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Supplementing electronic tagging with conventional tagging to redesign fishery closed areas

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ABSTRACT

Fishery closed areas provide a resource management tool to protect predictable spawning aggregations of migratory fish species. Movement by individual fish however challenges the effectiveness of fishery closed areas. Recent developments in electronic tags and movement modelling offer new information to quantify fine-scale usages of fishery closed areas by free-ranging individuals. Conventional tagging data, on the other hand, inform on population broad-scale distribution patterns with respect to closed areas. Using the Atlantic cod (*Gadus morhua*) population from the northern Gulf of St. Lawrence as a case study, we demonstrate how electronic tagging experiments can be supplemented with conventional tagging experiments to evaluate and redesign fishery closed areas. A geolocation model was used to estimate time of arrival, time of departure, and proportion of time that individual cod equipped with data-storage tags spent within a fishery closed area. Two optimization algorithms were developed to seek out the spatial and temporal designs that maximized the proportion of time that the fish equipped with data-storage tags spent inside the closed area, relative to its size and duration. Bootstrap analyses quantified the effects of inter-individual variability in closed area usages. Conventional tagging data were used to estimate the proportion of the spawning population density function encompassed by the closed area. Results from the electronic and conventional tagging experiments suggested that the fishery closed area in the northern Gulf of St. Lawrence should be displaced south along the 200-m isobath and that the enforcement period be reduced. Electronic tagging data also suggested that alternative migratory behaviours within a population lead to disproportional levels of protection between migratory and non-migratory groups. A re-examination of past conventional tagging experiments in combination with recent electronic tagging experiments provides new information to evaluate the spatiotemporal design of fishery closed areas

1. Introduction

The tendency of commercial fish species to aggregate during predictable spawning periods exacerbates their vulnerability to human exploitation. Fishery closed areas on migratory corridors and spawning grounds provide a resource management tool to help rebuild depleted populations (Murawski et al., 2000; Jensen et al., 2010). Fishery closed areas on spawning grounds have limited benefits if constant catch levels are applied outside closed areas (Horwood et al., 1998; Walters et al., 2007; West et al., 2009; Grüss et al., 2013). However, when appropriately designed and combined with other management measures that control for fishing effort in adjacent areas, fishery closed areas on spawning grounds may help rebuild a depleted migratory population by reducing mortality rates on the spawning stock biomass, and avoiding disruption of the reproductive activity (Beets and Friedlander, 1999; Rowe and Hutchings, 2003; Stefansson and Rosenberg, 2006). Although the level of protection afforded by a fishery closed area partly depends upon adult movements across closed area boundaries, and upon size of population distributional range relative to closed area size (Murawski et al., 2000; O'Boyle, 2011), adult movements and population distribution with respect to closed areas remain recurrent knowledge gaps to closed areas design and implementation (Sale et al., 2005; Grüss et al., 2011).

Recent advances in electronic fish tracking technologies and concurrent developments in the modelling of tracking data have revolutionized the study of animal movement (Nathan et al., 2008). Migration routes of numerous marine migratory species are now being reconstructed (Block et al., 2011), including pelagic (Block et al., 2005; Kraus et al., 2011) and demersal migratory fish species (Svedäng et al., 2007; Mitamura et al., 2009). When direct observations of fish positions are not available from the tag, fish positions are inferred from the recorded environmental variables using robust and widely available statistical geolocation models

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(Patterson et al., 2008; Evans and Arnold, 2009; Jonsen et al., 2013). Probability distribution functions of fish position resulting from geolocation models allow the quantification of fine-scale usages of closed areas by free-ranging adult fish (Andersen et al., 2007). As such, electronic tagging (ET) experiments offer unprecedented opportunities to refine the spatiotemporal design of fishery closed areas from fishery independent observations.

The cost of fish tracking devices limits the number of tagged individuals in practice. Although conventional tagging (CT) data are fishery dependent and have limited temporal resolution, the larger number of tagged fish facilitates inferences to the population for broad-scale patterns (Bolle et al., 2005; Espeland et al., 2008). Recapture locations from CT experiments are samples from the population density. They can therefore be used to estimate the tagged population density function over determined periods (Righton et al., 2007; Espeland et al., 2008). Recently, combinations of ET and CT experiments have been used to study seasonal migration across management division boundaries and to estimate stock exploitation rates (Righton et al., 2007; Kurota et al., 2009). In this study, we demonstrate that combination of ET and CT experiments can also be used to evaluate and redesign fishery closed areas. Indeed, the fine spatial and temporal scale observations gathered from ET experiments, and the broad-scale spatial observations gathered from CT experiments, provide different but complementary datasets to quantify the extent of movement across closed areas boundaries and the proportion of the spawning population density function encompassed by closed areas.

This study demonstrates how ET experiments can be supplemented with CT experiments to redesign fishery closed areas. A fishery closed area designed to protect a spawning aggregation of Atlantic cod (*Gadus morhua*) in the northern Gulf of St. Lawrence is the case study presented here. A geolocation model was used to estimate the proportion of time that Atlantic cod equipped with data-storage tags (DSTs) spent inside the closed area during the enforcement period. A spatial optimization algorithm and a temporal optimization algorithm were developed to refine the closed area design. Bootstrap analyses quantified the effects of inter-individual variability in closed area usages on the estimated proportion of time spent within the closed area. Kernel density estimations of recapture positions from three CT experiment programs (two pre-population collapse 1983–1985 programs and one post-population collapse 1995–2002 program), were used to estimate the proportion of the tagged population density function encompassed by the closed area. Encompassed proportions were estimated for four closed area designs identified beforehand with the two optimization algorithms.

The Atlantic cod population from the northern Gulf of St. Lawrence (nGSL, Fig. 1) collapsed in the late 1980s early 1990s (Fréchet et al., 2009). Despite two moratoriums on the fishery, a first one from 1994 to 1996 and a second one in 2003, a two decades long drastic reduction in the fishing effort, and a ban of commercial trawling for groundfish in the nGSL since 1997, the population is still considered as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2010). The bulk of the population overwinters in the relatively deep water of the Laurentian Channel (Campana et al., 1999). In early spring, cod start migrating towards the main spawning ground located off the southwest coast of Newfoundland, off St. George's Bay (Ouellet et al., 1997; Méthot et al., 2005). In late spring, cod leave the main spawning ground to reach summer feeding grounds along the Newfoundland west coast and the Québec North Shore (Yvelin et al., 2005). The documentation of a remaining spawning aggregation of Atlantic cod by combined acoustic, ichthyoplankton, and bottom-trawl surveys conducted in the springs 1993, 1994, 1995, and 1998 (Ouellet et al., 1997; McQuinn et al., 2005) led to the implementation of a seasonal fishery closed area in 2002 (FRCC, 2002; DFO, 2003). The closed area approximates 5000 km^2 and is delimited by the following coordinates: 48°15′N–49°10′N and 59°20′W–60°00′W (Fig. 1). The fishery closure prohibits all ground fishing activities yearly from April 1st to June 15th, in order to reduce adult mortality rate, avoid disruption of the reproductive activity, and prevent bycatch of Atlantic cod in other demersal fisheries, including redfish (*Sebastes* spp.), Atlantic halibut (*Hippoglossus hippoglossus*), witch flounder (*Glyptocephalus cynoglossus*), turbot (*Reinhardtius hippoglossoides*). However, in the absence of surveys and catch data during the enforcement period, no attempt has been made to evaluate and redesign the fishery closed area since its implementation in 2002.

2. Materials and methods

2.1. Electronic tagging

An ET experiment program using DSTs was conducted in the nGSL from 2007 to 2012. A total of 353 Atlantic cod (fork length >40 cm) were captured using baited handlines and surgically implanted with DSTs inside the abdominal cavity. Tagging locations were chosen to cover the three Northwest Atlantic Fisheries Organization (NAFO) management units in the nGSL (i.e. NAFO divisions 3Pn, 4R, and 4S, Fig. 1). DSTs recorded temperature and pressure over time. Lotek tag series LTD_1100 and LAT_1400 (Lotek Wireless Inc., www.lotek.com) were used in the experiments. T-bar anchor tags were fixed in the dorsal musculature to alert harvesters about the presence of the internal tag. Advertisement and reward campaigns were used to increase tag reporting rate. Data were successfully downloaded from 17 recovered DSTs. Time series with incomplete record during the April 1st–June 15th period were removed. A total of 14 DSTs were used in this study (Table 1).

2.2. Geolocation

A geolocation model was used to reconstruct migration routes of Atlantic cod equipped with DSTs in the nGSL (Le Bris et al., 2013). The low tidal range in the Gulf of St. Lawrence prevented the use of the tidal location method to infer fish position (Metcalfe and Arnold, 1997; Hunter et al., 2003). The model instead compared the daily maximum depth (i.e. deepest depth) and the associated temperature recorded by the tag, with depth and temperature from bathymetric and seasonal bottom temperature grids (Galbraith et al., 2012). The model relied on a hidden Markov model (HMM) to compute the posterior probability distribution function of fish daily location (Pedersen et al., 2008; Thygesen et al., 2009). HMMs consist in two coupled stochastic models: the process model and the observation model. For each tracked day, the process model simulated individual fish movement in the plane using a diffusion equation:

$$\frac{\partial \varphi(\mathbf{x},t)}{\partial t} = D\left[\frac{\partial^2 \varphi(\mathbf{x},t)}{\partial x^2} + \frac{\partial^2 \varphi(\mathbf{x},t)}{\partial y^2}\right] \tag{1}$$

where $\varphi(\mathbf{x},t)$ is the probability distribution function of the fish position (i.e. the probability that the fish is located at position $\boldsymbol{x} = [x,y]$ at time $t = \{1, \ldots, T\}$), and D represents the diffusion rate. This partial differential equation was discretized in space onto a 2 km resolution grid (i.e. 331 × 476 regular grid cells) and time (number of recording days T) and solved using finite differences.

The observation model refined positions predicted by the movement model by assigning a likelihood value based on the match between bathymetry and bottom temperature at the estimated position $x(x,y)$ and the daily maximum depth and associated temperature recorded by the tag $y(z,tp)$. Atlantic cod is a demersal fish species. It was assumed that Atlantic cod in the nGSL visit