*,
J. Garrido†, D. Hornero†, J. A. Donázar*,
J. A. Sanchez-Zapata‡, J. R. Benítez§,
M. Barcell§
**Department of Applied Biology, Estación Biológica de Doñana, CSIC, Pabellón del Perú, Avda María Luisa, s/n 41013 Seville, Spain*
e-mail: negro@ebd.csic.es
†Food Biotechnology Department, Instituto de la Grasa, CSIC, Avda Padre García Tejero 4, 41012 Seville, Spain
‡Area de Ecología, Departamento de Biología Aplicada, Universidad Miguel Hernández, 03312 Alicante, Spain

§Zoo de Jerez, Taxdirt s/n 11404 Jerez de la Frontera, Spain

1. Mundy, P., Butchart, D., Ledger, J. & Piper, S. *The Vultures of Africa* (Academic, London, 1992).
2. Hurd, P. L., Weatherhead, P. J. & McRae, S. B. *Behav. Ecol.* **2,** 69–76 (1991).
3. Hutchings, M. R., Gordon, I. J., Kyriazakis, I. & Jackson, F. *Anim. Behav.* **62,** 955–964 (2001).
4. Brush, A. H. *FASEB J.* **4,** 2969–2977 (1990).
5. Britton, G. *FASEB J.* **9,** 1551–1558 (1995).
6. Mínguez-Mosquera, M. I. & Hornero-Méndez, D. *J. Agric. Food Chem.* **41,** 1616–1620 (1993).
7. Vogel, A. I. *Elementary Practical Organic Chemistry* (Logmans, Green & Co., London, 1957).
8. Negro, J. J., Tella, J. L., Blanco, G., Forero, M. G. & Garrido-Fernández, J. *Physiol. Biochem. Zool.* **73,** 97–101 (2000).
9. Hill, G. E. *Nature* **350,** 337–339 (1991).
10. Rohwer, S. A. *Evolution* **29,** 593–610 (1975).
11. Zahavi, A. & Zahavi, A. *The Handicap Principle* (Oxford Univ. Press, Oxford, 1997).
12. Tella, J. L. *et al. Physiol. Zool.* **71,** 708–711 (1998).
13. Díaz-Delgado, R. & Pons, X. *Forest Ecol. Manag.* **147,** 67–74 (2001).

Competing financial interests: declared none.

Biodiversity

Invasions by marine life on plastic debris

Colonization by alien species poses one of the greatest threats to global biodiversity[1]. Here I investigate the colonization by marine organisms of drift debris deposited on the shores of 30 remote islands from the Arctic to the Antarctic (across all oceans) and find that human litter more than doubles the rafting opportunities for biota, particularly at high latitudes. Although the poles may be protected from invasion by freezing sea surface temperatures, these may be under threat as the fastest-warming areas anywhere[2] are at these latitudes.

Like humans, marine organisms are now experiencing unparalleled availability, distribution and duration of transport. Floating debris is the most common seagoing transport system[3–5] and is responsible for the widespread distribution of many marine animals that use it to hitch a ride. Natural debris such as volcanic rock, or pumice, and wood have always carried organism propagules. But there has recently been an explosive increase in anthropogenic debris as a result of massive amounts of plastic entering the oceans — for example, the amount of debris doubled from 1994 to 1998 around the coastline of the United Kingdom[6], and in parts of the Southern Ocean it increased 100-fold during the early 1990s[7].

I examined about 200 items of debris washed ashore on each of 30 islands (Fig. 1), which were scattered over a geographical range extending from Spitsbergen in the Arctic to Signy Island in the Antarctic. I found that 20–80% of this debris was anthropogenic (man-made) in origin (Fig. 2a), of which the highest proportion was in the Southern Ocean (as land there has no forests, there is scarcely any local natural debris). There was generally less anthropogenic debris at low latitudes in the Southern Hemisphere than at equivalent northern latitudes, presumably because there are fewer people there and more ocean.

Many types of animal use marine debris as a mobile home, particularly bryozoans, barnacles, polychaete worms, hydroids and molluscs (in order of abundance), and I found that among the most numerous were animals with cosmopolitan distributions. The successful natural dispersal of species with longer-lived planktonic larvae, such as the bryozoan *Membranipora*, is unsurprising, but most of the other colonizing animals, such as the hydroid *Halecium*, have brooded or brief-duration larvae and no obvious means of dispersal. Oceanic debris therefore offers a major opportunity for dispersal of such species.

Another opportunity for invasion of new habitats by alien organisms is presented by their adherence to ships' hulls. Compared with boats, however, man-made debris is longer lasting, more pervasive and travels more slowly, factors that could favour the survival of colonists.

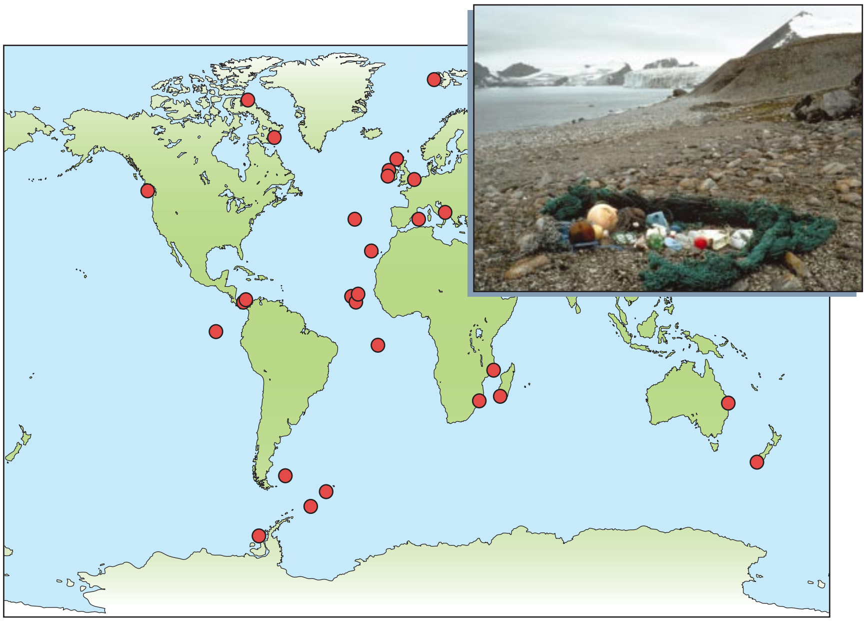

Figure 1 A global picture of shore debris. Dots show the locations of the sampling sites. Inset, typical examples of raft debris washed ashore. The movement of such debris has increased the propagation of colonizing fauna, threatening biodiversity in many regions.

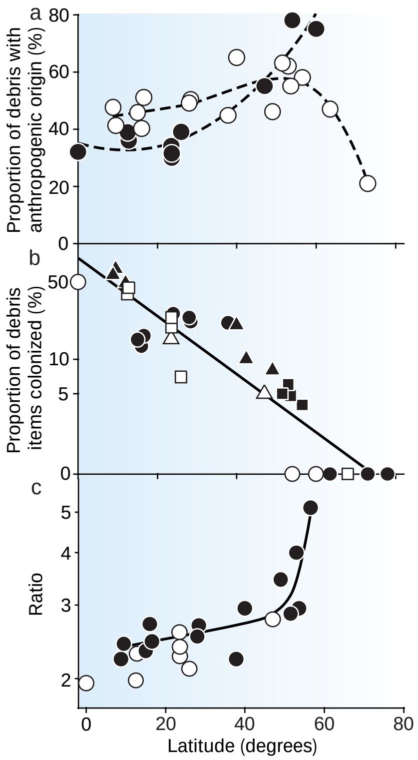

Figure 2 Colonization of man-made and natural debris by marine organisms at different latitudes. **a,** Proportion of man-made debris found offshore at 30 remote islands (Fig. 1); debris is classed as either anthropogenic (mainly plastic) or natural (mostly wood, but not lumber); $n \approx 200$ for each point. Open symbols, islands in the Northern Hemisphere; filled symbols, islands in the Southern Hemisphere. **b,** Variation with latitude, hemisphere and remoteness of island shorelines in the proportion of marine debris of each type that was colonized by fauna. Symbols represent the distance of each island from the continental mainland: circles, hundreds of kilometres; triangles, tens of kilometres; squares, less than 10 km. Fitted regression line has associated $r^2 = 72.7$, and significance by ANOVA: $F = 85$, $P \leqslant 0.001$. **c,** Variation with latitude and hemisphere in the ratio of propagules on non-anthropogenic to those on anthropogenic debris on island shores. Data are calculated from the proportional colonization by different types of debris shown in **a** at the latitudes given in **b**. The best-fit curve is exponential and has associated $r^2 = 0.74$ and significance by ANOVA: d.f. $= 4$, $F = 10.25$, $P = 0.002$.