ORIGINAL RESEARCH

An experimental study on ghost fishing in rocky coastal reefs in southern Brazil

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ABSTRACT. A ghost fishing experiment was conducted using gillnets in a rocky reef off the state of Santa Catarina, southern Brazil. Scuba divers monitored changes in the structure of the nets and catches for 92 days. One hundred and twenty-six entangled animals were observed, including target and non-target fishing species: 13 teleosts (N = 52; 43%) and four crustaceans (N = 74; 57%). The crab *Menippe nodifrons* was the most frequently entangled species (N = 36; 28%). Entanglement rates decreased over time following a logarithmic model for fishes and crustaceans, and an exponential model for both taxa combined, attributed to the degradation, and tangling of the nets and biofouling. The area of the net decreased linearly over time, collapsing after 92 days. This study provides the first experimental evaluation of the impacts of ghost fishing caused by gillnets in Brazilian rocky reefs.

Key words: Derelict gillnets, entangled, marine litter.

Estudio experimental sobre pesca fantasma en arrecifes costeros rocosos del sur de Brasil

RESUMEN. Se realizó un experimento de pesca fantasma utilizando redes de enmalle en un arrecife rocoso frente al estado de Santa Catarina, en el sur de Brasil. Los buzos monitorearon los cambios en la estructura de las redes y las capturas durante 92 días. Se observaron ciento veintiséis animales enmallados, entre especies de pesca objetivo y no objetivo: 13 teleósteos (N = 52; 43%) y cuatro crustáceos (N = 74; 57%). El cangrejo *Menippe nodifrons* fue la especie más frecuentemente enmallada (N = 36; 28%). Las tasas de enmalle disminuyeron con el tiempo siguiendo un modelo logarítmico para peces y crustáceos, y un modelo exponencial para ambos taxones combinados, atribuidos a la degradación y enredo de las redes y bioincrustaciones. El área de la red disminuyó linealmente con el tiempo, la cual colapsó después de 92 días. Este estudio proporciona la primera evaluación experimental de los impactos de la pesca fantasma causada por redes de enmalle en los arrecifes rocosos de Brasil.

Palabras clave: Redes de enmalle abandonadas, enmallado, basura marina.

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INTRODUCTION

Reports of abandoned, lost, or otherwise discarded fishing gears (ALDFG), also called derelict fishing gears, first appeared in the scientific literature in the early 1970s (Smolowitz 1978). However, it was not until the 1990s that this issue was recognized as an emerging threat (Shomura and Yoshida 1985; Goldberg 1995). Fishing, and derelict gears, have direct and indirect impacts on coastal and marine ecosystems (Macfadyen et al. 2009). The inappropriate disposal of solid waste indirectly damages aquatic populations, leading to economic losses to the fishing activity (Dayton et al. 1995). Hundreds of marine species have been affected by fishing gear entanglement and ingestion (NOAA 2014). Weather, operational fishing factors and gear conflicts are probably the most significant aspects causing the loss or discard of fishing gears at sea (Macfadyen et al. 2009), where they can entangle, trap, or kill fishes and other aquatic animals, a phenomenon called 'ghost fishing' (Kura et al. 2004).

Commercial and non-commercial species of fishes and crustaceans, birds, marine mammals, and turtles are affected by ghost fishing around the world (Matsuoka et al. 2005; Brown and Macfadyen 2007; Beneli et al. 2020), a phenomenon that has worsened with the use of synthetic, slow-degrading material, which might persist for decades in the environment. The subject has gained increasing attention in the last two decades (Gilman et al. 2012, 2016) and is currently well documented (Gilman et al. 2021). Derelict gillnets represent one of the highest risks amongst marine commercial fishing gears due to their global adverse effects (Gilman et al. 2021).

Direct measurements of fishing capacity of lost gill and trammel nets by diving observations date back to the 1990s (Kaiser et al. 1996; Erzini et al. 1997). When nets are lost, they continue to fish before becoming physically damaged or heavily colonized by incrusting biota, thus losing their catching ability. Catch rates and the evolution of lost gillnets would allow for estimating total mortality of marine life due to derelict gears (Ayaz et al. 2006; Akiyama et al. 2007; Baeta et al. 2009). A quantitative assessment of the direct impact of derelict gears on marine resources must take into account the rate of loss of such species, the effective impact lifespan of the gear, and the market value of the species caught (Gilardi et al. 2010).

A growing concern about litter in aquatic systems has also been observed in Brazil, with reports for freshwater (Iriarte and Marmontel 2013; Azevedo-Santos et al. 2022), oceanic (Santos et al. 2012; Grillo and Mello 2021), and coastal regions (Mascarenhas et al. 2008; Machado and Fillmann 2010; Vieira et al. 2011; Andrades et al. 2020; Pinheiro et al. 2021), and its subsequent impacts on estuarine fauna (Possatto et al. 2011; Dantas et al. 2012). There are also a few studies on derelict fishing gears and ghost fishing (Chaves and Robert 2009; Adelir-Alves et al. 2016), including a review of ALDFG (Link et al. 2019) and the negative impacts of ghost nets on Brazilian marine biodiversity revealed by digital media (Azevedo-Santos et al. 2021). However, till now, a quantitative assessment of the direct impact of derelict fishing gears on marine resources had not been conducted in Brazil.

This study simulated ghost fishing by derelict gillnets aiming at quantifying entanglement rates for fish and crustaceans, and at assessing net collapse over time in shallow rocky reefs off the state of Santa Catarina, in southern Brazil.

MATERIALS AND METHODS

Study site

The coast of the state of Santa Catarina is 531 km long (Figure 1), corresponding to 7% of the

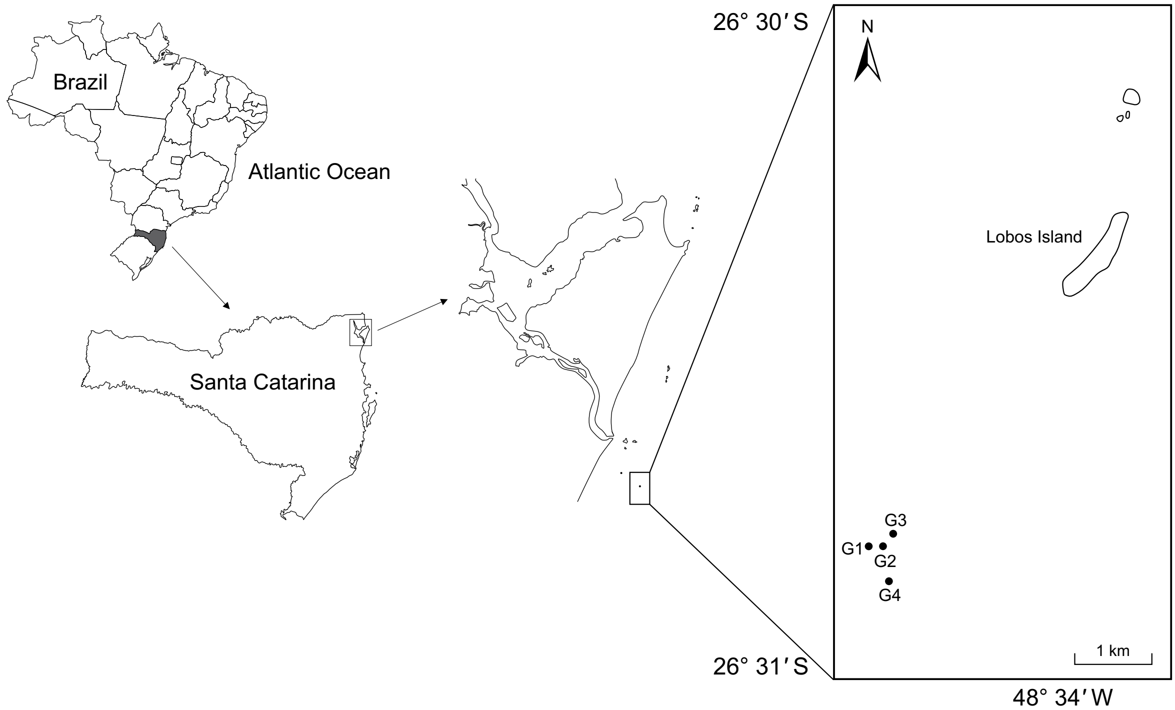

Figure 1. Location of gillnets (G1, G2, G3, G4), near Lobos Island, northern coast off the state of Santa Catarina, southern Brazil. Map: Diogo A. Moreira.

Brazilian coast, and belongs to the biogeographical province of the Southwest Atlantic or Brazilian Province (Floeter and Gasparini 2000). The region is influenced by two main atmospheric systems, the South Atlantic Subtropical Anticyclones (SASH) and the Atlantic Polar Migratory Anticyclone. These anticyclones are the generating sources of the Atlantic Tropical Mass (ATM) and the Atlantic Polar Mass (APM), respectively. The Atlantic Polar Front (APF), resulting from the contact between these two air masses, is responsible for part of the local precipitation, controlled by the presence of the mountains of Serra do Mar, Eastern Santa Catarina, and Serra Geral. Total annual rainfall is higher on the northern coast of the state (1,800 mm). The average number of cold fronts is quite similar in all seasons, with a slight decrease in the summer and a slight increase in the winter. SASH and APM anticyclones lead to an alternate prevailing wind regime between northeast (SASH) and south (cold fronts) (Carvalho et al. 1998; Pereira et al. 2009).

Experiment and data analysis

The experiment was set up in rocky reefs, 7 km (4 nm) off the northern coast of the state of Santa Catarina (Figure 1). An echosounder was used to check local depth and slope to subsequently deploy four gillnets. Nets were arranged vertically in 12 m deep areas, fixed on the rocky bottom with anchors on both sides, flagged with a surface buoy, and georeferenced (G1 26° 31′ 11.88″ S, 48° 33′ 56.16″ W; G2 26° 31′ 11.82″ S, 48° 33′ 55.20″ W; G3 26° 31′ 10.98″ S, 48° 33′ 54.48″ W; G4 26° 31′ 14.22″ S, 48° 33′ 54.78″ W). Rectangular gillnets (20 m long and 2 m high) of green polyamide monofilament (diameter = 0.7 mm; mesh size = 10 cm between opposite knots), placed around 50 m apart from each other, were used with floaters on the top line and lead sinkers on the bottom line, like those used by local fishers.

Two scientific divers conducted visual census on the nets using scuba diving (Heine 1999; Donohue et al. 2001; Pollock and Godfrey 2007). All nets were surveyed from March 29th to July 1st, 2012, with different time intervals (1, 9, 29, 55, 75, and 92 days after deployment). Each net was monitored for 30-40 min and the resulting data were recorded on a PVC clipboard using pencil; underwater photos and/or videos were taken. All entangled animals were identified to the lowest taxonomic level (Figueiredo and Menezes 1978, 1980, 2000; Fonteles-Filho 1999; Melo 1996; Menezes and Figueiredo 1980, 1985; Menezes et al. 2003), counted, and tagged with plastic clamps to prevent double counting.

To assess the entanglement, all divers followed the same procedure in each subsequent dive, recording the condition of previously observed entanglements and registering new entanglements. To evaluate the structural evolution of nets, the height between the top and bottom lines of each gillnet was measured along their length (0, 2.5, 7.5, 10.0, 12.5, 15.0, 17.5, 20.0 m) to calculate the area of the net over time. A linear model was fitted to the rate of reduction in area, and consequently in fishing capacity, due to the collapse of the net (% original area = -a ln(day + b). Sketches of each gillnet were drawn to show the reduction of the net area throughout the time. All nets were removed immediately after the final survey.

Entanglement rates (ER: number of entangled animals/day/net) were calculated by taxa (crustaceans, fishes) by counting the number of animals newly entangled between surveys and dividing by the number of days between observations (Gilardi et al. 2010). Nonlinear models (logarithmic: ER = a ln(Day) + b, and exponential: ER = a e^{bDay}) were checked for fishes, crustaceans, and total quantity (fishes and crustaceans) (Faraway 2002; Zar 2010).

The local market price of target species (USD kg^{-1}) was used as a proxy to indicate commercial importance. The recreational importance was defined based on personal observation (JAA).

RESULTS

A total of 126 animals were observed entangled in all four gillnets: four species of crustaceans (n = 74; 57%) and 13 species of fish (n = 52; 43%) (Table 1). The stone crab *Menippe nodifrons* Stimpson, 1859 was the most frequent species (n = 36; 28%). Eight of the entangled fish species and one crustacean *Panulirus laevicauda* (Latreille, 1817) have commercial importance (Table 1).

The number of entangled fishes surpassed the number of crustaceans in the first two dives, reaching 59% of total catches in Day 9 (Figure 2). After this period, the percentage of entangled fishes decreased until reaching zero, 92 days after the deployment of the nets. Crustacean entanglements increased over a longer period and decreased later.

Entanglement rates for fishes [ER = -0.269 ln(Day) + 1.1715] and crustaceans [ER = -0.164 ln(Day) + 0.826] showed higher coefficients of determination in logarithmic models (R^2 = 0.91 and 0.90, respectively) (Figure 3 A). When fishes and crustaceans were combined, the entanglement rate [ER = 1.3748 $e^{-0.032Day}$] had a higher coefficient with an exponential model (R^2 = 0.98) (Figure 3 B).

The fishing area of the nets decreased over time, due to the accumulation of detritus, biofouling, and damages such as broken meshes (Figure 4 A and 4 B). Their physical fishing capacity was reduced to 26% of the original value after 75 days of immersion (Figure 5). The rate of loss of fishing capacity was fitted to a linear model (% original area = -0.938Day + 88.112; R^2 = 0.96). Thus, it is expected that gillnets are totally collapsed within 94 days, on average, under the experimental conditions.

Table 1. List of taxa (class, family, species) caught in the ghost experiment conducted off the coast of Santa Catarina in 2012, total number of individuals caught per species (N), relative abundance (%), fishing importance (FI) in price per unit of weight (P-USD kg^{-1}), fished by recreational fishers (RF), and no commercial or recreational importance (—).

Class	Family	Species	N	%	FI
Crustacea	Xanthidae	*Menippe nodifrons* Stimpson, 1859	36	28	RF
	Majidae	*Mithrax hispidus* (Herbst, 1790)	20	15	RF
	Portunidae	*Cronius ruber* (Lamarck, 1818)	17	13	—
	Palinuridae	*Panulirus laevicauda* (Latreille, 1817)	1	1	RF/P-7.00
Teleostei	Haemulidae	*Anisotremus virginicus* (Linnaeus, 1758)	17	13	—
		Anisotremus surinamensis (Bloch, 1791)	4	3	RF/P-1.06
	Pomacentridae	*Abudefduf saxatilis* (Linnaeus, 1758)	7	6	—
	Epinephelidae	*Epinephelus marginatus* (Lowe, 1834)	2	2	RF/P-3.82
		Mycteroperca acutirostris (Valenciennes, 1828)	3	2	RF/P-2.27
	Scaridae	*Sparisoma frondosum* (Agassiz, 1831)	2	2	RF
	Monacanthidae	*Stephanolepis hispida* (Linnaeus, 1766)	1	1	RF/P-1.06
	Holocentridae	*Holocentrus adscensionis* (Osbeck, 1765)	1	1	—
	Priacanthidae	*Priacanthus arenatus* Cuvier, 1829	1	1	RF/P-1.06
	Sparidae	*Diplodus argenteus* (Valenciennes, 1830)	2	2	RF
	Carangidae	*Chloroscombrus chrysurus* (Linnaeus, 1766)	3	2	RF/P-1.06
		Caranx crysos (Mitchill, 1815)	1	1	RF/P-1.68
		Caranx latus Agassiz, 1831	1	1	RF/P-1.68
	Not identified*	—	7	6	—

*Animal in advanced state of decomposition.

DISCUSSION

This study estimated entanglement rates and the mean time of collapse of the derelict gillnets under experimental condition for the first time in Brazil. Crustaceans and fishes were the groups most affected, as has been observed around the world (Gilman et al. 2016), with the highest proportion corresponding to crustaceans (Kaiser et al. 1996; Revill and Dunlin 2003; Akiyama et al. 2007; Gilardi et al. 2010; Queirolo and Gaete 2014). In other ghost fishing experiments, the capture of mollusks was reported (Akiyama et al. 2007; Baeta et al. 2009; Queirolo and Gaete 2014), but it was not observed here. Ghost fishing is thought to be more problematic in passive fishing gears after being set and subsequently lost or abandoned, as they continue capturing animals for some time (Gilman 2015).

A temporal pattern was observed, with ghost catches initially showing a high proportion of fishes, before becoming dominated by crustaceans, as observed in other areas (Kaiser et al. 1996; Erzini et al. 1997; Akiyama et al. 2007; Brown and Macfadyen 2007; Baeta et al. 2009). The later predominance of crustaceans has been associated with their proximity to the seabed and with their scavenger habit, using dead and decomposing individuals trapped in the nets as food, resulting in cyclical catching by the fishing gear (Macfadyen et al. 2009). Thus, crustaceans are easily turned into targets for entanglement,

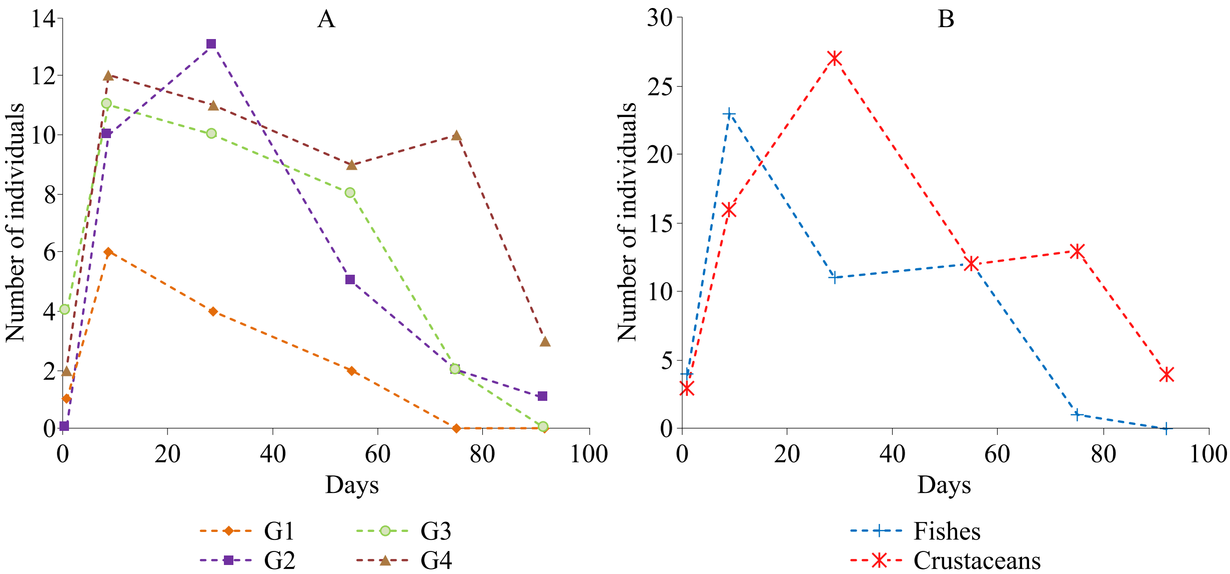

Figure 2. A) Number of individuals caught by each gillnet (G1, G2, G3, and G4). B) Total number of fishes and crustaceans caught in all four nets during the experiment.

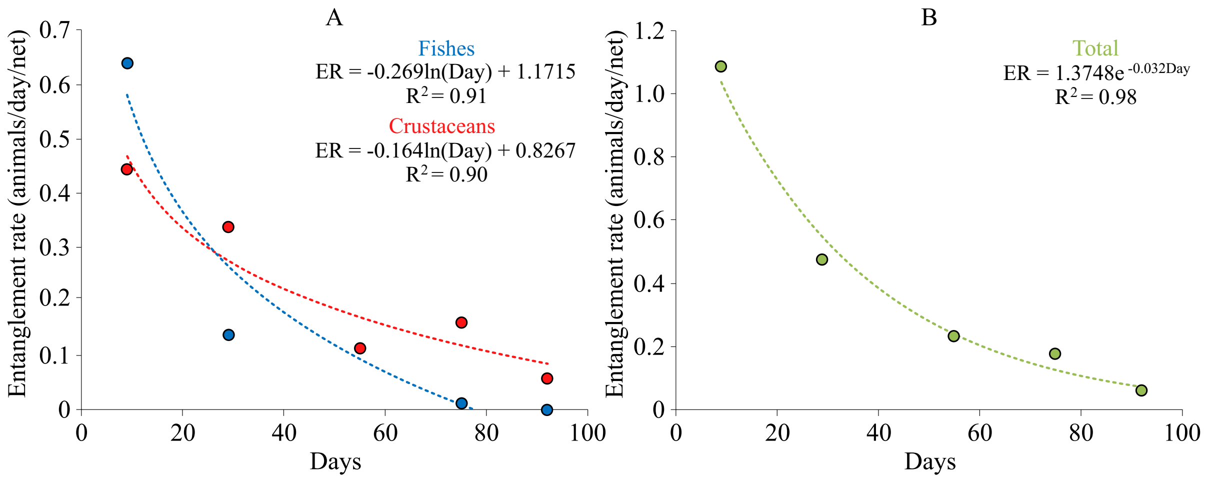

Figure 3. Entanglement rates (ER, animals/day/net) and fitted nonlinear models during the experiment conducted off the coast of Santa Catarina. A) Fishes and crustaceans (logarithmic model). B) Total (exponential model).

even after the nets present a reduction in their fishing area (Revill and Dunlin 2003; Baeta et al. 2009). Ghost fishing is often cyclical, with its duration and extent depending on the gear type, water depth, currents, and local environment, among other factors (Macfadyen et al. 2009).

Even though the analyzed nets may have been exposed to different environmental conditions, their catching efficiency followed similar patterns, with exponential models indicating rapid declines in catch rates after a few weeks (Brown and Macfadyen 2007; FAO 2009). Our study found a higher value of catch rate ($e^{-0.032t}$) compared to those reported in Izmir Bay, Turkey

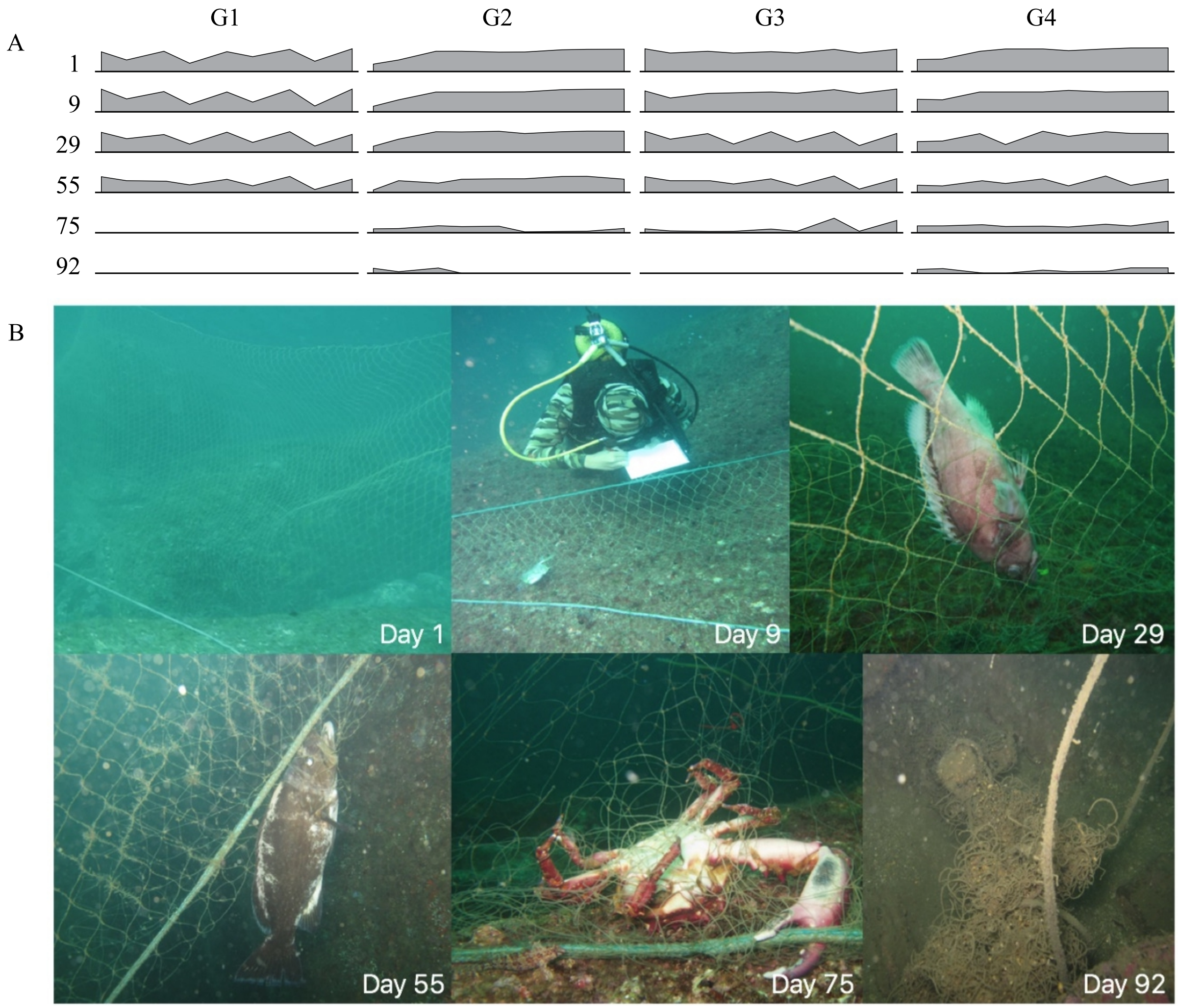

Figure 4. Fishing area of gillnets (G1, G2, G3, and G4) over a 92-day-period. A) Sketches were based on measurements of the net height (initially 2 m) and length (20 m). B) Images of the gillnet structural deterioration over the experiment period.

($e^{-0.0127t}$), in Tateyama Bay, Japan ($e^{-0.0154t}$), and in Laguna Verde, Chile ($e^{-0.0158t}$) (Ayaz et al. 2006; Akiyama et al. 2007; Queirolo and Gaete 2014, respectively), but smaller than the ones observed in Algarve, Portugal ($e^{-0.0542t}$) (Erzini et al. 1997). The catching efficiency of ghost gillnets is determined by their vertical profile, gradually declining with the exposure to storms and fouling. Biofouling, and subsequent increase in visibility, might occur rapidly in subtropical conditions, contributing to a faster decline in entanglement rates (catching efficiency) observed in our study.

A sharp decrease in the functional area of the experimental gillnets in the first weeks after deployment appears to be the pattern, followed by a gradual decline until stabilization near the bottom. Reductions to 21% of the original area after 17 weeks (Erzini et al. 1997), to 18% after 10 weeks (Revill and Dunlin 2003), and to less than 10% after 64 days of immersion (Queirolo and Gaete 2014) were reported. Thereafter, in most

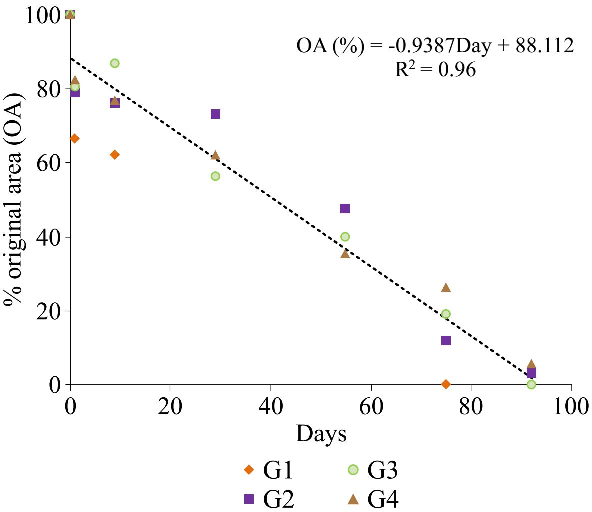

Figure 5. Reduction of fishing capacity (area) of the experimental gillnets (G1, G2, G3, and G4) over time, and linear model fitted.

studies, the rate of loss of fishing capacity decreased till reaching zero after 115 days (Queirolo and Gaete 2014), 15-20 weeks (Erzini et al. 1997), one year (Ayaz et al. 2006), or even two years of abandonment (Revill and Dunlin 2003; Tschernij and Larsson 2003). In contrast to the exponential models reported by some authors (Erzini et al. 1997; Queirolo and Gaete 2014), the fishing capacity loss rate in our experiment followed a linear model (b = -0.9387), resulting in an estimated total collapse of the nets after about 94 days. This shorter time, revealed by the linear model fitted, might have been influenced by the smaller length (and, consequently, area) of our nets, compared to those used in other experiments, making the nets more vulnerable to damages and collapse.

Degradation of the structural integrity of the net seems to be the primary cause of collapse. Some abandoned or lost gillnets may collapse immediately and have lower fishing efficiencies. Conversely, longer nets, fleets of nets, or nets snagged on rock, coral, or wrecks might be slow to collapse, or even be stretched again and continue killing for a longer time (Macfadyen et al. 2009). Length of individual nets used in the experiments around the world varied from 10 m (Akiyama et al. 2007) to 100 m (Erzini et al. 1997; Revill and Dunlin 2003). Additionally, some of the experiments used individual nets, keeping one side free or united to others by ropes, and some used fleets of 52-65 m nets, resulting in lengths of 200-250 and 378-480 m (Tschernij and Larsson 2003). The time elapsed between abandonment and total collapse of the nets varied from three months to two years and might be related to these differences in total net size, besides local environmental conditions observed. In one of the experiments with the longest collapse time reported, large fleets were employed (Tschernij and Larsson 2003); in another, the collapse time was very long when nets were deployed in wrecks, but similarly short when deployed in open areas (Revill and Dunlin 2003), as in the present study. In both cases, very few animals were caught after nine months of immersion.

In this study, all entangled crustaceans are reef-associated and have nocturnal habits (Fonteles-Filho 1999; Rieger and Girald 2001). The entangled fishes, pelagic or demersal, were also considered reef-associated, as they are included in local lists of reef fishes (Adelir-Alves and Pinheiro 2011) and depend on rocky reefs for at least part of their life cycle (Carvalho-Filho 1999). The stone crab (*M. nodifrons*), the most commonly entangled species, also inhabits reef environments (Melo 1996). Even though this species is not commonly used for human consumption in the state of Santa Catarina, probably due to its small size in relation to other commercially exploited species, it is occasionally caught by recreational fishers for their own consumption or to prepare traditional dishes for tourists (Oshiro 1999). Crabs are amongst the most abundant animals caught by ghost fishing, with *Cancer porteri* Rathbum, 1930 reaching ~ 82% in Laguna Verde, Chile (Queirolo and Gaete 2014).

Ghost fishing is undesirable from both the economic and conservation standpoints. Eight of the species entangled during our experiment are targeted by local fishers, including species of high market price, such as the dusky grouper (*E. marginatus*) and the smooth-tail spiny lobster (*P. laevicauda*). Fishes are amongst the main resources globally caught in total weight, representing 85% of the total catch but only 66% of the value, while crustaceans reach the highest market value, resulting in 22% of the total global value (FAO 2020). The dusky grouper is considered overexploited or threatened in Brazil (MMA 2016) and is categorized as vulnerable by the International Union for Conservation of Nature (Pollard et al. 2018). No marine turtle, bird, or mammal was captured during our experiment, but the risk of these species being entangled should not be disregarded, as it has been documented elsewhere (NOAA 2014). Marine mammals, reptiles, and elasmobranchs from 40 different species were recorded as entangled in, or associated with, ghost gears (Stelfox et al. 2016).

The accumulation of nets on the sea floor raises concern, as they often cover previously established benthic communities (Saldanha et al. 2003). On the other hand, fragments of gillnets colonized by sessile organisms can also act as artificial reefs, providing shelter, food, and support for fishes and invertebrates (Watters et al. 2010; Mordecai et al. 2011). Ringneck blenny *Parablennius pilicornis* (Cuvier, 1829) and yellowline arrow crab *Stenorhynchus seticornis* (Herbst, 1788) were also observed using gillnets in a similar way (JAA, personal observation). Seahorse *Hippocampus reidi* Ginsburg, 1933 has been observed using fragments of gillnets as substrate (Mai and Rosa 2009), but not in our study.

Weak monitoring and surveillance prevent the proper implementation of governance frameworks, including measures to monitor, prevent, and remediate ALDFG and ghost fishing (Gilman 2015). Effective management measures are required to augment compliance and reduce a growing worldwide threat. Experimental studies with ghost fishing are important to give support to the decision-making process on required regulations. Measures to reduce the impact of ghost fishing have been debated, including ways to prevent loss or even retrieval of derelict gears and the development of fishing gears made of biodegradable materials (Matsuoka et al. 2005; McElwee et al. 2011; Morishige and McElwee 2012). Gear retrieval programs could minimize the impact on aquatic animals. However, the most effective measure to reduce the impact of ghost fishing may be to directly inform fishers about the impact of their derelict gears and discuss mechanisms to prevent it. Thus, the FAO Code of Conduct for Responsible Fisheries (FAO 1995) could be effectively implemented.

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