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Ecosystem thresholds as tools to achieve an ecosystem-based approach to fisheries

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Introduction

Various international agreements require/encourage participating parties to implement an ecosystem-based approach to fisheries (EAF). For example, the Code of Conduct for Responsible Fisheries of the United Nations' Food and Agriculture Organisation, adopted in 1995, states that *Management measures should not only ensure the conservation of target species but also of species belonging to the same ecosystem or associated with or dependent upon the target species* (<http://www.fao.org/3/v9878e/v9878e00.htm>). The sixth Aichi Target of the Convention on Biological Diversity's Strategic Plan for Biodiversity 2011–2020 reads: *By 2020 all fish and invertebrate stocks and aquatic plants are managed and harvested sustainably, legally and applying ecosystem based approaches, so that overfishing is avoided, recovery plans and measures are in place for all depleted species, fisheries have no significant adverse impacts on threatened species and vulnerable ecosystems and the impacts of fisheries on stocks, species and ecosystems are within safe ecological limits* (<https://www.cbd.int/convention/text/default.shtml>).

Tools available to manage fisheries so as to avoid harmful impacts on associated or dependent species (ADS) include marine spatial planning (e.g. Ludynia et al. 2012, Sherley et al. 2018) and the identification and implementation of ecosystem thresholds. The latter have been widely applied to minimise by-catch mortality of ADS in fisheries (e.g. Rollinson et al. 2017) and are increasingly proposed as means to ensure sufficient quantities of prey for marine predators, such as seabirds, which compete with fisheries for forage resources (e.g. Cury et al. 2011, Smith et al. 2011, Sydeman et al. 2017). The potential use of ecosystem thresholds is summarized briefly below.

Forage abundance thresholds

In a meta-analysis of long-term studies for seven marine ecosystems from around the globe, Cury et al. (2011) demonstrated a ubiquitous threshold in prey (fish and krill) abundance, below which seabirds suffered reduced and more variable productivity. The threshold was equal to the long-term average biomass of prey and equivalent to one-third of the maximum observed prey biomass. Similar threshold relationships were established for 13 of the 14 seabirds considered, including both species (African Penguin *Spheniscus demersus* and Cape Gannet *Morus capensis*) from the Benguela ecosystem (Figure 1). The "1/3 for the birds" threshold provides a benchmark for management of forage fish fisheries at a level that would sustain seabird productivity over the long-term. Another example provided by Robinson et al. (2015) showed that annual mortality of adult African Penguins at Robben Island increased markedly when the biomass of sardine *Sardinops sagax* aged 1 y or older off west South Africa fell below about 25% of its maximum value (Figure 2).

The lower forage threshold observed for adult mortality (25%) than for breeding success (33%) confirms the theoretical prediction of Cairns (1987) that decreases in forage abundance would influence breeding success ahead of survival. It is noteworthy that off west South Africa, Cape Gannets are better able to buffer effects of reduced prey abundance than African Penguins (Distiller et al. 2012, Sherley et al. 2014, 2019, Robinson et al. 2015). After a fisheries-related eastward displacement of the main forage resources, and the collapse of sardine along the Western Cape (Coetzee et al. 2008), gannets, due to their movement capabilities, fed on alternative food such as saury *Scomberesox saury* and hake *Merluccius* spp. offal, whereas African Penguins

were not able to (Grémillet et al. 2008, 2019, Crawford et al. 2014, Figure 3). The ability to forage more widely and other life-history characteristics of seabirds influence empirically-derived ecosystem thresholds for fisheries (Furness and Tasker 2004).

Forage availability thresholds

It is not only the absolute abundance of prey but also its availability in the water column that impacts the demographic parameters and population trends of seabirds. For example, Crawford et al. (2019) used long-term information on the diet of Cape Gannets off west South Africa to derive an index of the availability of anchovy and sardine to seabirds in this region, terming it a Forage Availability Index (*FAI*). They demonstrated a substantial decrease in the availability of anchovy and sardine to seabirds in the 2000s after better availability in the late 1990s (Figure 4). Breeding numbers of Cape Gannets and Cape Cormorants were significantly related to the *FAI* in a non-linear manner, as was the survival of adult African Penguins at both Dassen and Robben islands linearly (Figure 5). For gannets the numbers breeding increased when the *FAI*, which increases as anchovy and sardine contribute more to the diet, was $> c. -1$ (Figure 5a) and for cormorants when it was $> c. 1$ (Figure 5b). For penguins survival was generally lower when the *FAI* was negative than positive and decreased markedly when the *FAI* was $< c. -1.5$ (Figure 5c, d). The higher threshold for Cape Cormorants than Cape Gannets at which numbers breeding were predicted to increase probably resulted from the fact that, unlike Cape Gannets but similarly to African Penguins, Cape Cormorants are mostly unable to access alternative food such as saury and hake offal (Crawford et al. 2019).

Notably, even the fishery has considered a change in availability important. A deeper occurrence close to the seabed by anchovy appears to have reduced its availability to purse-seiners and is suggested as one of the reasons contributing to a large under-catch in South Africa of the total allowable catch in recent years (DAFF 2016). In a related modelling study from another upwelling system, depth of prey primarily determined foraging success of Peruvian Boobies *Sula variegata* and Guanay Cormorants *Phalacrocorax bougainvillorum*, which feed mainly on Peruvian anchoveta *Engraulis ringens* in the Humboldt upwelling system off western South America (Boyd et al. 2017). Peruvian Boobies and Guanay Cormorants are the ecological equivalents of Cape Gannets and Cape Cormorants in the Benguela system (Crawford et al. 2006).

Fisheries mortality threshold

In addition to contributing to collapses of forage resources (e.g. Essington et al. 2015), fishing may cause localised depletion of prey and the fisheries mortality rate (*M*) can be used as another management threshold. For example, the performance of three species of *Pygoscelis* penguins breeding near the Antarctic Peninsula was reduced when local harvest rates of Antarctic krill *Euphausia superba* were $\geq 10\%$ of the estimated biomass (Watters et al. 2020). By comparison, the exploitation rate of South Africa's sardine west of Cape Agulhas increased substantially after 1999 and reached 44% in 2006 (Coetzee et al. 2008).

Quality thresholds

It is also worth mention that not only the abundance or availability of prey may influence its ability to sustain predator populations, but also its condition. Poor food quality appeared to be the cause of unprecedented breeding failures at many seabird colonies on the east coast of Britain in 2004 (Wanless et al. 2005). In South Africa, the condition of sardine deteriorated in the 2000s (Ndjaula et al. 2013).

Consumption thresholds

Saroux et al. (2020) investigated consumption thresholds on forage fish stocks by seabirds in five marine ecosystems: off Norway, South Africa and Peru, in the Baltic Sea (Sweden) and at Shetland (Scotland). In each of these systems, the predation pressure, estimated as the proportion of a forage fish stock consumed by seabirds, was generally low but increased sharply when prey biomass decreased below a threshold of 15 to 18% of its maximum recorded value (Figure 6). A threshold of 18% was considered as a limit not to be reached for the sake of forage fish, and below which extra cautious management of fisheries may be required. Similarly Essington et al. (2015) advised that a risk-based management scheme that reduces fishing when populations become scarce would protect forage fish and their predators from collapse, with little effect on long-term average catches.

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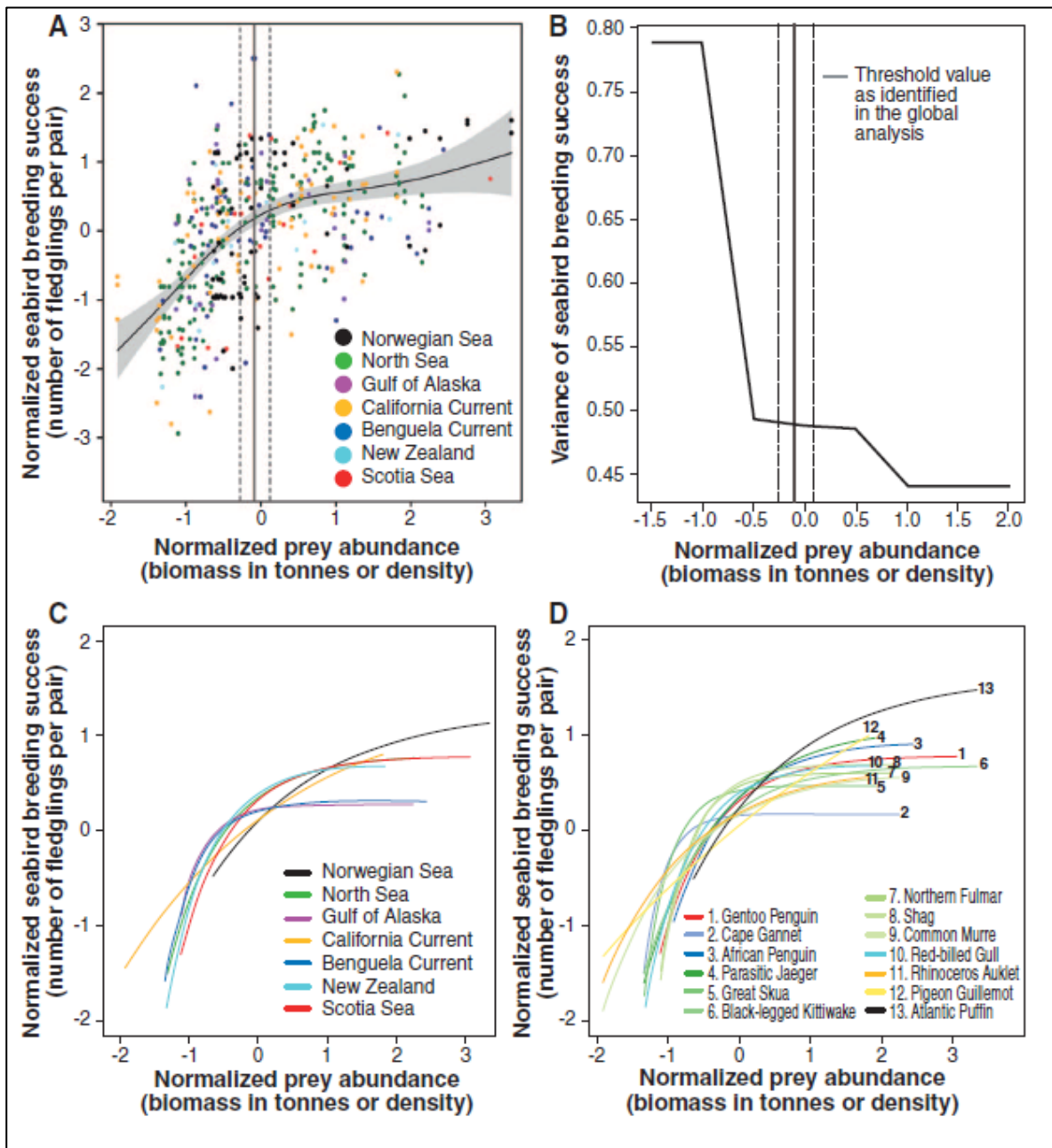


Figure 1 (reproduced from Cury et al. 2011). (A) Relationship between normalized annual breeding success of seabirds and normalized prey abundance. Each data point from the time series was plotted together with the predictions of a General Additive Model (GAM) (solid line, grey area represents the 95% confidence interval). The threshold in the non-linear relationship (orange vertical line) was detected from a change-point analysis and its confidence interval (black dashed vertical lines) was estimated from a bootstrap analysis. (B) Change in variance across the range of normalized food abundance shows greater variability of seabird breeding success below the threshold. (C) Similar relationships were established when the data were presented for all species within each ecosystem and (D) for individual seabird species using a hyperbolic type II model (S2), which was identified as the best fitting model (except for the Arctic Tern where the model fit was not significant). Note that the colours in (A) and (C) represent the dataset for each ecosystem, and in (D) for each seabird species.

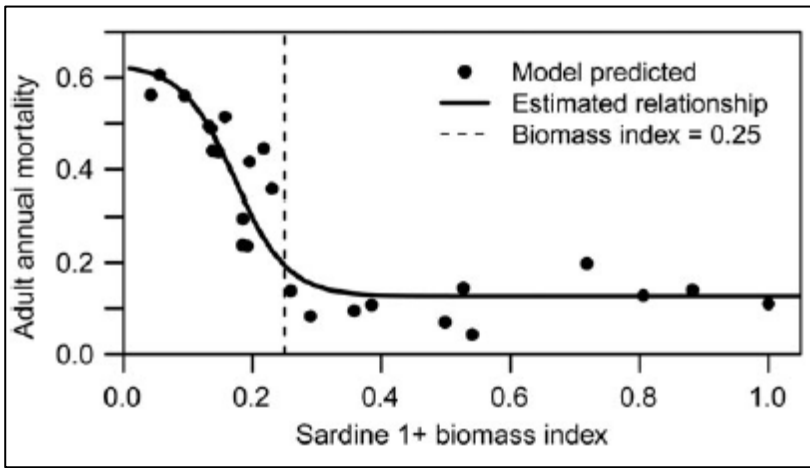


Figure 2 (reproduced from Robinson et al. 2015). The estimated relationship between the sardine 1+ biomass index (scaled to the maximum November survey estimate of 2003) and model-predicted mortality of adult African Penguins at Robben Island. The vertical dashed line is at 25% of the maximum observed biomass.

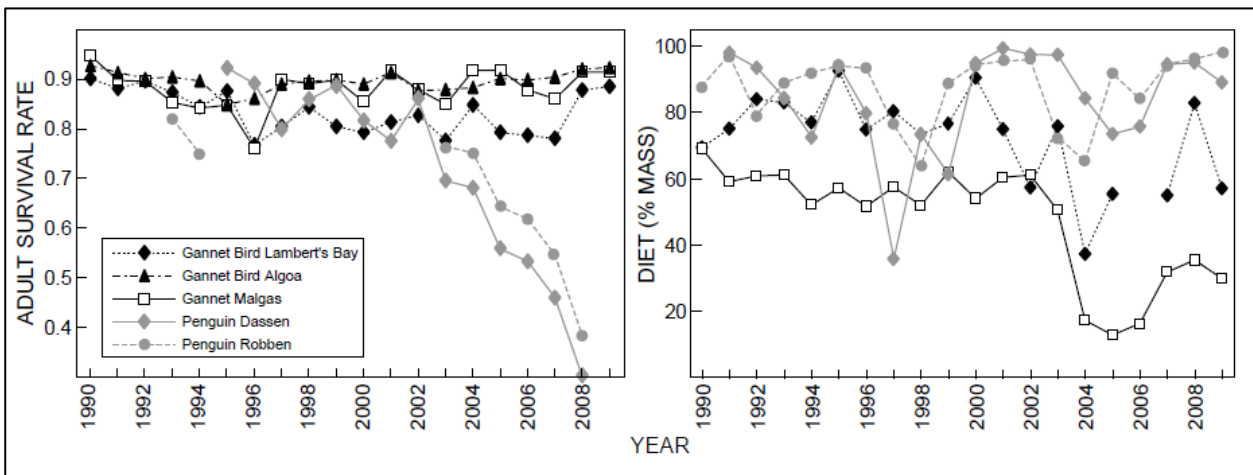


Figure 3 (reproduced from Crawford et al. 2014). Left: trends at five islands off South Africa (Bird at Lambert's Bay, Malgas, Bird at Algoa Bay, Dassen and Robben) in the annual adult survival rate of African Penguins and Cape Gannets, 1990–2009. Right: trends at four islands off South Africa (Bird at Lambert's Bay, Malgas, Dassen and Robben) in the combined contribution of anchovy and sardine to the diets of these seabirds, 1990–2009. As fish prey shifted eastwards, the contribution of anchovy and sardine to the diet of Cape Gannets fell because they were able to supplement their diet by feeding on fishery waste, but African Penguins were unable to do so and experienced greatly decreased survival.

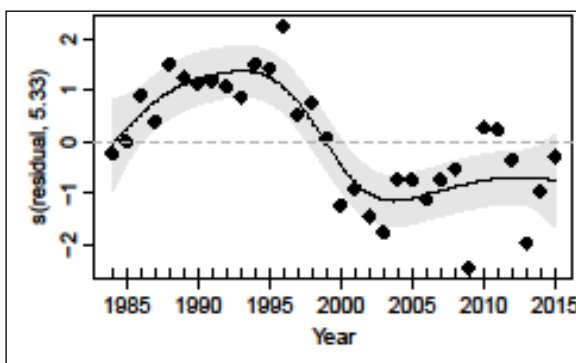


Figure 4 (reproduced from Crawford et al. 2019). Change over time in the relationship between the *FAI* and the combined spawner biomass of anchovy and sardine west of Cape Agulhas. Diamonds show residual differences between z-score normalized *FAI* values and z-score normalized estimates of forage fish biomass (residual = $Z_{FAI} - Z_{biomass}$). On the y-axis, $s[x,y]$ indicates the smoothing term, where x is the explanatory variable and y is the estimated degrees of freedom of the smoothing term. The grey shading shows pointwise 95% confidence intervals.

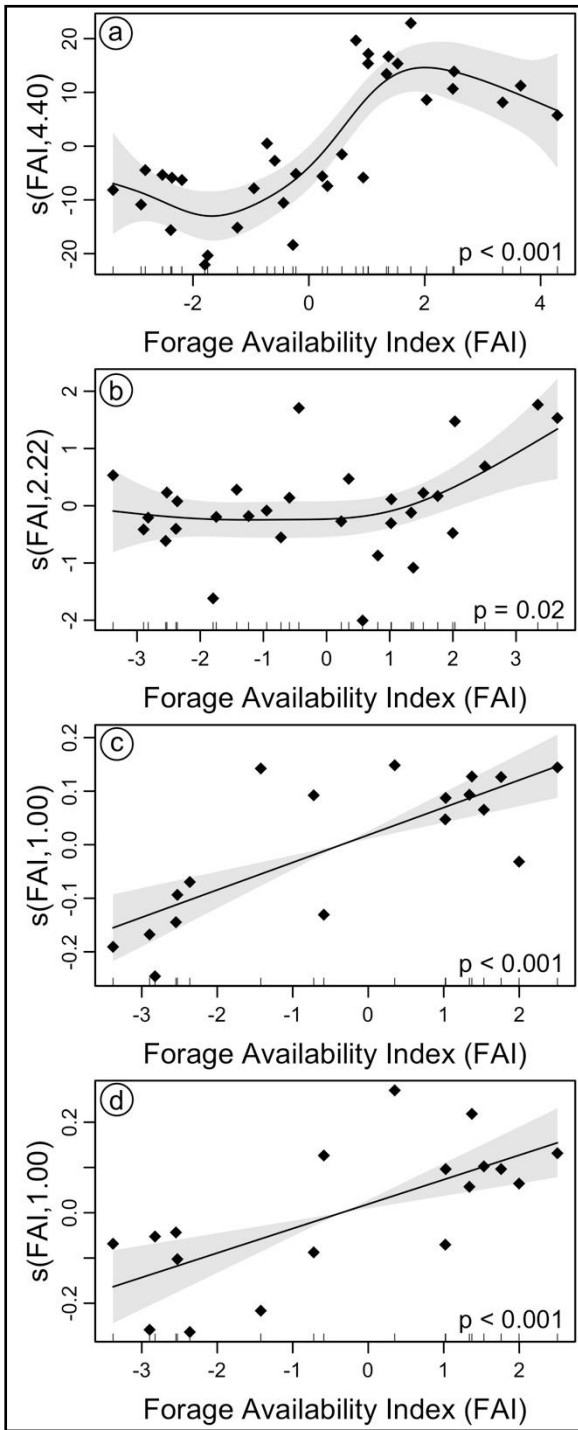


Figure 5 (reproduced from Crawford et al. 2019). Results of generalized additive modelling of the effects of the *Forage Availability Index (FAI)* on four indicators of seabird performance in South Africa. The *FAI* represents the combined contribution of sardine and anchovy to the diet of Cape Gannets. The indicators of seabird performance are a) numbers of nests at which Cape Gannets were breeding between 1978/79 and 2015/16; b) numbers of nests at which Cape Cormorants were breeding between 1978/79 and 2015/16; c), d) apparent survival of adult African Penguins at Dassen and Robben islands, respectively, between 1994/95 and 2011/12. On the y-axis, $s[x,y]$ indicates the smoothing term, where x is the explanatory variable and y is the estimated degrees of freedom of the smoothing term. The grey shading shows pointwise 95% confidence intervals and diamonds show the partial residuals around the significant covariate effects.

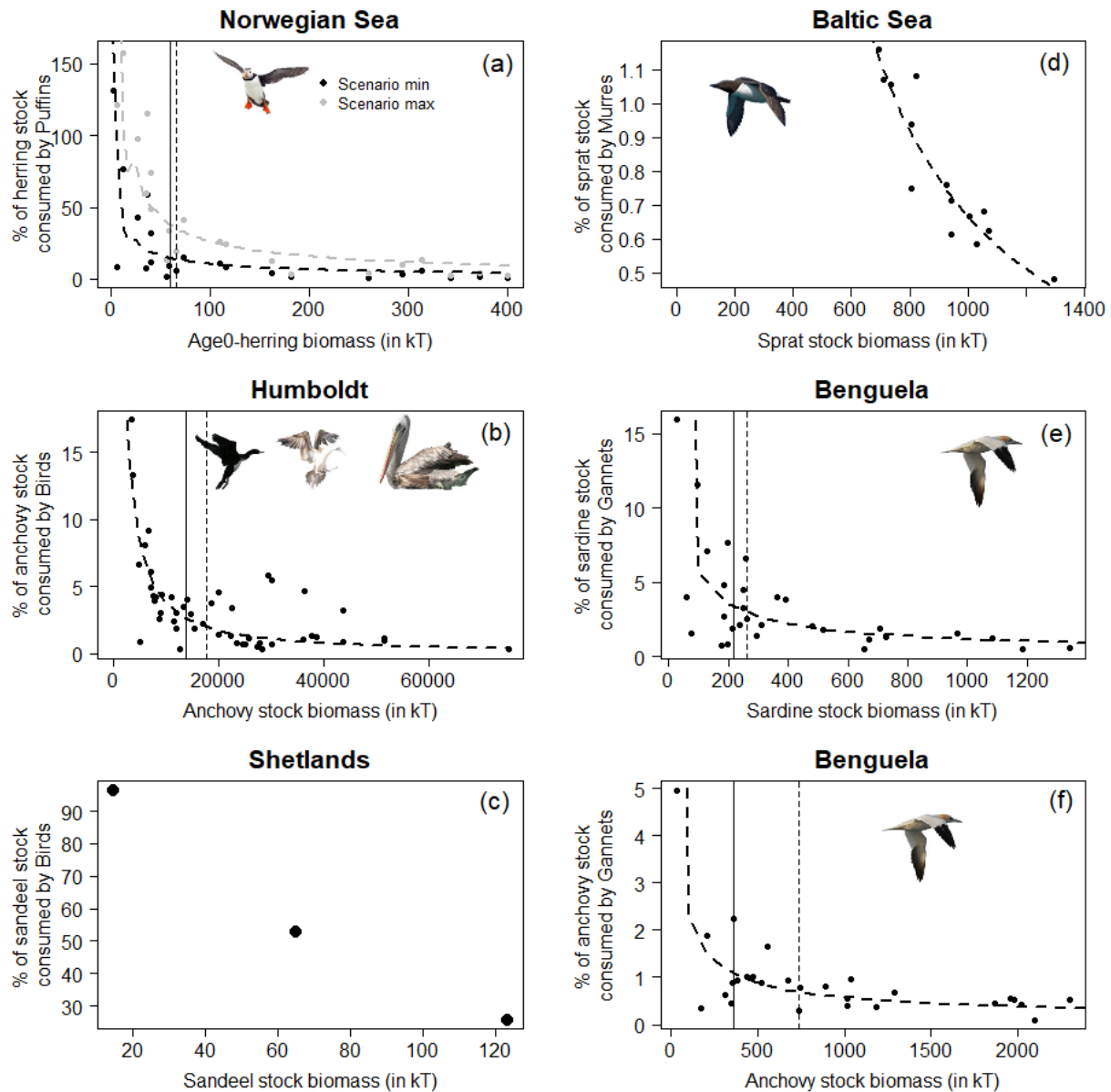


Figure 6 (reproduced from Saraux et al. 2020). Relationships between the stock biomass of prey (thousand tonnes) and the percentage of the stock consumed by seabirds. When two variables were significantly related, dashed lines represent the fit of the best relationship between these variables. The thresholds in the non-linear relationships between stock biomass and the percentage of the stock consumed by seabirds were calculated from change-point analyses and are indicated by vertical solid lines, while the median stock biomass is indicated by a dashed vertical line.

ⁱ Although recognizing the usefulness of the meta-analysis of Cury et al. (2011), Butterworth (2015) argued such thresholds were not pertinent in South Africa where management procedures provide advice for forage resource management. This was *inter alia* because breeding success was only one component of the overall recruitment process, which in a model of African Penguins had shown no dependence on abundance of young-of-the-year anchovy *Engraulis encrasicolus* (Robinson et al. 2015), and size compositions of fish eaten by African Penguins might be smaller than those caught by the South African purse-seine fishery. However, African Penguins recruit to their breeding population at an age of c. 5 y after wandering widely in the Benguela system and in that period would be expected to utilize a variety of prey resources and sizes (e.g. Crawford et al. 2013, Sherley et al. 2013). Furthermore, they eat fish of similar size to those caught by the fishery (e.g. Hockey et al. 2005, Zepe 2016). In addition, Cape Gannets were not considered by Robinson et al. (2015).

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