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SOME INITIAL THOUGHTS ON THE POTENTIAL USE OF MICE FOR INFORMING TARGETS OR THRESHOLDS FOR HARVEST RATES TO TAKE INTO ACCOUNT IMPACTS ON PREDATORS OF FISHING ON SMALL PELAGICS.

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1. Introduction

The determination of harvest rates for lower trophic level species that will ensure not only sustainable use of the target species but also avoid undue impacts on their predators requires the use of models that incorporate both goals i.e. some form of ecosystem model.

Several ecosystem models have been developed for the southern Benguela ecosystem, including EwE models (Shannon et al., 2020), an Atlantis model (Ortega-Cisneros et al., 2018) and an OSMOSE model (Travers et al., 2014). Further developments are underway, including more detailed inspections of predator-prey dynamics in the EwE model described in Shannon et al. (2020), and application of Ecospace modelling to improve the fits to available catch and abundance data (Ortega-Cisneros and Shannon, 2025). These models represent a valuable resource for improved understanding of ecosystem interactions

Ecosystem models have important roles to play in management at conceptual and strategic levels (e.g. Plagányi et al., 2012, Shannon et al., 2020) but unavoidably high levels of uncertainty in many ecosystem models constrains their use for tactical decision-making. Plagányi et al. (2012) proposed that models that are suitable for provision of tactical advice include estimation of the value of at least some of the parameters from data from the system being modelled, and make use of statistical diagnostic tools to assess the performance of the model. The authors suggest that ecosystem models that include only the species considered to have important interactions with the targeted species can fulfil the necessary statistical properties for application in tactical management. They refer to such models as Models of Intermediate Complexity for Ecosystem assessments (MICE), also sometimes referred to as minimum realistic models (MRM).

Punt et al. (2016) considered that MICE are the best approach for management strategy evaluations (MSE) for comparison of the strength of alternative candidate strategies for achieving management goals that address the target fisheries and broader ecosystem objectives.

There are several examples of application of MICE and MRM in fisheries management. Three of those are:

An MRM was developed to investigate interactions between the Cape fur seal and the South African Cape hakes fishery (Punt and Butterworth, 1995). The model included only the two hake species *Merluccius capensis* and *M. paradoxus*, Cape fur seal *Arctocephalus pusillus pusillus*, other predatory fish and the hake fishery. Those three ‘predator’ groups were estimated to account for more than 90% of total mortality of Cape hake. The two hake species were modelled separately in age-structured models using parameters obtained from stock assessments. The parameters of the seal model were obtained from biological studies and fitting to counts of pup abundance. The parameters for the other predatory fish group were obtained from stock assessments of similar species. The results from the base-case model indicated that the impact of reducing the seal population on the hake fishery would be minimal and could even be detrimental. That result was insensitive to changes of most of the more uncertain model parameters.

A MICE was developed to investigate the indirect impacts of the fishery for the northern subpopulation of Pacific sardine (*Sardinops sagax*) on two predators, in particular brown pelicans (*Pelecanus occidentalis*) and California sea lions (*Zalophus californianus*), in the Southern California Bight (Punt et al., 2016). The model included three forage species (sardine, northern anchovy *Engraulis mordax*, and 'other forage' species), a category for 'other prey', and the two predator species. The model was a spatially-structured, population dynamics model with separate components for prey and predators. Parameters were either based on literature values, estimated from available data or calculated from other variables. The model was used to evaluate the consequences for the fishery and ecosystem of the sardine management systems in place at that time for Mexico, the USA, and Canada. The authors noted that there was still a lot of uncertainty in the system and advised exploring the sensitivity of results to alternative model formulations and parameter values when providing advice on management strategies.

The Atlantic States Marine Fisheries Commission (ASMFC) selected the Northwest Atlantic Coastal Shelf - Model of Intermediate Complexity for Ecosystem Assessment (NWACS-MICE) for the development of ecological reference points (ERPs) that took into account the effects of Atlantic menhaden harvest on its predators (Chagaris et al. 2020). An existing Ecopath with Ecosim model of the NWACS was reduced from 61 to 17 species/functional groups. It focused on three key prey species, (Atlantic menhaden *Brevoortia tyrannus*, Atlantic herring, and bay anchovy) and four key predator species (striped bass, bluefish, weakfish, and spiny dogfish). The parameters of the model were obtained from results of stock assessments or from the full NWACS model, and it was calibrated to time series of observed abundance and catch, using time-series of fishing mortality as forcing functions. Striped bass (*Morone saxatilis*) was considered to be the predator most sensitive to menhaden harvest and was used as an indicator of ecosystem impacts. ERPs were based on the tradeoff relationship between the equilibrium biomass of striped bass and menhaden fishing mortality (F) and were adopted by the Atlantic Menhaden Management Board.

2. *Developing a MICE for Small Pelagics in the Southern Benguela*

There are two fundamental questions to be considered for development of a MICE. The first of those is the preferred form of the model, whether, for example, a population dynamics model as in Punt and Butterworth (1995) and Punt et al. (2016) or an EwE-MICE model as in Chagaris et al. (2020), or some alternative. In principle, use of more than one type of model could provide useful comparative information.

The second question is the optimal level of complexity that would "incorporate the best features of existing single-species models of relative simplicity and the ability to apply standard statistical methods for parameter estimation, but also take account of broader ecosystem considerations" (Plagányi et al., 2012). The ecosystem interactions that need to be considered depend on the particular objectives that the model is intended to achieve. In this case the objectives being addressed focus on identification of ecosystem performance statistics or reference points, against which alternative candidate management procedures can be evaluated .

The diet matrix assembled by Shannon et al. (2020,Table S4) indicates that one or more of anchovy *Engraulis encrasicolus*, sardine *Sardinops sagax* and redeye round herring *Etrumeus whiteheadii* (hereafter referred to as redeye) accounts for at least five percent of the diet of 17 species or species groups. Anchovy makes up at least five percent of the diet of 12 of those predators, sardine of six of them (all also included in the 12 consuming five percent or more anchovy), and 10 with at least five percent of round herring in their diets (five of which do not occur in the anchovy or sardine consumers groups and five that occur in either one or both of those groups) (Table 1).

Table 1. Proportional contributions of anchovy, sardine and redeye round herring to the diets of predators. The table includes all predators for which one of these small pelagic species makes up 0.05 or more of their diet (the sum of recruits and adults for anchovy and sardine). Yellow highlights indicate species where the prey species accounts for > 0.10 to 0.29 of the diet, and red highlighting indicates 0.30 or higher. Data from Table S4, Shannon *et al.*, 2020.

Prey species	**Anchovy**		**Sardine**		**Redeye**
Predators		**Predators**		**Predators**	
Snoek	0.43	Sciaenids	0.10	Adult Hmack	0.06
Tuna & Swordfish	0.26	Yellowtail	0.15	Snoek	0.11
Sciaenids (geelbek/kob)	0.10	Cetaceans	0.07	Yellowtail	0.10
Yellowtail	0.15	African Penguin	0.20	Chokka Squid	0.05
Large *M. capensis*	0.30	Cape Gannet	0.32	Other cephalopods	0.05
Small *M. paradoxus*	0.08	Cape Cormorant	0.07	Large *M. capensis*	0.09
Seals	0.25			Small *M. paradoxus*	0.05
Cetaceans	0.30			PF Demersals	0.11
African Penguin	0.59			PF Chondrichthyans	0.05
Cape Gannet	0.26			African Penguin	0.05
Cape Cormorant	0.91				
Other seabirds	0.13				

Of those 17 species, snoek *Thyrsites atun*, large *M. capensis*, the cetaceans species group, African penguin *Spheniscus demersus*, Cape cormorant *Phalacrocorax capensis* and Cape gannet *Morus capensis* have 30% or more of anchovy or sardine in their diets and may therefore be of higher priority for including in a MICE.

In a study on linefish dependency on small pelagics, Parker et al. (2020) identified significant effects of anchovy biomass on the CPUE of silver kob *Argyrosomus inodorus* and yellowtail *Seriola lalandii*, and significant effects of sardine biomass on the CPUE of geelbek *Atractoscion aequidens.* Silver kob and geelbek constitute the group Sciaenids in Shannon et al. (2020). The biomass of redeye did not have a significant effect on any of the four linefish species examined.[1]

Table 1 is taken from the diet composition used as input for the EwE model reported in Shannon et al. (2020). However, as those authors note, diet can vary considerably depending on the availability of prey. This is well illustrated by the changes in diet of penguins at Dassen and Robben Island between 1989 and 2021 (Figure 1, from Makhado et al., 2023). Results from the other major penguin breeding sites show similar variability (Makhado et al., 2023), as do the diets of Cape gannets at Lamberts and Malgas Islands (N. Makhado, DFFE, *pers.comm.*). Variability can also be expected in other predators. It will be important to make allowance for such variability in a MICE developed to assess the impacts on predators of fishing on the small pelagic species.

[1] The four linefish species considered by Parker et al. (2020) were geelbek, silver kob, snoek and yellow tail.

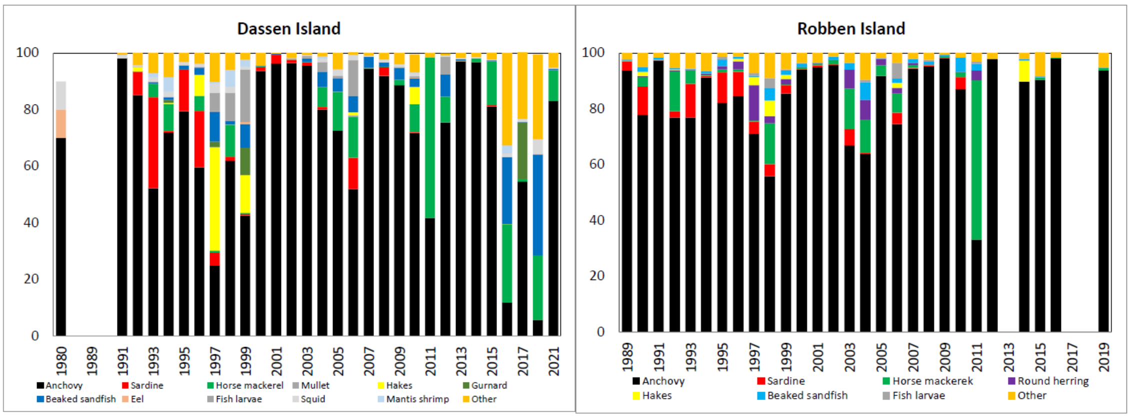


Figure 1. The annual contribution of anchovy, sardine and fish larvae (mostly anchovy and sardine) to the diet of adult African penguins returning to Dassen and Robben Islands during the breeding season, 1989–2023. From Makhado et al. (2023).

3. *Impacts of predators on small pelagics*

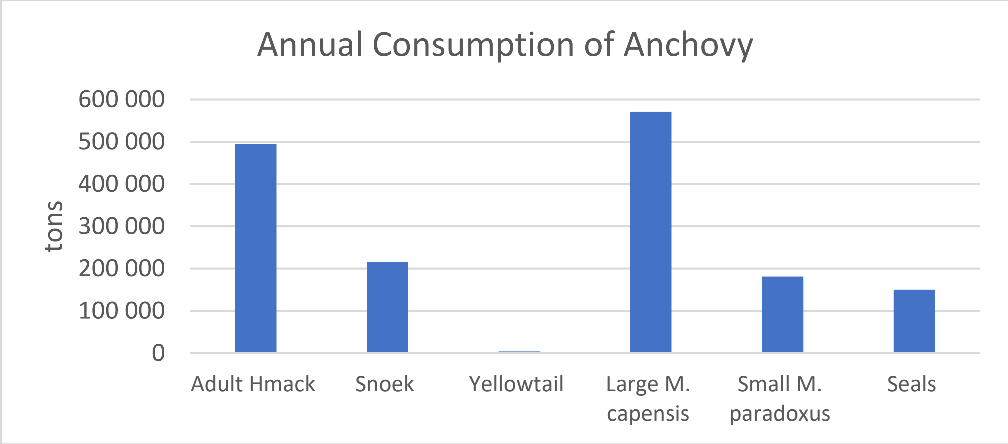
The focus of the EIMTG has been on the impacts on predators of fishing on small pelagic species. A MICE developed to explore those impacts should therefore focus on predators that are particularly dependent on one or more of those small pelagic species as a food source. Diet composition, as discussed in the previous section, is a key indicator of that dependence.

Conversely, consumption by predators has an impact on their prey, contributing to natural mortality. This is unlikely to be taken into account explicitly in a MICE intended to explore the reverse impacts, but the estimated total consumptions per year by some predators are provided here as examples (Figures 2 and 3). The methods used to estimate total consumption per predator are given in the Appendix. Consumption of individual prey species was calculated as total consumption multiplied by the proportion of that prey species in the diet (Table 1 and Shannon et al., 2020).

The examples shown here are of single-species components (for which recent biomass estimates are more readily available), and either, i) because of high biomass, could be expected to show relatively high consumption of anchovy or sardine (i.e. horse mackerel, hakes and seals) or ii) have a high dependence on those species and are likely candidates for a MICE model (i.e. snoek, yellowtail, seabirds).

Fish predators, particularly horse mackerel and the Cape hakes (but excluding yellowtail), consume the most anchovy, followed by seals, Cape gannet, the other two seabirds and yellowtail. Cape gannet is estimated to have the highest consumption of sardine of the predator species shown here, followed by adult horse mackerel and then snoek. Consumption of both species by Cape gannet is considerably higher than that of penguins and Cape cormorant because of its greater abundance (more than 140 000 breeding pairs compared to approximately 24 000 of Cape cormorant and 10 000 penguin breeding pairs, Appendix).

Anchovy accounts for relatively high proportions of the diet of Tuna and swordfish (26%) and the cetaceans group (30%) but estimates of their annual consumption are not shown here because biomass estimates could not be obtained in time. Their biomasses within the southern Benguela ecosystem, and hence consumption, are likely to be closer to the linefish species than those of horse mackerel and the hake species.



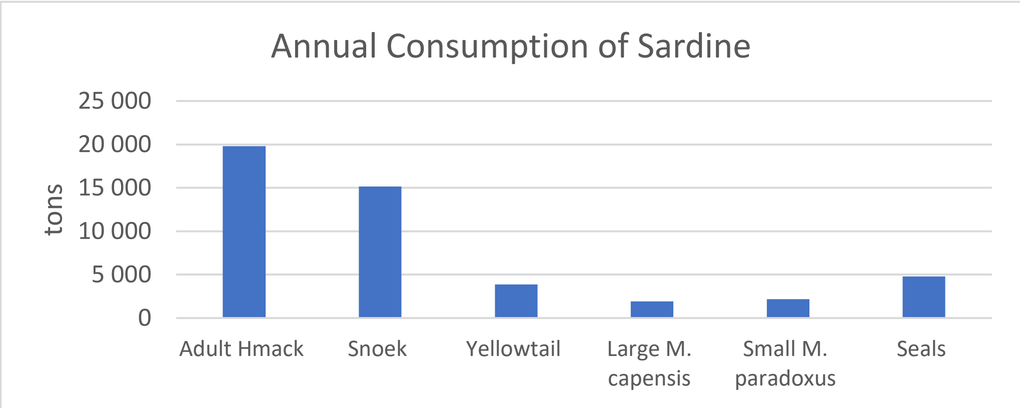


Figure 2. Estimated annual consumption of anchovy and sardine by selected fish and mammal predators, calculated from most recent biomass estimates and proportions of the prey species in diets (obtained from Shannon et al., 2022). Note differences in scale of consumption between the two graphs.

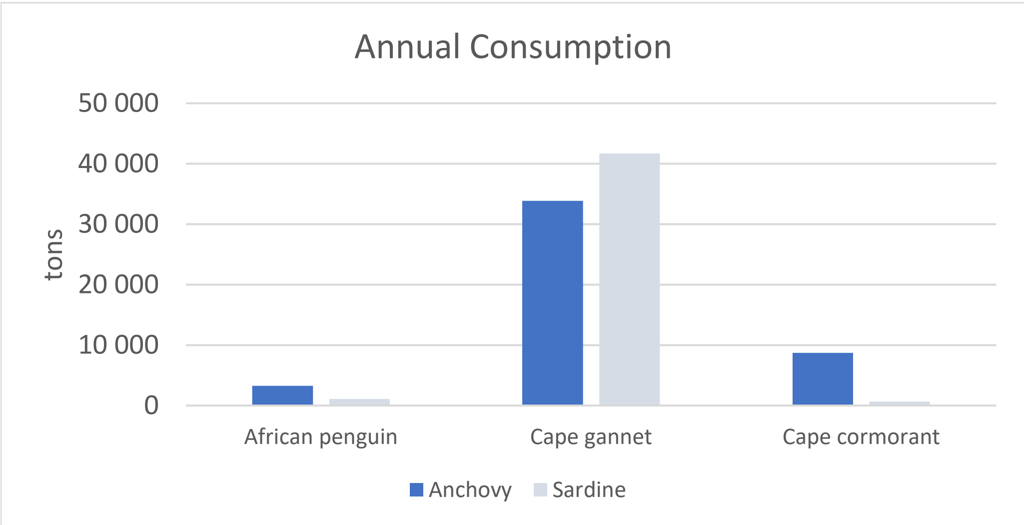


Figure 3. Estimated annual consumption of anchovy and sardine by selected seabird predators, calculated from most recent abundance estimates, daily food requirements (Gaglio et al. 2018) and proportions of the prey species in diets (Shannon et al., 2022).

4. *Predator status*

The status of individual predator species is potentially also an important factor in deciding which species to include in an ecosystem model for determining the impacts of fishing of small pelagics. Of the species most dependent on small pelagics in their diets, the three seabird species are of the greatest conservation concern (Table 2). Silver kob and geelbek are ranked as being depleted and may therefore also be given a higher priority in determining which species should be included.

Table 2. Status of predator species with a relatively high dependence on small pelagics, as reflected in diet composition.

Species	Status	Reference
Snoek	Abundant, light fishing pressure.	DFFE, 2025
Tuna&Swordfish	Varies	DFFE, 2025
Sciaenids - geelbek	Depleted	Parker et al., 2020
Sciaenids – silver kob	Depleted, optimal fishing pressure	DFFE, 2025
Yellowtail	Optimal abundance and fishing pressure	DFFE, 2025
M. capensis	Abundant, light fishing pressure.	DFFE, 2025
M. paradoxus	Optimal abundance and fishing pressure	DFFE, 2025
African Penguin	Critically endangered	IUCN Red List[2]
Cape Gannet	Endangered	IUCN Red List
Cape Cormorant	Endangered	IUCN Red List
Seals	Least concern	IUCN Red List
Cetaceans	Varies	

5. *Conclusions and questions*

The EIMTG concluded that ecosystem models, in particular MICE, could provide valuable information on the impacts of the small pelagic species on predators, and therefore on optimal harvest rates taking ecosystem impacts into account. MICE (in the case of fisheries) that only include the species considered to have important interactions with the target species can have the statistical characteristics that are required for confident application in tactical management (Plagányi et al. 2012). This has been demonstrated in application of MICE in a number of cases for tactical and strategic purposes, including the three reported here.

There are two fundamental questions to be considered in development of one or more MICE for use in ecologically-oriented management of South Africa's small pelagic fishery, both relating to the species to be included. The first of those is whether to include redeye as an important prey species or not. The important role of anchovy and sardine as prey in the Southern Benguela, including for seabirds and some linefish species, is clear but that of redeye is less so (e.g. Table 1).

From a different perspective, there is considerable overlap in the diets of the three species, which consist of phytoplankton and/or zooplankton (Shannon et al., 2020). Inter-specific competition may

[2] IUCN Red List. https://www.iucnredlist.org/species/2066/66991045

therefore be a factor in driving productivity of the three, although other factors such as temperature and distribution would influence that. Taking these factors into account, would there be value in also examining the impacts of fishing for the three species in terms of inter-specific competition?

With reference to the primary objective, assessing the impact on predators of fishing for small pelagics, a decision will need to be made on how many predator species or groups to include and which, noting the need to limit the number for statistical reasons. The degree of dependence of a predator on the small pelagic species is clearly a key consideration, as well as its conservation status and the potential role of food in affecting that status.

It is important that a MICE developed to provide advice on harvest rates has the statistical properties necessary for use in tactical management. As described in the Introduction, there are examples of application of MICE or MRMs that were based on population dynamics and at least one that used a simplified EwE model. One of the examples given also has spatial structure. If the capacity is available, there could be value in developing more than one kind of MICE but the question arises as to whether, *a priori*, preference should be given to any particular type of MICE for the objectives to be addressed in this case.

6. *Acknowledgements*

Thanks are given to A. Ross-Gillespie and S. Holloway (MARAM) for providing estimates of 2024 biomasses of hakes and horse mackerel respectively, to A. Makhado and M. Masotla (DFFE) for recent estimates of numbers of African penguin, Cape gannet and Cape cormorant, and to M. Seakamela for information on recent counts of seal pups. S. Kerwath (DFFE) is also thanked for providing the references to recent assessments of snoek and yellowtail (Yemane and Kerwath, 2024a, b).

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Appendix: Calculation of estimated total annual consumption (all species, not only small pelagics).

a) *Fish*

Species	Biomass (t)	Reference	Q/B (Shannon et al., 2020)	Population annual total consumption (t)
Horse mackerel (adult)	1 979 000	Holloway, pers.comm.	10	19 790 000
Snoek	100 921	Yemane and Kerwath, 2024.	5	504 603
Yellowtail	5 142	Yemane and Kerwath, 2024.	5	25 711
Large M. capensis (≥ 3 yrs)	434 000	Ross-Gillespie pers.comm.	4.4	1 909 600
Small M. paradoxus (< 3 yrs)	135 000	Ross-Gillespie pers.comm.	16	2 160 000

b) Seabirds

Species	Number (breeding pairs)	Reference	Daily food intake (g)	Reference	Population annual consumption (t)
African penguin	10 000	Makhado et al. (2023)	758	Gaglio et al., 2018	5 533
Cape gannet	142 786	Latest counts, Makhado and Masotla, pers.comm	1250	Gaglio et al., 2018	130 292
Cape cormorant	24 049	Latest counts, Makhado and Masotla, pers.comm	547	Gaglio et al., 2018	9 603

c) Seals

Butterworth et al. (1995) estimated the total seal population in 1993 as approximately 1.7 million individuals and total consumption to be in excess of 2 million tons, of which 600 000 tons was consumed off the West Coast of South Africa. In an analysis of trends in the seal population from 1972-2004, Kirkman et al. (2007) concluded that the biomass of seals had been relatively stable since then, around the 1993 estimate. M. Seakamela (DFFE) confirmed that more recent seal pup counts indicate that conclusion still applies. It is therefore assumed that the total consumption of 600 000 tons by seals in South Africa estimated by Butterworth et al (1995) is still valid.