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A system dynamics approach to modelling multiple drivers of the African penguin population on Robben Island, South Africa

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ABSTRACT

The African penguin (*Spheniscus demersus*) population in southern Africa has experienced rapid decline in the 20th century and as of 2010 is listed as “endangered” on the IUCN Red List. There is an urgent need for decision support tools to enable effective management of colonies. We present a system dynamics model of the penguin population on Robben Island, South Africa, that combines a demographic simulation with the modelling of multiple pressures including food availability and food competition by commercial fisheries, oil spills, predation by terrestrial and marine predators, and extreme climate events. The model is stochastic, stage-specific and resource-driven, and incorporates both well-defined, quantitative field data and qualitative expert opinion. Survival rates for eggs, chicks, immatures and adults were adapted from field data and an earlier model of this population to create a simulation of a stable population used in a variety of scenarios and sensitivity tests. The modelled population was found to be strongly driven by food availability and to a lesser degree by oiling and marine predation, while climate events and terrestrial predation had low impacts. Food biomass levels (small pelagic fish) in the penguins' foraging area around the island (used during nesting) and further afield (used during the rest of the year) had an equal influence in driving population development in the short and long run. The impact of short-term (three years) fishing restrictions currently being trialled around the island was found to be generally beneficial to the modelled population, but easily masked by food-driven variability in population growth. The model produced population dynamics similar to those observed in 1988–2009 when immigration and a plausible change in predation pressure during this period were simulated. The model is being extended to other colonies to provide tools for specific management decisions and to enable the study of meta-populations by modelling migration between colonies. Our results suggest that improving food availability and mitigating the impact of oiling would have the highest beneficial impact on this penguin population.

1. Introduction

1.1. The African penguin

The African penguin (*Spheniscus demersus*) is endemic to Southern Africa and breeds at 28 sites in South Africa and Namibia (Crawford et al., 1995a,b, 2011). In 2010, after ten years of being classified as “vulnerable”, African penguins were upgraded to endangered status on the IUCN Red List of Threatened Species (IUCN, 2010), in recognition of a rapid population decline. It is estimated that <26 000 breeding pairs currently exist, while at the start of the 20th century there were ∼570 000 breeding pairs (Shannon and Crawford, 1999). Over the following 50 years numbers halved and the decline continued until there were only ∼18 0000 adults in the early 1990s (Crawford et al., 1995a,b). The penguin population has decreased to <5% of what it was just over a hundred years ago, and seven islands now support 80% of the population (BirdLife International, 2013). Factors thought to contribute to that rapid decline include competition for food with commercial fisheries, predation by seals, sharks and terrestrial predators, oiling,

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loss of habitat from historic guano harvesting, interspecific competition for nesting sites, disease, and human disturbance (Crawford et al., 1995a,b; Whittington et al., 2000; Shaw et al., 2012).

1.2. Modelling dynamics of the African penguin population

It has become increasingly urgent to understand the concrete causes and delineate management actions to address this decline. Two previously published studies have modelled the population dynamics of African penguins. Shannon and Crawford (1999) describe a model used to evaluate the effects of egg harvesting on Dassen Island in the early 20th century (which was found to invariably lead to a population decline), and oiling in the latter half of the 20th century. The model used a quarterly time step with annual survival and mortality for adult penguins, and demonstrated the significant value of rehabilitation of oiled birds to a colony's viability. Whittington et al. (2000) presented a population viability analysis implemented as an individual-based simulation model where each penguin is individually tracked and demographic events such as breeding or mortality are recorded at each discrete time step. It focussed on Robben Island and showed that, using best estimates of demographic parameters, the population could not sustain itself without immigration due to low breeding success and survival rates. It was concluded that the increase in the Robben Island penguin population that occurred in the late 1980s and 1990s could not have occurred without immigration of at least 1000 birds each year.

Under the Ecosystem Approach to Fisheries (see Garcia et al., 2003), to which South Africa is committed (Cochrane et al., 2004), it has become increasingly important to explore means of assessing ecosystem effects of fishing and of providing management advice in the light of multiple factors affecting marine ecosystems. The extension of the above-mentioned modelling approaches of a vulnerable marine predator in mathematical frameworks linked to traditional fish stock assessment models is restricted by the necessity for the factors and relationships involved to be well parameterized. Statistical modelling on interactions between the small pelagic fishery and the African penguin population at Robben Island is currently underway under the auspices of the Pelagic Scientific Working Group at the Department of Agriculture, Forestry and Fisheries (DAFF) (Robinson, 2012; Robinson and Butterworth, 2012). However, difficulties associated with parameter estimation due to scarcity of data have meant that explicit consideration of multiple pressures driving penguin population dynamics necessitates a move to a different paradigm. In a system dynamics framework expert opinion can be incorporated to qualitatively define relationships that would not be included under traditional stock assessment modelling. A mediated, participatory modelling approach allows the effective participation of key stakeholders, including those outside academia.

1.3. A system dynamics approach to model penguin population dynamics

Both the required flexibility and accessibility can be provided by a system dynamics approach, which is a computer-aided modelling approach that can be used to understand dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular causality (System Dynamics Society, 2013). This is particularly useful when, as in this case, there are significant feedback loops and the system may involve non-linearity and relationships best defined by a graph. In addition, model components and interactions can be graphically depicted on-screen, which aids stakeholders in understanding the model structure and the relationships between variables. System dynamics provide a complementary modelling approach that is intended less as a predictive tool than as a method of exploring the effect of a variety of different inputs on long-term trends. Comparable modelling environments have been used to simulate the dynamics of a stingray population under pressure from tourism (Semeniuk et al., 2010), or the demography of captive populations (Faust et al., 2003), among others. We present a system dynamics model to examine the effects of various external pressures, food availability and food competition by commercial fishing on a penguin population while accounting for stage-structured demography and stochasticity. We focus on Robben Island, situated in Table Bay off Cape Town, South Africa (Fig. 1), since the locality hosts one of the larger colonies is subject to a multitude of pressures, and features one of the most detailed and long-running sets of breeding records for African penguins. Robben Island was recolonized with nine breeding pairs in 1983, the colony having been previously extinct since the 1800s (Crawford et al., 1999). Subsequently there was rapid growth of the colony with a peak of just over 8500 breeding pairs in 2004. The number of breeding pairs then started to fall until ~2500 breeding pairs were estimated to exist on Robben Island in 2010 (Sherley et al., 2013a) and in 2013, an estimated 1200 pairs breed on the island (Department of Environmental Affairs, unpubl. data). The growth of the colony was found to be strongly correlated with the growth of the South African sardine stock (Crawford et al., 2001). The model aims to explore possible management strategies that could be beneficial to the African penguins on Robben Island.

2. Material and methods

A strength of the system modelling approach adopted in this study is that it involves stakeholders and harnesses their inputs from conceptualization of the model and throughout model development and interpretation of model results, employing a participatory/mediated modelling approach (van den Belt, 2004; Starfield and Jarre, 2011). Qualitative relationships and selection of pressures used in the modelling study are based on expert opinion sourced from a group of researchers from the University of Cape Town and the South African National Biodiversity Institute, researchers and managers from government organizations (the Department of Environmental Affairs, Branch Oceans and Coasts, and Cape Nature), and members of conservation organizations (BirdLife SA). The expert group of stakeholders met regularly to guide model parameterization and development. The use of sensitivity analyses allowed differences in opinion to be taken into account and the model parameters to be adjusted to explore the effects.

2.1. Model structure

All major process groups in the model have stochastic components, either in the form of random sampling from a database or parameter-controlled variation around a configurable mean. Detailed model structure and equations are given in Appendix A. Values and sources of parameters as well as information on the stochastic or deterministic nature of different groups of processes are shown in Table B.1 (Appendix B). The model was implemented in VenSim Professional V6.0.0.1 (Ventana Systems). Full equations in VenSim syntax can be found in Appendix C (online).

Penguin population structure as implemented in the model is shown in Fig. 2.

Eight age classes are distinguished: Eggs, Chicks, two Immature age classes (immature penguins born in year y and immature penguins born in year $y-1$) and four Adult age classes (adults aged 2, 3, 4 and 5 or older). The model uses the month as a time step. The main dynamics of the model are monthly mortality and annual survival.