

the British Veterinary Zoological Society and Bat Conservation International.

Acknowledgments to Tony Sainsbury, Michael Waters, Marcus Fritze and sample contributors for their practical assistance, and to Eric Petit and Serena Dool for comments.

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# Opportunities and costs for preventing vertebrate extinctions

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Despite an increase in policy and management responses to the global biodiversity crisis, implementation of the 20 Aichi Biodiversity Targets still shows insufficient progress [1]. These targets, strategic goals defined by the United Nations Convention on Biological Diversity (CBD), address major causes of biodiversity loss in part by establishing protected areas (Target 11) and preventing species extinctions (Target 12). To achieve this, increased interventions will be required for a large number of sites and species. The Alliance for Zero Extinction (AZE) [2], a consortium of conservation-oriented organisations that aims to protect Critically Endangered and Endangered species restricted to single sites, has identified 920 species of mammals, birds, amphibians, reptiles, conifers and reef-building corals in 588 ‘trigger’ sites [3]. These are arguably the most irreplaceable category of important biodiversity conservation sites. Protected area coverage of AZE sites is a key indicator of progress towards Target 11 [1]. Moreover, effective conservation of AZE sites is essential to achieve Target 12, as the loss of any of these sites would certainly result in the global extinction of at least one species [2]. However, averting human-induced species extinctions within AZE sites requires enhanced planning tools to increase the chances of success [3]. Here, we assess the potential for ensuring the long-term conservation of AZE vertebrate species (157 mammals, 165 birds, 17 reptiles and 502 amphibians) by calculating a conservation opportunity index (COI) for each species. The COI encompasses a set of measurable indicators that quantify the possibility of achieving successful

conservation of a species in its natural habitat (COI<sub>n</sub>) and by establishing insurance populations in zoos (COI<sub>c</sub>).

COI<sub>n</sub> considered costs of land acquisition and management in the species’ range country [4], likelihood of political instability and/or politically motivated violence (including terrorism) affecting conservation operations on the ground, as well as the latent impact of urban expansion on the species’ natural habitat (Supplemental information). Global distribution of the COI<sub>n</sub> for all AZE vertebrates is shown in Figure S1 (Supplemental information). COI<sub>c</sub> included costs of managing a zoo population of at least 500 individuals of a species [5], together with a measure of breeding expertise available for AZE vertebrates in zoos in the International Species Information System [6] or, for amphibians, bred in Amphibian Ark programs [7]. Although reintroduction costs are also important to consider, we did not include these because of a lack of adequate data.

Conservation opportunities for AZE vertebrates in their natural habitat were high, given that ~39% of species had high COI<sub>n</sub> (maximum = 10) values (Figure 1A). Mean (± SD) COI<sub>n</sub> for all species was 6.22 ± 1.80 (reptiles (6.89 ± 1.64), mammals (6.46 ± 1.79), amphibians (6.19 ± 1.70) and birds (6.03 ± 2.07)). Opportunities for management in zoos were low for all taxonomic groups (Figure 1A). Mean COI<sub>c</sub> for all species was 2.79 ± 2.88 (maximum = 10) (reptiles (7.06 ± 4.70), birds (3.03 ± 3.01), amphibians (2.69 ± 2.72) and mammals (2.39 ± 2.64)). Overall, 15 species had a high COI<sub>n</sub> and COI<sub>c</sub>, and another 15 a low COI<sub>n</sub> and COI<sub>c</sub>.

Total annual costs for effectively managing all AZE vertebrates in their natural habitat were US\$ 1.18 billion (Supplemental information). AZE site costs (per species and year) were lowest for reptiles (US\$0.59 ± 0.65 × 10<sup>6</sup>), followed by mammals (US\$0.95 ± 1.52 × 10<sup>6</sup>), amphibians (US\$1.20 ± 1.91 × 10<sup>6</sup>) and birds (US\$2.53 ± 4.74 × 10<sup>6</sup>). These differences were largely due to variations in total annual costs of managing existing protected areas in the more expensive developed countries than in developing nations [4]. By region, estimated AZE site costs were highest for South America and lowest for northern Africa (Figure 1B). Total annual costs for effectively managing all AZE vertebrates in zoos were US\$0.16 billion (Supplemental

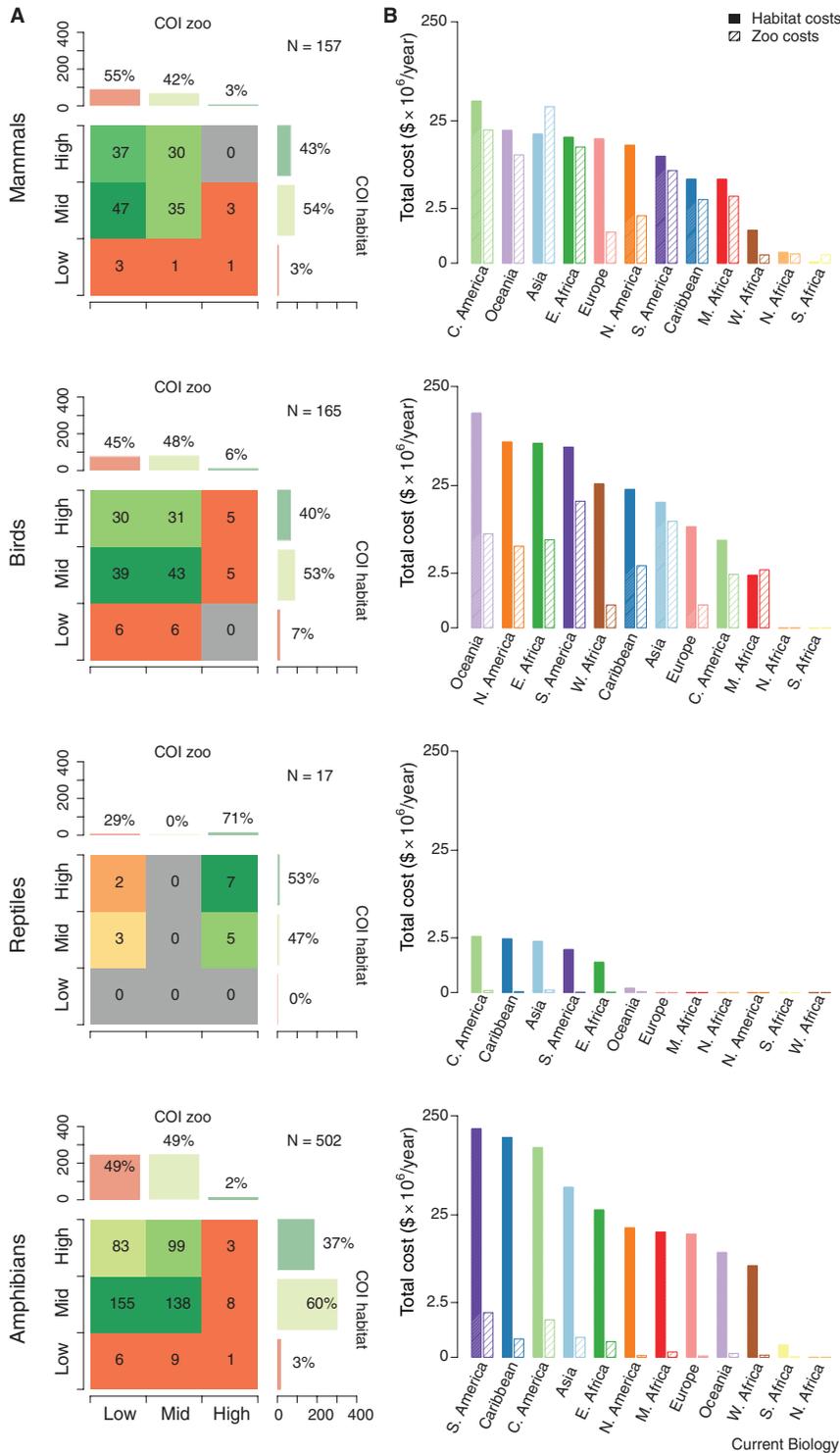


Figure 1. Conservation opportunity index (COI) and costs for protecting mammals, birds, reptiles and amphibians included in the Alliance for Zero Extinction (AZE). (A) Number of species with a low ( $0 < \text{COI} \leq 3.33$ ), medium ( $3.33 < \text{COI} \leq 6.67$ ) or high ( $6.67 < \text{COI} \leq 10$ ) COI in zoos ( $\text{COI}_z$ , horizontal barplot) and in their natural habitat ( $\text{COI}_h$ , vertical barplot). (B) Total annual costs for conserving species in their natural habitat and in zoos per region.

information). Costs (per species and year) were lowest for amphibians and reptiles ( $\text{US}\$0.01 \pm 0.00 \times 10^6$ ), followed by birds ( $\text{US}\$0.35 \pm 0.01 \times 10^6$ ) and mammals ( $\text{US}\$0.62 \pm 0.94 \times 10^6$ ).

Although conservation success is more likely to be achieved through the protection of the species' natural habitat, safeguarding species in zoos should be considered as a

complementary action. This is especially crucial for many AZE amphibians, since any neglect of investment in insurance zoo populations will likely be insufficient to protect many species from the major driver of amphibian declines worldwide – the fungal disease chytridiomycosis [7]. Hence, dedicated resources on a global scale must be made available in zoological and other institutions for developing expertise to breed threatened species and for emergency response to population declines. However, even if conservation opportunities are high for a species, as we show, a lack of timely action will result in failure. A salient example of this is the Christmas Island pipistrelle (*Pipistrellus murrayi*), an AZE bat species, which despite possessing one of the highest  $\text{COI}_h$  (9.5) and a  $\text{COI}_z$  of 5.0 became extinct [8]. Successes are nonetheless possible, as exemplified by AZE species such as the Mauritius kestrel (*Falco punctatus*), whooping crane (*Grus americana*), pygmy hog (*Porcula salvania*) and ploughshare tortoise (*Astrochelys yniphora*) [5].

We estimated that for protecting AZE vertebrates around  $\text{US}\$1.3$  million per species is required, a figure that compares well with McCarthy *et al.*'s [9] modeled median annual costs per species ( $\text{US}\$0.85$  million, range:  $\text{US}\$0.04$ – $8.96$  million) to achieve downlisting within 10 years. Such investment for protecting high-biodiversity value sites and threatened species within them is trivial when compared to what governments spend globally each year on other sectors.

There is probably time to protect a large number of AZE vertebrates from extinction. However, at least 15 AZE species are in imminent danger given their low COI. Innovative strategies, such as the One Plan approach [10], which combines conservation actions inside and outside a species' natural habitat, must be rapidly implemented. Worryingly, however, with less than five years to 2020 to achieve significant protection of these 'worst-off' species, conservation opportunity evaluations like ours need to be adopted and used rapidly to help achieve immediate conservation benefits.

#### Supplemental Information

Supplemental information including experimental procedures, one figure, three tables, and acknowledgements can be

found with this article online at <http://dx.doi.org/10.1016/j.cub.2015.01.048>.

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# Coupled computations of three-dimensional shape and material

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Retinal image structure arises from the interaction between a surface’s three-dimensional shape, its reflectance and transmittance properties, and the surrounding light field. Any local image structure can be generated by an infinite number of different combinations of surface properties, which suggests that the visual system must somehow constrain the possible scene interpretations. The research on this has searched for such constraints in statistical regularities of two-dimensional image structure [1,2]. Here, we present a new class of displays in which the perception of material properties cannot be explained with two-dimensional image properties. The displays manipulate the perceived three-dimensional shape of identical luminance gratings, and demonstrate that perceived three-dimensional shape can alter perceived surface reflectance.

The material properties of a surface physically constrain the rate that luminance varies with its three-dimensional surface orientation. For simplicity, we restrict attention to singly-curved surfaces, which project luminance gradients that only vary along the direction of the surface curves. The steepness of the luminance gradients depends on the surface’s three-dimensional shape, surrounding light field, and reflectance function. The left side of Figure 1A depicts a matte (Lambertian) surface that projects a luminance gradient that varies as a cosine of the angle between the surface normal and the direction of the incident illumination. The steepness of luminance gradients generated by a specular surface depends on a surface roughness parameter, which modulates the ‘spread’ of the specular lobe. For a fixed surface geometry and moderate amounts of surface roughness, specular surfaces will typically generate steeper luminance gradients than Lambertian surfaces (Figure 1A).

Thus, for a fixed surface geometry, the rate that luminance varies as a function of local three-dimensional

surface orientation could potentially provide information about a surface’s material properties. However, identical luminance gradients can sometimes be generated by surfaces with different reflectance functions if three-dimensional shape and the light field are chosen appropriately. For example, a matte surface can generate the same gradient as the specular surface in Figure 1A if its three-dimensional surface orientation varies more rapidly than the specular surface. If the visual system exploits constraints imposed by three-dimensional shape to derive material properties, then it should be possible for an identical luminance gradient to appear as either a matte or specular material by simply changing the perceived three-dimensional shape. Previous work has suggested that specular reflectance can be derived directly from the two-dimensional images, which implies that the perception of specularity could be derived prior to any explicit representation of three-dimensional structure [1–7].

To assess whether the visual system exploits three-dimensional geometric constraints to derive material properties, we exploited previous work which showed that perceived three-dimensional shape [8–10] and illumination direction [8,10] can be altered by manipulating the shape of bounding contours. Figure 1B depicts a pair of identical luminance gratings. The only physical difference between the left and right images is the shape of the bounding contours that flank the grating along its left and right sides. The shape information provided by the contours transforms the perceived three-dimensional shape and the illumination direction of the two surfaces, as has been shown previously [8–10]. Note, however, that there is also a clear change in perceived material properties of the two surfaces: the left image appears matte, whereas the right image appears metallic.

To experimentally document these percepts, observers selected the surface that appeared more metallic from a pair of images. We tested all possible combinations of the two three-dimensional shapes with six different luminance gradients parametrically varying in steepness (see Figure S1 in the Supplemental Information). Figure 1B plots the proportion of times that each three-dimensional shape appeared more specular than the comparison