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Spatiotemporal physical barrier analysis of southern king crab (*Lithodes santolla*) catch rates in Magallanes, Chilean Patagonia (2014–2020)

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Abstract

Spatiotemporal patterns on fishing success and catch rates were analyzed for the southern king crab (*Lithodes santolla*) fishery in Chilean Patagonia (48ºS-55ºS). The analysis considered the effects of physical barriers on the spatial distribution within two complex coastal geography fishing zones. The north zone (50–54°S), close to Puerto Natales, has the more complex coastal topography, with numerous islands, archipelagos, channels, and inland sea. Instead, the south zone (55°−56°S) is relatively free of barriers. Operational data from 2014 to 2020 were obtained on board by scientific observers. The best spatiotemporal model was an opportunistic spatial pattern characterized by different yearly spatial realizations for fishing success and catch rates, with seasonal and bathymetric effects for catch rates. The higher catch rates in the north zone are probably associated with the size of crab aggregations, which tend to disperse over a wider area due to physical barriers. In contrast, the south zone has fewer physical barriers and more concentrated crab aggregations. Therefore, catch per unit effort in the southern king crab fishery should consider the effects of physical barriers on the spatial correlations and other covariables for fishing power and catchability effects.

Introduction

Understanding the temporal, spatial, or spatiotemporal effects on catch rates is essential in fisheries analysis, especially in cases where a fishery operates in complex geographical areas. For example, physical barriers such as islands, archipelagos, inland seas, and channels affect the stationary isotropic spatial correlation assumed by most spatial models (Bakka et al., 2019, Gómez-Rubio, 2020).

The primary data sources in fisheries analysis and stock assessment include catch, relative abundance indices, age, size, and sex composition data from catches or surveys (Hilborn and Walters, 2013, Maunder and Punt, 2004). For example, fishery-dependent abundance indices, such as catch per unit effort (CPUE) or catch rates, are typically analyzed by accounting for fixed sources of variation and operational, functional, or structural covariates of fishing fleets. The analysis aims to reflect proportional changes in stock abundance rather than availability, catchability, or relative fishing power (Burch et al., 2011, Kimura, 1981, Maunder et al., 2020, Maunder and Punt, 2004).

In classical standardization, the year effect (i.e., the temporal component) is assumed to be a proxy for abundance. However, such changes are at best assumed to be similar among geographic strata and assumed to be independent, where changes differ from a constant intercept. Thus, catch rates are frequently analyzed through generalized linear (mixed) models (GLM/GLMM) or generalized additive (mixed) models (GAM/GAMM) (Xiao et al., 2004). When standardizing indices, the interaction between years and other spatial categorical variables involves choosing a reference level. If the categorical variable is treated as a random effect, the average level of that variable must be chosen, or weighted by area size (Maunder et al., 2020, Venables and Dichmont, 2004).

An alternative is to consider hierarchical Bayesian spatiotemporal models. In this context, Thorson (2019), Thorson et al. (2020), and Maunder et al. (2020) have pointed out that spatiotemporal models could improve the estimation of relative abundance indices as they assume that catch rates could be more similar between nearby locations and years, indicating spatial and temporal correlation (Thorson et al., 2020). Often, spatiotemporal models consider spatial processes by assuming them to be stationary and isotropic, i.e., when the statistical properties are the same at any point within the study area and when the intensity of the spatial process does not change regardless of the direction (Gómez-Rubio, 2020, Lindgren and Rue, 2011). Thus, the covariance between any two points depends on the distance rather than the relative position, and the stationary and isotropic Matérn correlation function has been used to model the spatial structure in catch rates standardization (Cavieres and Nicolis, 2018, Izquierdo et al., 2022).

However, complex geographical areas of inland seas, islands, and archipelagos act as physical barriers that could significantly affect fishing success and catch rates. Hence, the assumption of independence and homogeneity implicit in modeling abundance indices through GLM/GLMM, GAM/GAMM, or the stationary assumption for the spatial correlation in spatial and spatiotemporal models may not hold. Some options to account for 2D/3D Gaussian process smoothers are implemented in GAM (i.e., mgcv package for R) by using a stationary or nonstationary kernel and spatial correlation functions like spherical, power exponential, and Matern (Simpson, 2018, Wood, 2017, Wood, 2020a, Wood, 2020b), as well as soap-film smoothers (Wood et al., 2008; Augustin et al., 2013; Maina et al., 2018). Nevertheless, we utilize here the approach to geographic barriers proposed by Bakka et al. (2019) in the context of hierarchical Bayesian spatiotemporal models using INLA (Integrated Nested Laplace Approximation) (Gómez-Rubio, 2020, Rue et al., 2009).

Moreover, the spatial structure in spatiotemporal models could vary depending on the complexity of the physical barriers, which could be significant in fisheries where fishers move fishing for the target species from low to higher fishing yield during the fishing season or to recurrent areas where the target species tend to be more abundant (Pet-Soede et al., 2001). According to Paradinas et al. (2017), a constant spatial field in time implies a persistent distribution, i.e., when a fleet remains yearly in the same fishing grounds. On the other hand, an opportunistic distribution means a spatial field yearly changing, probably associated with different yearly realizations in the fishing ground. Thus, hierarchical Bayesian spatiotemporal models are powerful and adaptable in measuring the underlying spatial field of fishery-dependent data (Cosandey-Godin et al., 2015, Martı´nez-Minaya et al., 2018, Paradinas et al., 2017).

In Chile, the southern king crab fishery (*Lithodes santolla*) is artisanal in the inland sea of Patagonia, south of 40ºS to Cape Horn (54°56′S). The southern king crab has a wide distribution that extends from Uruguay to Tierra del Fuego in the Atlantic (Wyngaard et al., 2016) and from the Los Ríos region (42°S) to Cape Horn (54°56′S), including the Strait of Magellan (53°28′S) and the fjords around Tierra del Fuego in Chile (Molinet et al., 2020). From a social point of view, the southern king crab fishery shares similar characteristics with Latin American small-scale fisheries (Salas et al., 2007), particularly labor-intensive, remote fishing grounds and landing sites, seasonal work, and low bargaining power among fishers. Indeed, fishing operations are carried out by harvesting vessels and transporting vessels. The extractive vessels generally set sail at the beginning of the season and remain in the fishing zone during the whole extractive period (Bozzeda et al., 2019). The transporting vessels supply the extractive vessels with fuel and various supplies or crew members' replacements. The vessels also transport the catch collected during fishing operations to the landing points in Punta Arenas (53°10′S-70°55′W) and Puerto Williams (54°56′S-67°36′W) (Fig. 1).

King crabs (family Lithodidae) in Chile, like other lithodids exploited in the northern hemisphere, are managed according to the so-called "3 S rule" (sex, season, and size), which means that females must be returned to the water; there is a closed season, and a minimum legal size of carapace length (CL) (Otto, 2014, Sainz, 2018). Applying these administration and management measures tends to optimize the reproductive potential of stocks subject to commercial fishing. It is worth mentioning that the measures in force in Chile are the following: a) traps are the only fishing gear, b) prohibition of landing and commercialization of females, c) minimum legal size of 120 mm CL for males, d) fishing season between July 1 and November 30; e) male specimens must arrive live to processing plants, and f) registration of new fishers is suspended in the Magallanes Region.

The southern king crab fishery is considered data-limited due to the lack of information required for an integrated stock assessment (Yáñez-Rubio, 2017). Indeed, obtaining operational data is challenging, and little is known about the fleet size's impact on the target species (Bozzeda et al., 2019). Nevertheless, Yáñez-Rubio (2017) standardized the catch per unit effort utilizing year, month, and bottom depth as factor effects in a GLM, but without spatial effects. Indeed, Yáñez-Rubio (2017) utilizes fishery-dependent data from daily landings records with limited resolution about the origin of the fishing grounds. Because fishing effort is likely to aggregate at locations where fishers expect a high concentration of the target species (Vasconcellos, Cochrane, 2005), it is essential to understand the spatial and spatiotemporal effects that require high spatial resolution data.

In this paper, we utilized limited but high-quality data collected by scientific observers on board vessels targeting southern king crab to address the issue of physical barrier effects on the spatial distribution of catch rates by comparing two significant fishing grounds in the Chilean Patagonia, i.e., the north and south zones (Fig. 1). These zones present different physical barriers than could affect the southern king crab catch rates. The artisanal fishers visit the same fishing grounds annually since they expect similar success and yield compared to the most recent year, implying a persistent spatial distribution of fishing success and catch rates. Alternatively, since fishers can move from locally depleted small zones to better ones within a large-scale fishing ground (Pet-Soede et al., 2001), an opportunistic distribution of fishing success and catch rates is another possibility. In this context, we analyze whether fishing success and catch rates are distributed in persistent local fishing areas under a constant nonstationary spatial field that does not change interannually or in small fishing areas set up as an opportunistic nonstationary spatiotemporal field that changes locally from one year to the next.

Section snippets

Study area and data

The study area is located in southern Chilean Patagonia, Magallanes administrative region (48–54°S), with a complex coastal topography composed of inland seas, channels, islands, and archipelagos that act as physical barriers (Fig. 1). In the Magallanes region, the southern king crab artisanal fishery operates in two zones, one located in a northern area (48–54°S), close to Puerto Natales (51°43′S-72°30′S), and another zone in the south (55°−56°S) with irregular operations in the Beagle Channel …

Results

The operational data for fishing success and catch rates ranged between 482 and 810 records in the north zone and between 111 and 266 records in the south zone. Yearly, the fishing success in the north zone ranged between 91.0% and 94.8%, while it fluctuated between 94.0% and 98.1% in the south zone. The average catch per trap ranged between 11.8 and 23.4 kg per trap in the north, and between 31.0 and 35.5 kg per trap in the south zone (Table 1). In addition, the standard deviation of the catch …

Discussion

Artisanal fisheries often operate along complex coastal geography, where inland seas, channels, islands, and archipelagos act as physical barriers. Such is the case of the southern king crab fishery in southern Chilean Patagonia, with two different fishing grounds. The north zone (50–54°S), close to Puerto Natales, has the most complex coastal topography. Instead, the south zone (55°−56°S) is relatively free of barriers compared to the northern zone. Nevertheless, the results provide insight…

CRediT authorship contribution statement

R.E. Hernández-Rodriguez: Conceptualization, Investigation, Data curation, Writing – original draft preparation. **L. A. Cubillos:** Conceptualization, Project management, Formal analysis, Methodology, Writing – review & editing.…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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