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Indexing the health of the environment for breeding seabirds in the Benguela ecosystem

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Time-series of the sizes of breeding populations of 10 species of seabird were used to develop indices of the health of the Western Cape seabird community of South Africa. For each species, a target range was defined running from some minimum value to infinity or to some maximum value for species that may cause harm to other species or be a nuisance to humans. If populations were within the target range, their individual health index was set at 1, whereas outside the range, this index decreased linearly with population size. These individual indices were integrated into one for the total community, also running from 0 to 1 and therefore allowing representation as a percentage of the overall management target (=1). Three indices were developed, weighting each species equally and using different weighting methods to account for the IUCN conservation status of the species. All indices increased between the 1950s and 1970s and then decreased again, the lowest values being observed in the late 1990s.

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Introduction

South Africa's Marine Living Resources Act No. 18 of 1998 (Government Gazette 395:18930 of 27 May 1998) includes objectives to conserve marine living resources and to maintain a sound ecological balance. Currently, there is no quantitative mechanism in place to measure the extent to which these objectives of the Act are being attained. Time-series of data exist for many individual marine species covered by the Act, but as yet, no attempt has been made to generate a composite time-series, or index, from these. One of the best sets of individual time-series relates to numbers of breeding seabirds, and we show how these data can be assembled into a composite index, which measures the extent to which the objectives of conserving and maintaining the ecological balance of the seabird component of marine living resources are attained. The data refer to 10 species breeding along the coast of South Africa, mainly in the Benguela ecosystem, from 1956 to 1999.

More generally, our aim is to provide the foundation of a method for computing environmental indices that incorporate the concepts of sustainable utilization and ecological conservation. The method develops concepts presented by Bibby (1999), modified to meet the specific application context, and uses a target range of population sizes for all species included in the index. Once the minimum of the target range is reached, further increases in population size do not alter the index, unless the species is one for which, on the grounds of becoming a pest or negatively impacting other species, a maximum population size also has been set. For these species, the index decreases if population sizes exceed the upper limit. If population sizes for all species included are above the minimum, and those for potential pest species are below the maximum, the index takes on its maximum value of 100. Thus, the proposed index can readily be evaluated as a percentage, and has a simple interpretation. The basic approach can be easily adapted to other situations.

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Motivation, methods, and material

Our approach to computing an index based on population sizes of breeding seabirds differs from familiar financial indices by having an upper limit, which for convenience of interpretation, we have set at 100. Financial indices are designed to increase as each component of the index increases. For example, a stock market index is a weighted average of the prices of the shares that make up the index, and behaves in such a way that an increase in the price of any share leads to an increase in the overall index.

An example is used to illustrate the motivation for setting an upper limit. The population of the dark-bellied brent goose (*Branta bernicla bernicla*) in western Europe decreased from several hundred thousand birds in the 1930s to fewer than 16 500 birds in 1955 (Madsen *et al.*, 1999). The decrease was due to a wasting disease that decimated vast beds of its food plant, eelgrass (*Zostera* spp.), and to hunting. It was at that time one of the rarest geese in Europe, and was afforded strict protection. Since then, population size has increased steadily, and by the late 1990s, the population had grown to 300 000 birds. Because the quantity of food on the intertidal saltmarshes had become inadequate, the burgeoning population crossed the sea walls and started to graze pastures and winter cereals, leading to reduced agricultural productivity. In less than 40 years, the status of the brent goose shifted from being in danger of extinction towards becoming a pest (Madsen *et al.*, 1999). If numbers were to increase further, the species at some stage would almost certainly become a serious problem to agriculture. Intuitively, increases in numbers of brent geese beyond some level should be reflected in a decrease in the environmental index, rather than an increase.

Among the species considered here, Hartlaub's gull (*Larus hartlaubii*) has a rank of about 10 among the rarest of the world's 51 gull species, with almost the entire population living within the Benguela ecosystem, and the subspecies of the kelp gull (*Larus dominicanus vetula*) is endemic to southern Africa (Wetlands International, 2002). The conservation of these taxa and the maintenance of viable populations are regional responsibilities. Both species are thought to have increased in abundance during the twentieth century in response to additional food having been made available at refuse dumps, abattoirs, and from fishing activities (Hockey *et al.*, 1989). However, recent evidence indicates that numbers of Hartlaub's gulls decreased in the 1990s (Crawford and Underhill, 2003). They have proved a nuisance in urban areas, through noise and soiling, and pose a threat to aircraft near airports through collisions (Williams *et al.*, 1990). Kelp gulls breeding at offshore islands pose a threat to other seabirds sharing the islands, because they steal eggs and small chicks, including some with IUCN (The World Conservation Union) listing as threatened (Du Toit *et al.*, 2003). For both species, it is clearly undesirable that unlimited increases in their population sizes should be reflected in increases in the index of health of the seabird community. Therefore, sensible conservation management should define a target range between minimum and maximum population sizes.

The environmental health index we wish to design needs to have a property that causes it to reach its maximum value (100%) when all species included are within their target intervals. When all species are extinct, the index must be zero. With such a design, the index is readily interpreted as a percentage, a "mark" out of 100%, a familiar concept to most: high values close to 100% indicate satisfaction with environmental conditions, low values dissatisfaction.

This requires a mathematical function for each species that is zero when population size is zero and that reaches a maximum value when the population is within the target range, which, without loss of mathematical generality, may be taken as one. For species for which maximum values have also been defined, the transformation function needs to decrease to zero once the maximum has been exceeded. In the prototype index developed here, we make use of simple functions consisting of series of straight lines (Figure 1), acknowledging that more complex functions are possible, but would need justification.

Reliable data for breeding population sizes of seabirds in the Benguela ecosystem are available from the 1950s onwards (Table 1), largely attributable to the foresight of Rand (1963), who undertook extensive surveys in the earlier years. Threat categories were taken from Barnes (2000) and Du Toit *et al.* (2003).

In financial indices, each component is given a weighting factor. For example, in stock exchange indices, it is a common practice to weight each share in proportion to the total value of all shares in the company at some point of time. Likewise, each species needs to be given a weight in calculating environmental health indices. We consider three choices here. The simplest approach is to give all species equal weight. A more sophisticated approach is to have weights depending on IUCN threat categories. We use two

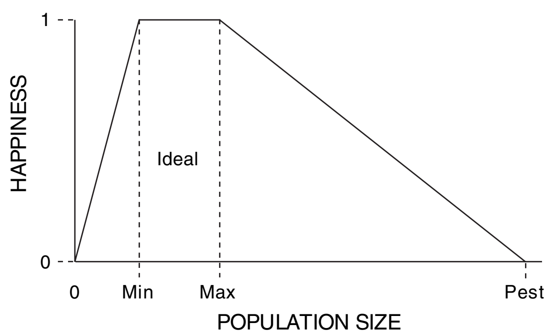

Figure 1. The mathematical function used to transform observed population sizes into a contribution to the index, making use of minimum and maximum target populations.

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Table 1. IUCN threat categories (En: endangered; Vu: vulnerable; Nt: near-threatened; Lc: least concern), population sizes (1950–1999; Cape gannets in hectares occupied; others in pairs breeding; information from sources summarized in Hockey *et al.*, in press), and provisional target range (∞ = no upper limit) of 10 species of seabirds in South Africa (AFP, African penguin; CAG, Cape gannet; CAC, Cape cormorant; BAC, bank cormorant; CRC, crowned cormorant; WBC, white-breasted cormorant; GWP, great white pelican; KEG, kelp gull; HAG, Hartlaub's gull; SWT, swift tern).

	Species									
	AFP ('000)	CAG	CAC ('000)	BAC	CRC	WBC	GWP	KEG	HAG	SWT
	IUCN category									
	En	Vu	Nt	En	Nt	Lc	Nt	Lc	Lc	Lc
Population size by period										
1950s	197	1.96	77	410	1 088	391	26	6 000	6 000	5 000
1960s	190	2.32	90	500	1 025	354	136	6 486	6 400	4 800
1970s	183	2.67	103	593	967	317	246	6 486	6 803	4 700
1980–1984	175	3.07	100	638	953	288	256	7 270	6 880	4 610
1985–1989	168	3.96	96	682	938	259	265	8 063	6 941	4 414
1990–1994	152	3.93	90	686	1 314	204	504	12 006	3 782	4 654
1995–1999	99	4.59	30	386	1 413	261	508	15 170	4 352	4 656
Population target range										
Minimum	200	2.0	100	1 200	1 500	300	100	6 000	6 000	6 000
Maximum	∞	∞	∞	∞	∞	∞	1 000	16 000	16 000	∞

sets of weights for threat categories: set 1 has weight 1 for species of "Least concern", 2 for "Near-threatened", 3 for "Vulnerable", 4 for "Endangered"; set 2 has these values squared, i.e. 1, 4, 9, and 16, respectively. With the weighted indices, species in higher threat categories have greater impact on the values; in set 2 this effect is exaggerated to the extent that an "Endangered" species is regarded as 16 times more important than a species of "Least concern". These weights would need to be modified in line with changes to threat categories each time they are reviewed. Other sets of weights could be based on taxonomic uniqueness, endemism, or on the importance of the role the different species play in the ecosystem.

The index is generated by computing the value of the transformation function for the population size of each species (range 0–1). Each value is then multiplied by the given species-specific weight. The resulting values are added, and the sum is divided by the sum of the weights to bring the value back into the interval 0–1, then multiplied by 100 to express it as a percentage (Table 2).

Careful thought needs to be given to establishing the minimum and, where applicable, maximum target levels of populations. In general, if a species is classified as threatened in terms of IUCN criteria, its population should be below the minimum target. For African penguins (*Spheniscus demersus*), stochastic modelling and empirical information on decreases in colonies were used to estimate the minimum viable population for the species (Crawford *et al.*, 2001). As this population had a 10% risk of extinction within 100 years (Crawford, 2004), it was considered that the minimum target population should be about four times greater. For swift terns (*Sterna bergii*), the minimum target population was taken to be the present level of abundance based on the small population size, for which a decrease would lead to a classification of Vulnerable in terms of IUCN criteria (Crawford, 2004). For other species, minimum target levels were not rigorously estimated but, for the purposes of this paper, were based on previous levels of abundance and information on loss of colonies (Crawford *et al.*, 1999).

Table 2. Schema for the calculation of the seabird index. For each species, the transformation value (TV) is given by the population size (PS; here during the 1950s) divided by the minimum of the target range (with maximum 1). The index is given by the sum of products of TV and the weight factor (W; here set at 2), divided by the sum of W, (40.9/57) × 100 = 71.8%. Species abbreviations as in Table 1.

Parameter	AFP	CAG	CAC	BAC	CRC	WBC	GWP	KEG	HAG	SWT	Sum
PS	197	1.96	77	410	1 088	391	26	6 000	6 000	5 000	
TV	0.99	0.98	0.77	0.34	0.73	1.00	0.26	1.00	1.00	0.83	
W	16	9	4	16	4	1	4	1	1	1	57
Product	15.8	8.8	3.1	5.5	2.9	1.0	1.0	1.0	1.0	0.8	40.9

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Maximum target populations also were not rigorously determined. For the kelp gull, they were based on levels at which these species might be expected, from past observation, to inflict substantial mortality on less numerous seabirds. For Hartlaub's gull, the maximum target was based on a level at which substantial urban breeding might be expected.

The great white pelican (*Pelecanus onocrotalus*) in South Africa appears to be becoming the analogue of the dark-bellied brent goose in western Europe. During the first half of the twentieth century, the pelican was regarded as an undesirable species on the guano islands of the Western Cape. Its breeding population was subjected to considerable disturbance, moved between islands, and was reduced to 20–30 breeding pairs when it settled to breed on Dassen Island in the 1950s (Crawford *et al.*, 1995). Within 50 years, the population increased 20-fold, and is becoming a conservation problem. Groups of pelicans consumed almost the entire annual offspring of Cape cormorants (*Phalacrocorax capensis*) and kelp gulls at Dassen Island for several years (Crawford *et al.*, 1997; Hockey *et al.*, in press) and recently have also eaten chicks of swift terns at Dassen Island. There is indication that pelicans are moving to other islands to feed on chicks of other species (Hockey *et al.*, in press). However, the present population in the Western Cape breeds at just one locality and hence remains susceptible to catastrophic factors such as disease.

Results

Individual species displayed widely contrasting trends in breeding population sizes during the five decades 1950s–1990s (Table 1). The most pronounced relative change was for great white pelicans. The number of breeding pairs was well below the minimum population target of 100 pairs in the 1950s, but has grown steadily since then to approximately the midpoint of the suggested target range. The species showing the largest decrease was the African penguin, the number of breeding pairs approximately halving. The area of breeding Cape gannets (*Morus capensis*) more than doubled, as did the number of breeding pairs of kelp gulls. Cape cormorants and bank cormorants (*P. neglectus*) showed increases followed by decreases. For the remaining four species, white-breasted cormorants (*P. carbo lucidus*), crowned cormorants (*P. coronatus*), Hartlaub's gulls, and swift terns, the numbers of breeding pairs remained relatively stable.

Overall, the unweighted and the two weighted indices all showed trends that first increased and subsequently decreased (Figure 2). All three indices peaked during the 1970s, and decreased sharply during the last period (1995–1999). The final value of the unweighted index was 5% less than its initial value, whereas those for weight sets 1 and 2 were 7% and 12% less, respectively (Figure 2).

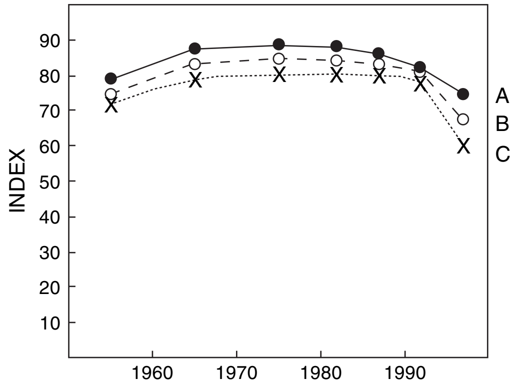

Figure 2. Indices for the health of breeding seabird populations off South Africa. See text for details of the unweighted index (A), and the indices with the two sets of weights associated with IUCN threat categories, set 1 (B) and set 2 (C).

Discussion

Although their overall trends were similar, the unweighted and the two weighted indices show interesting differences (Figure 2). The indices that were weighted according to the threat status of the species showed larger declines than the unweighted index. The explanation of this difference is that the species for which breeding populations increased, tended to be in one of the lower threat categories (kelp gull, great white pelican). Conversely, both species belonging to the highest threat category (African penguin, bank cormorant) decreased. The weighting by IUCN category makes the index sensitive to species in the high threat categories. This is an important property for the index to have.

It should be noted that linear interpolation between zero and the minimum target population for a species makes the rate at which the transformation value for that species changes strongly dependent on the choice of the minimum value. The target ranges for population sizes (Table 1) represent just our personal perspective on this issue. Such initial values should be discussed and modified by stakeholders at a properly facilitated workshop. Similarly, although in our investigation, species with a maximum target population never exceeded that level, the point above this level at which the transformation function would cut the x-axis will influence the rate at which the transformation value will change. Further thought needs to be given to objective means of selecting that point.

The conservation status of South African seabirds has only recently been assessed using IUCN criteria (Barnes, 2000; Du Toit *et al.*, 2003). It can be expected that the conservation status of a species will change with time; it will be necessary for the index to take account of any such change. Assuming that any species classified as threatened is below its minimum target population, a possible way to achieve this might be to take the square of the

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transformation value for that species, without further weighting. No correction is required, because the square automatically ranges between 0 and 1.

From a political and advocacy perspective, the ability to produce the "seabird index" on an annual basis should increase its relevance to, and impact on, decision-makers. From a scientific and management perspective, an annual index will help in understanding the year-on-year impact on the breeding populations of seabird species of varying degrees of food abundance and scarcity.

Criteria other than sizes of breeding populations could also be used as inputs to an index of the health of the marine environment for seabirds. For example, South Africa's Marine Living Resources Act has objectives to minimize marine pollution and to achieve economic growth. In order to incorporate these considerations, the index could be expanded to include, e.g., time-series of numbers of African penguins oiled each year, available from 1970 onwards (Nel *et al.*, 2003), and of numbers of visitors to major seabird-viewing sites, such as the gannet colony at Lambert's Bay and the penguin colonies at Robben Island and The Boulders. The objectives would be to minimize numbers of birds oiled and maximize numbers of visitors to colonies. When no birds were oiled, the value for the index would be 1; when the number oiled was above a certain value, it would be 0. When there were no visitors to colonies, the index would be 0; above a certain value it would be 1. For the number of visitors, there would be the possibility that management satisfaction would decrease when tourists exceeded a certain number, if they started negatively to affect populations. Above this level, the index would decrease.

At a later stage it may be possible to expand the index, to provide not just an indication of the health of the environment for breeding seabirds, but the health of the ecosystem as a whole. Other seabird indices may be useful in this process. For example, the Marine Living Resources Act has an objective of ecologically sustainable development. The diet of the Cape gannet has been monitored on a monthly basis since December 1977, and it provides useful information on the performance of prey populations (Berruti *et al.*, 1993). Elsewhere, indices of seabirds have also been shown to reflect food availability (Monaghan *et al.*, 1992). It will be necessary to consider how any additional variables may be included in the index in such a manner that the purpose of the index, namely to inform decision-makers on attainment of legislated objectives, will benefit.

Concluding remarks

To determine an environmental health index, we need to specify what we are attempting to measure, to choose the appropriate species to be monitored, to decide on target population limits for these species, to define the mathematical function that transforms the observed population size into a contribution to the index, and to decide on the relative weights for each species within the index. At each step, decisions need to be made and justified. We do not have final answers on these matters, and we present the method as a prototype to be developed and refined.

We have applied our approach to a set of time-series observations, which, first, was available to us, and, second, had immediate relevance to our research interests. Our intention is that other researchers and conservationists working in the environment will adapt this approach to their own contexts.

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