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Using spatial population models to investigate the potential effects of the Ross Sea region Marine Protected Area on the Antarctic toothfish population

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ABSTRACT

One aim of Marine Protected Areas (MPAs) is to protect a representative portion of the environment through spatial closures to extractive practices such as fisheries. Although they usually involve the displacement of fisheries, their design rarely takes into account the effect of displacing that fishery on the target fish population. We used a spatially explicit population model of Antarctic toothfish in the Ross Sea region to investigate the effects of the endorsed Ross Sea region MPA on the fishery dynamics and the spatial distribution of the toothfish population. Our study indicates that the MPA will likely improve protection of the juvenile population residing on the Antarctic Shelf, while the number of areas with high levels of depletion is unlikely to increase compared to status quo management. Results also suggested a small increase in the catch limit under the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) harvest management rules, but with a slight reduction in catch rates. We have showed that spatial modelling tools can help inform MPA planning by simultaneously quantifying potential effects on the fish population and the ability to achieve conservation goals.

1. Introduction

Marine Protected Areas (MPAs) are increasingly used as a tool to conserve, manage and protect the oceans. Traditionally, MPAs aimed to eliminate potential threats to parts of the ecosystem in particular locations or to protect a representative portion of particular habitats, by implementing spatial prohibitions on extractive practices such as fisheries (IUCN, 2013). However their aims have diversified, and can include enhancing benefits to the fishery they are applied to (e.g., Brown, 2016; Gruss, 2014; Rassweiler et al., 2012). MPAs can be designed by optimising the size and location of these spatial closures based on the specific protection objectives of the MPA and taking into account the cost of the changes to extractive and other practices (see syntheses in, for example, Crowder and Norse, 2008; Ehler and Douvere, 2009; Groves et al., 2002; Leslie, 2005).

Spatial analyses are required to understand the biological and financial implications of such closures (Sanchirico 1999). The effects of proposed spatial closures and other spatial management options on fleet behaviour and their financial returns have been studied (Bastardie et al., 2014; Holland, 2000; Lehuta et al., 2013). Results from these studies showed that the design of each proposed MPA had strong impacts on its effectiveness to protect species as well as on the cost to the fishery, and could be either positive or negative. Furthermore, accurately anticipating the consequences of alternate proposed spatial management scenarios on the fish populations requires understanding the spatial demographics, movement patterns, and dynamics of impacted populations as well as the fleet behaviour at the scale of the proposed spatial management or smaller (Botsford et al., 1993; Christensen et al., 2009).

Studies investigating the potential impact of MPAs on the ability to accurately estimate biomass within stock assessment models have shown that MPAs could result in a bias in the estimation of the fish population, particularly for larger MPAs, if data are not available inside the MPA or if a single area model is used averaging processes inside and outside the MPA (McGillard et al., 2014; Pincin

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Table 1
Biological parameters used for Antarctic toothfish in the model.

Relationship	Parameter	Value
Natural mortality	M (y^{-1})	0.13
Von Bertalanffy growth curve	t_0 (y)	−0.117
	k (y^{-1})	0.091
	L_∞ (cm)	174.5
	c.v.	0.1
Length-weight regression	a	$1.051e^{-08}$
	b	3.036
	c.v.	0.1
Maturity	a_{50} ($\pm ato_{95}$)	12.2 (±2.8)
Stock recruit steepness (Beverton-Holt)	h	0.75
Recruitment variability	σ_R	0.6
Ageing error (CV)	c.v.	0.1
Initial tagging mortality	(%)	10
Initial tag loss (per tag)	(%)	3.3
Instantaneous tag loss rate (per tag)	(y^{-1})	0.062
Tag detection rate	(%)	98.8
Tag related growth retardation	(y)	0.5

Table 2
Depletion level of the total biomass in 2048 as a proportion of the unfished biomass in 1995 ($1 - B_{2048}/B_0$) and mean fish age at the start of the fishery (at B_0) and in 2048 (at B_{2048}) for each zone.

Metric	Scenario	Shelf	Slope	North
Depletion in 2048 ($1- B_{2048}/B_0$)	1. Status quo	0.28	0.40	0.47
	2. MPA and historic distribution	0.23	0.40	0.51
	3. MPA and spreading distribution	0.23	0.40	0.51
	4. Proportional to vulnerable biomass	0.26	0.39	0.49
Mean age at B_0		6.6	10.3	17.7
	1. Status quo	6.0	8.6	15.3
	2. MPA and historic distribution	6.1	8.6	15.0
	3. MPA and spreading distribution	6.1	8.6	15.0
Mean age at B_{2048}	4. Proportional to vulnerable biomass	6.0	8.7	15.1

and Wilberg, 2012; Punt et al., 2016). Spatial population models have also been used to investigate the likely impacts of alternate spatial fisheries management scenarios on fish populations as part of MPA design (e.g., Colloca et al., 2015; Edwards and Plagányi, 2011; Metcalfe et al., 2015), showing that specific portions of the fish populations (either juveniles or lager older fish) need to be protected for the MPA to achieve an ecosystem conservation goal. However, limitations of current modelling approaches to provide useful advice include the spatial scale at which fish movement is often modelled (e.g., Bastardie et al., 2014; Lehuta et al., 2013), and the fact that displacement of fishery effort is often not included in these models, therefore ignoring increased effort and associated negative impacts on other parts of the ecosystem (see Gruss, 2014 for a review).

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) is the international body which manages the conservation and rational use of Antarctic Marine Living Resources, including Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region. Spatial management is carried out through a network of open and closed areas, whereby the closed areas are designed to protect target and by-catch species from the effects of fishing (Conservation Measure 32-02 CCAMLR-XXIV, 2015; Hanchet et al., 2015b). These open and closed areas were initially set arbitrarily circumpolar to protect a proportion of the ecosystem prior to fishing, and have been modified through time as knowledge of the ecosystem has increased. In October 2016, CCAMLR established the Ross Sea region Marine Protected Area (RSR MPA), the first of its kind in international waters (CCAMLR, 2016), following scientific advice. The RSR MPA was designed to protect the biodiversity of the Ross Sea region. One of its objectives is to protect areas of importance in the life cycle of Antarctic toothfish, with all other objectives centred on other ecosystem functions.

The fishery for Antarctic toothfish in the Ross Sea region started in 1997, expanding to taking the catch limit from 2005 onwards. The population size of Antarctic toothfish in the Ross Sea region has been assessed using a single area stock assessment (Mormede et al., 2014a). This stock assessment and subsequent updates are used to set the catch limit in the Ross Sea region. In 2015, the spawning stock biomass was at 70% of unfished spawning stock biomass (30% depletion), i.e. this stock is still in a fishing-down phase (CCAMLR, 2015). A spatial population model of toothfish was developed for the Ross Sea region to investigate the potential bias of the single area stock assessment that ignores the spatial structure of the population and the fishery (Mormede et al., 2014b). Results showed that the single area model was likely to under-estimate the biomass of the stock by 30–50%.

This study aims to investigate the effects of the redistribution of the location of catches of toothfish on both the toothfish population and its fishery due to the inception of the RSR MPA. We use the spatial model developed by Mormede et al. (2014b) and apply spatial management simulations reflecting the RSR MPA design. We investigate the effects of the corresponding fishing displacement scenarios on the toothfish population, whether localised depletion will occur in the Ross Sea region as well as its degree and location, along with alternate effort displacement scenarios. We also quantify the effect that the MPA might be expected to have on the catch limit and catch rates under current CCAMLR harvest management rules.

2. Methods

2.1. Antarctic toothfish in the Ross Sea region

Antarctic toothfish are a large nothotenoid fish found around the Antarctic continent. They are closely related to Patagonian toothfish (*Dissostichus eleginoides*), but generally found at lower latitudes than Patagonian toothfish which lacks anti-freeze protein. Patagonian toothfish are caught in small numbers in the northern part of the Ross Sea region and are not included in this analysis. Antarctic toothfish mature at about 10 years of age for males and 15 years for females (50% maturity) and grow to a maximum size of 1.8 m at about 35 years of age (Hanchet et al., 2015a; Parker and Grimes, 2010). Biological parameters for Antarctic toothfish are summarised in Table 1. In the Ross Sea region, Antarctic toothfish are a top predator, with stable isotope levels of carbon and nitrogen (δ15N and δ13C) similar to that of Weddell seals and killer whales (Pinkerton et al., 2010). They are expected to have a moderate trophic importance in the Ross Sea foodweb whereby changes to the toothfish population are unlikely to cascade through the ecosystem by direct trophic effects (Pinkerton and Bradford-Grieve, 2014). However, Antarctic toothfish might be an important part of the diet of other top predators at specific times of the year such as Weddell Seals during lactation and post-lactation recovery periods (Eisert et al., 2013). As such, it is important to understand the impacts of any new management regime on expected toothfish population distribution and trajectories given the potential ecosystem impacts it may cause throughout the Antarctic Ocean.

The Ross Sea region is likely to comprise an enclosed unit stock of Antarctic toothfish, centred on the Ross Sea gyre. The life cycle