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Extended abstract

Estimating Patagonian toothfish (*Dissostichus eleginoides*) movement on the Kerguelen Plateau: reflections on 20 years of tagging at Heard Island and McDonald Islands

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Over the last 20 years >52 000 tagged Patagonian toothfish have been released during research surveys and commercial fishing at Heard Island and McDonald Islands. These data have been previously used to estimate demographic parameters, however, little attention has been given to movement estimation. While most toothfish are recaptured near their location of release, some fish moved long distances of >500 km. Recaptures have been observed from Kerguelen and Crozet Islands and three fish travelled >2 500 km to be recaptured at Marion and Prince Edward Islands. The observed movements demonstrate some level of population connectivity of toothfish across the Kerguelen Plateau and with those at Crozet and Marion and Prince Edward Islands. We describe toothfish movements and discuss our efforts to estimate movement rates across the Kerguelen Plateau.

Introduction

Conventional tagging studies in which fish are marked with external tags provide information on release and recapture locations and biological processes such as fish growth. Consequently, tagging studies have been used in many fisheries to estimate growth (Francis, 1988; King and McFarlane, 2010; Aires-da-Silva et al., 2015; Eveson et al., 2015) fish movement, levels of connectivity between fish populations and stock boundaries (Hilborn, 1990; Gillanders et al., 2001; Marlow et al., 2003), fishing and natural mortality (Frusher and Hoenig, 2003; Polacheck et al., 2006; McGarvey, 2009) and stock abundance (Thorsteinsson, 2002; Pine et al, 2003).

On the Kerguelen Plateau in the southern Indian Ocean, Patagonian toothfish (*Dissostichus eleginoides*) supports valuable fisheries in the French exclusive economic zone (EEZ) around the Kerguelen Islands to north and in the Australian EEZ around Heard Island and McDonald Islands (HIMI) to the south (Duhamel et al., 2011; Welsford et al., 2011). Tagging of Patagonian toothfish in the Australian EEZ commenced in 1998, a year after the fishery started, with the primary objective of investigating toothfish movement within the Australian EEZ and across the Kerguelen Plateau (Constable et al., 2001; Williams et al., 2002). Between 1998 and 2017, over 52 000 tagged fish have been released, first by the demersal trawl fishery, then also by the demersal longline fishery which commenced in 2003. The proportion of the catch harvested by longline increased steadily since 2003 and almost the entire catch has been taken by longline since 2014 (Ziegler and Welsford, 2019). Over the years, tagging data from the HIMI fishery has provided information on population linkages (Williams et al., 2003), fish growth (Williams et al., 2002; Candy et al., 2007), natural mortality (Candy, 2011; Candy et al., 2011) and abundance estimates on the main trawl grounds (Williams and de la Mare, 1995; Williams et al., 2002). As the longline fishery increased its spatial distribution around HIMI, tagging data from longline releases and recaptures were also included as an index of abundance in the integrated stock assessment which is used to provide management advice on catch limits for toothfish in the Australian EEZ (Ziegler et al., 2014; Ziegler and Welsford, 2015; Ziegler, 2017; Ziegler and Welsford, 2019).

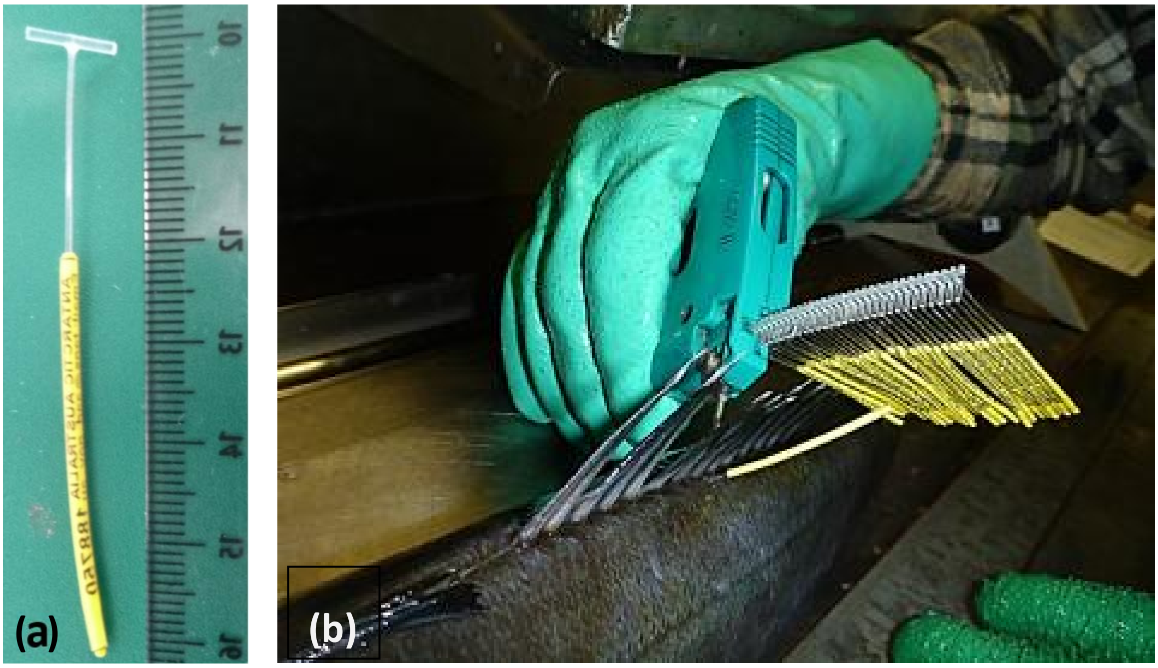

Figure 1: (a) T-bar tag and (b) T-bar tag insertion into a toothfish.

Movement patterns of Patagonian toothfish have been investigated for some time in the Southern Ocean, indicating a contrasting pattern of 'sedentary' and 'migratory' fish. On the Kerguelen Plateau, most of the toothfish recaptured travel only short distances (<50 km), however, some toothfish have left the Australian EEZ to be recaptured in the French EEZ around the Kerguelen Islands, and even further around Crozet Islands and Marion and Prince Edward Islands (Williams et al., 2002; Welsford et al., 2007, 2014). Péron et al. (2016) developed spatially explicit statistical models to quantify and predict the spatial distribution of Patagonian toothfish length structure and sex ratio which supported ontogenetic migration from shallow to deep waters as fish grow. Patagonian toothfish tagging studies at Macquarie Island and South Georgia have shown a similar pattern to the Kerguelen Plateau in observed movements with most fish recaptured within 50 km of their release location (Day and Hillary, 2017; Söffker et al., 2014a, 2014b).

In this study, we provide a description of observed fish movement within the HIMI EEZ and to adjacent areas, based on data from Patagonian toothfish that have been tagged in the trawl and longline fisheries at HIMI.

Fish tagging

For this study, data from Patagonian toothfish in the HIMI fishery between 1998 and 2017 were analysed. Toothfish have been tagged by scientific observers during commercial fishing and as part of an annual random stratified trawl survey (RSTS, Nowara et al., 2015). The number of annual tag releases has varied over time in the commercial fishery as it depended on catch volumes and objectives of the tagging study. Until 2015, fish were tagged at a rate of two fish per three tonnes of catch, but with increasing importance of longline tagging data in the stock assessment, this tagging rate was increased to two fish per tonne in 2015.

Fishery observers are responsible for the selection and tagging of fish, choosing healthy individuals of a size such that the size distribution of released fish is largely representative of that caught by the vessel. Fish were tagged with two conventional T-bar tags (Hallprint, Adelaide) on each side of the fish just under the second dorsal fin (Figure 1). Subsequent detection of T-bar tags on recaptured fish relies on visual examination by vessel crew and fisheries observers handling the fish. Some fish that were recaptured in a suitable condition were re-released and a few have been recaptured more than once. At recapture, all tagged fish were measured, weighed and, if not re-released, analysed for sex and maturity by a fishery observer. Some fish were also tagged with passive integrated transponder (PIT) tags which were inserted into the dorsal midline behind the fish head. However, the operation of detector systems on board of fishing vessels proved to be unreliable and the use of PIT tags was discontinued in November 2016. Consequently, data from these tags have not been used here.

Fishing fleet dynamic and selectivity

Until 2003, the Australian fishery was mainly constrained to three main trawl grounds on the shallow plateau <1 000 m. With the start of the longline fishery

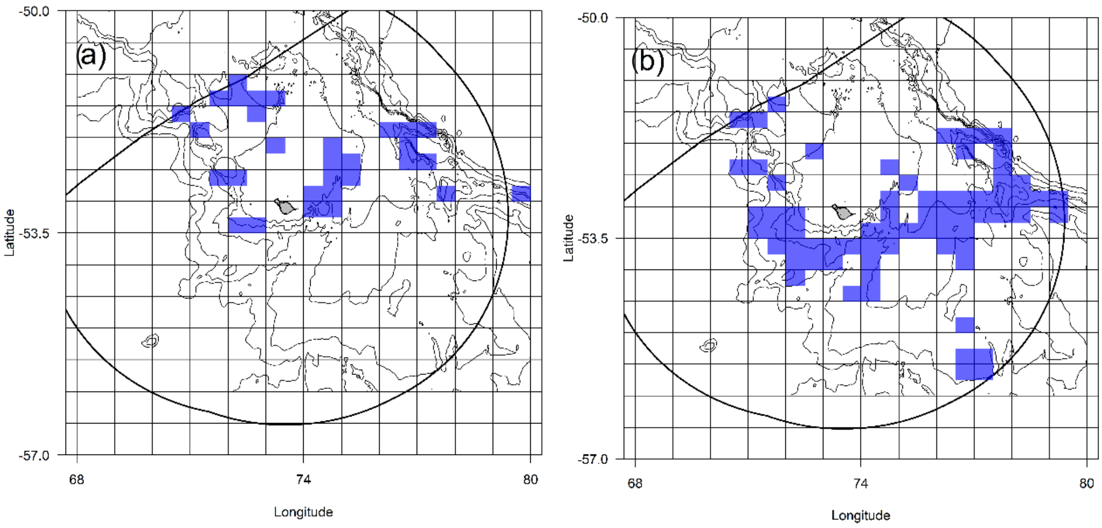

Figure 2: Spatial footprint of the Patagonian toothfish fishery at HIMI in (a) 2000 and (b) 2012.

in 2003, the Australian fleet initially concentrated in the southeast of HIMI and then progressively expanded to the west and south into deeper areas. The contrast between the spatial footprint of the fishery in 2000 and 2012 is shown in Figure 2.

Observed movement patterns

We examined the directions and distances moved by fish during their time at liberty between release and recapture for all tag recaptures from May 1998 to November 2015 during scientific and commercial fishing. Rose diagrams are used to indicate the direction and magnitude of fish movements where the direction was separated into 20° bins with the length of each bin representing the magnitude of movements in that direction. For the distance analysis, we calculate the minimum distance travelled as the geodesic distance of a linear path linking the release to the recapture locations, although it is likely that fish moved greater distances than this.

At the end of the 2017 fishing season, a total of 52 013 tagged fish had been released at HIMI and 9 417 tagged fish were recaptured (Table 1). The number of longline releases has increased substantially since 2003 with an increase in longline fishing effort. In addition, an increase in the catch limit and tagging rate in 2015 saw the number of tag releases exceed 8 000 tags. The total number of tags released during longline fishing (30 026) is almost double the number of commercial trawl releases (18 248). In addition, 3 435 tags were released during the trawl surveys undertaken annually since 1998 and 195 tags were released on fish caught with pots.

Most tagged fish were recaptured with the same fishing gear as the one with which they were initially caught (Table 2). This was the result of the fish movement pattern (see below) but also the relatively small spatial overlap between trawl and longline fishing locations, and differences in the size composition of fish released by the two gear types. With trawl generally operating in shallower areas, the size composition of fish captured and released from trawl is smaller compared to that of longlines (Figure 3). As a result, it could take some years for fish that have been tagged and released from trawl to grow into a size that is likely to be selected by longline fishing gear.

Time at liberty ranged from 1 day to 15 years, with variations in the distribution of time at liberty depending on gear type (Figure 4). Of fish that have been recaptured, around 75% of fish released in the trawl fishery were recaptured in their first year of liberty as opposed to only 24% of longline-released fish. The time at liberty for fish released by longline also shows peaks at regular time intervals of around one year. This annual pattern results from the timing of the fishing effort with longline vessels only being allowed to operate from April to October, whereas fishing with trawl gear is allowed throughout the entire year.

Most fish were recaptured within the HIMI EEZ but some fish were recaptured around Kerguelen Islands (n = 241) or Crozet Islands (n = 34) (Table 2, Figures 5 and 6). In addition, three fish were recaptured around Marion and Prince Edward Islands, travelling a minimum distance of 2 600 km. Short-range movements did not reveal any preferred directions, however, medium- and long-distance movements were biased towards the northwest direction probably due to the distribution of available habitat and higher likelihood of recapture effort in these directions (Figure 6).

Table 1: Number of toothfish that have been tagged and released at HIMI and subsequently recaptured either at HIMI or elsewhere (in brackets) by gear and fishing purpose (commercial versus research) between the start of tagging program in 1998 and 2017.

Season	Commercial						Research		Total	
	Longline		Pot		Trawl		Trawl			
1998	0	(0)	0	(0)	1 009	(77)	69	(0)	1 078	(77)
1999	0	(0)	0	(0)	762	(123)	0	(2)	762	(125)
2000	0	(0)	0	(0)	1 281	(259)	543	(3)	1 824	(262)
2001	0	(3)	0	(0)	1 134	(446)	127	(2)	1 261	(451)
2002	0	(4)	0	(0)	1 313	(539)	293	(10)	1 606	(553)
2003	154	(9)	0	(0)	1 373	(508)	104	(1)	1 631	(518)
2004	290	(8)	0	(0)	1 387	(659)	0	(8)	1 677	(675)
2005	290	(35)	0	(0)	1 256	(540)	138	(5)	1 684	(580)
2006	686	(39)	152	(0)	1 719	(553)	12	(2)	2 569	(594)
2007	604	(48)	0	(0)	1 380	(713)	36	(2)	2 020	(763)
2008	895	(97)	0	(0)	911	(332)	8	(1)	1 814	(430)
2009	1 251	(101)	13	(0)	1 179	(299)	73	(11)	2 516	(411)
2010	1 221	(138)	0	(0)	525	(187)	58	(4)	1 804	(329)
2011	1 198	(176)	0	(0)	986	(244)	252	(6)	2 436	(426)
2012	1 434	(99)	0	(0)	1 282	(447)	315	(5)	3 031	(551)
2013	1 473	(237)	30	(5)	337	(221)	179	(3)	2 019	(466)
2014	1 810	(334)	0	(0)	73	(18)	245	(4)	2 128	(356)
2015	7 717	(564)	0	(0)	131	(19)	503	(2)	8 351	(585)
2016	5 324	(541)	0	(0)	202	(32)	431	(3)	5 957	(576)
2017	5 679	(689)	0	(0)	7	(0)	159	(0)	5 845	(689)
Total	30 026	(3 122)	195	(5)	18 248	(6 216)	3 545	(74)	52 013	(9 417)

Table 2: Number of fish that were tagged and released at HIMI using longline, pot and trawls along with the number recaptured by recapture fishery and gear type between 1998 and 2016.

Recaptures		HIMI releases		
Fishery	Gear	Longline	Pot	Trawl
HIMI	Longline	2 535	5	304
HIMI	Pot	3	1	1
HIMI	Trawl	69	2	6 219
Crozet Island	Longline	6	0	28
Kerguelen Islands	Longline	82	1	158
Prince Edward and Marion	Longline	0	0	3
Not recaptured	-	27 331	186	15 079

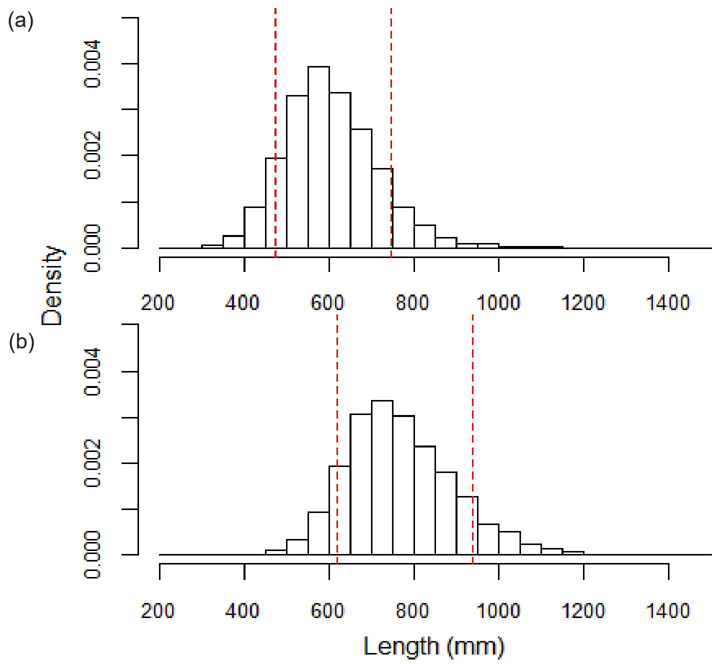

Figure 3: Size composition of tagged Patagonian toothfish released by (a) trawl and (b) longline between 1998 and 2016. Red dashed lines represent the 10th and 90th percentiles of the length of released fish.

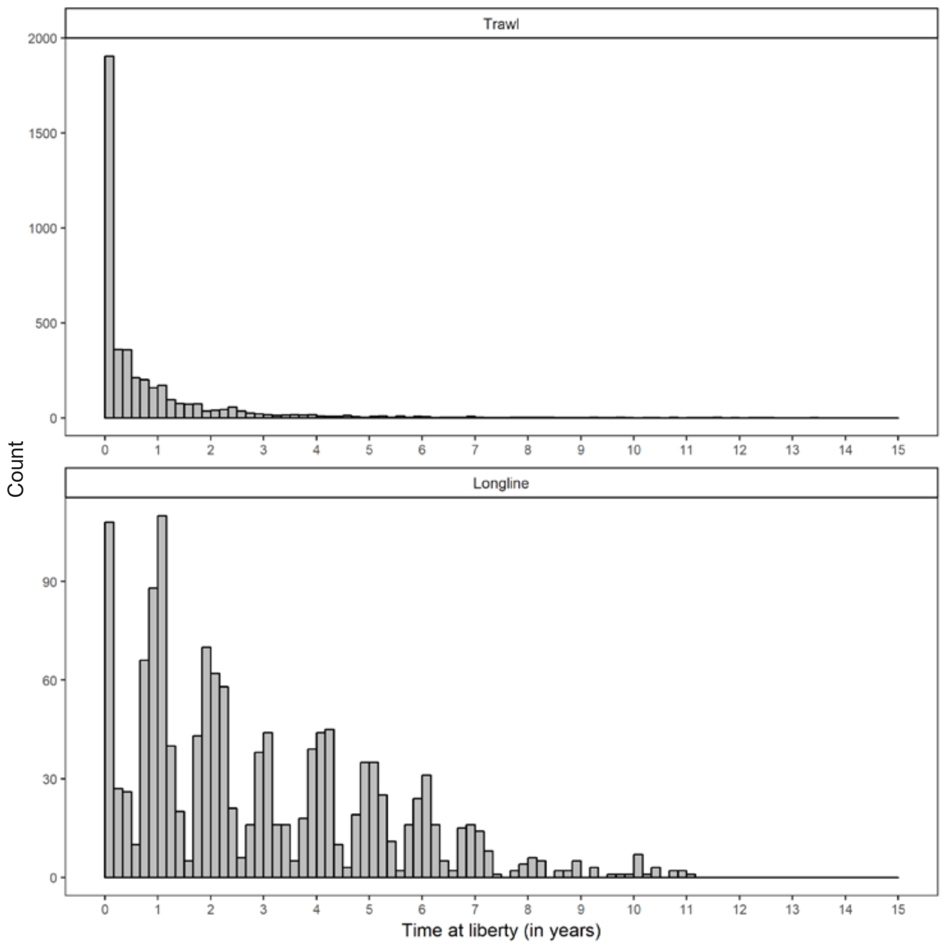

Figure 4: Frequency histograms of the time at liberty of fish tagged and released in the trawl and longline fisheries at HIMI.

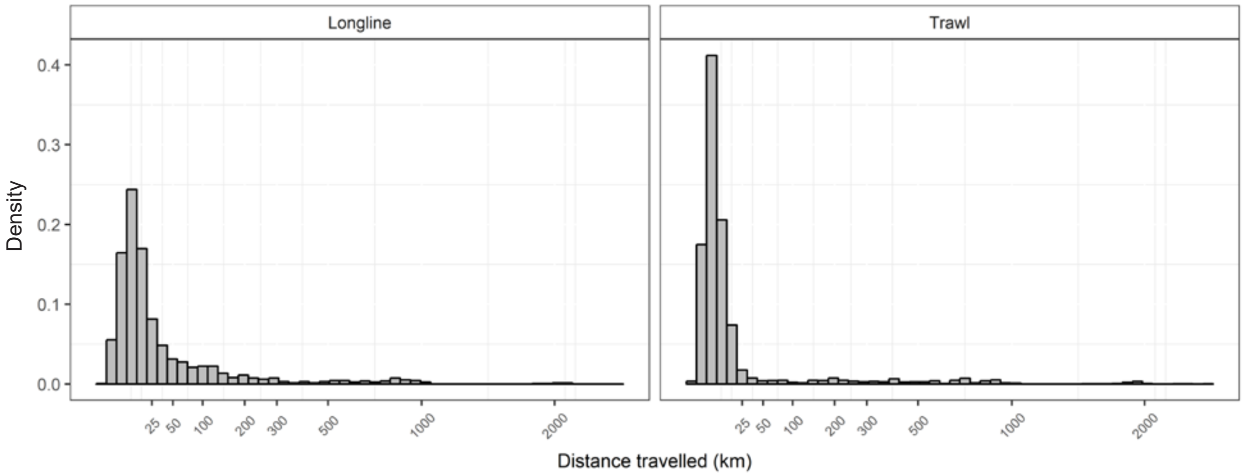

Figure 5: Histograms of the distance moved for fish released at HIMI by longline and trawl.

Discussion

Of the 52 000 Patagonian toothfish released at HIMI between 1998 and 2017, around 9 400 or 18% have been recaptured. While the majority of fish were recaptured within 50 km of their release location, around 270 have moved north or northwest and been recaptured around Kerguelen Islands and Crozet Islands, while three fish have moved up to 2 800 km to be recaptured around Marion and Prince Edward Islands. While it is possible that toothfish are moving to other suitable habitats located south or west of the Kerguelen Plateau, such as Elan Bank or BANZARE Bank where fishing effort is absent or limited, no recaptures have been observed in an easterly direction at the closest suitable habitat around Macquarie Island located >5 000 km away (Lamb, pers. comm.). These results confirmed that Patagonian toothfish stocks are connected in the southern Indian Ocean, which is in accordance with genetic studies conducted in the region (Toomey et al., 2016). These north and northwest movements indicate that toothfish are able to swim long distances upstream against the Antarctic Circumpolar Current which flows eastwards. Upstream movements of Patagonian toothfish were also reported between South Sandwich Islands and South Georgia Islands in the south Atlantic Ocean (Söffker et al., 2014c). Characteristics such as the size and sex of fish may also play a role in the movement of toothfish across the Kerguelen Plateau and warrants further investigation.

Our tagging study faced several limitations linked to the fact that the tagging program had multiple objectives and was not specifically designed to infer fish movement rates and directions. Firstly, the spatial dynamic of the fisheries (trawl and longlines) plays a crucial role in estimation of fish movement (Hilborn, 1990) and years of localised fishing effort could bias our ability to correctly estimate fish movement. Secondly, the tagging data were limited to the component of the population that is selected by trawl and longline gears and consequently little information was available on the movement of small, young fish and very large, old fish which are poorly selected by the fishing gear. Thirdly, when tagged fish spent several years at liberty, it is unknown when movement occurred, which limits our ability to understand the biological driver of fish movements.

With fish movement having the potential to bias tag-based population estimates (Pine et al., 2003; Agnew et al., 2006; Welsford and Ziegler, 2013) there was the need to estimate movement rates between HIMI and Kerguelen and account for movement with the stock assessments of both areas. Burch et al. (2017) used a catch-conditioned modification of Hilborn (1990) to estimate movement rates between HIMI and Kerguelen and correct for movement related bias in the stock assessment.

While we are unable to estimate movement rates from observed movements alone, understanding the characteristics of fish that have moved can provide important information about the stock. For movement between the HIMI and the Kerguelen EEZ to the north, annual migration rates were estimated to be ~1.1% from HIMI to Kerguelen and 0.4% from Kerguelen to HIMI (Burch et al., 2017). For the movement rates estimated, simulation modelling demonstrated that migration could be corrected for by increasing the tag-shedding parameter in the stock assessment model (Burch et al., 2017).

The impact of heterogeneous movement rates on the HIMI and Kerguelen stock assessments has yet to be determined, however, given the overall movement rate is estimated to be <2% hopefully the impacts are small.

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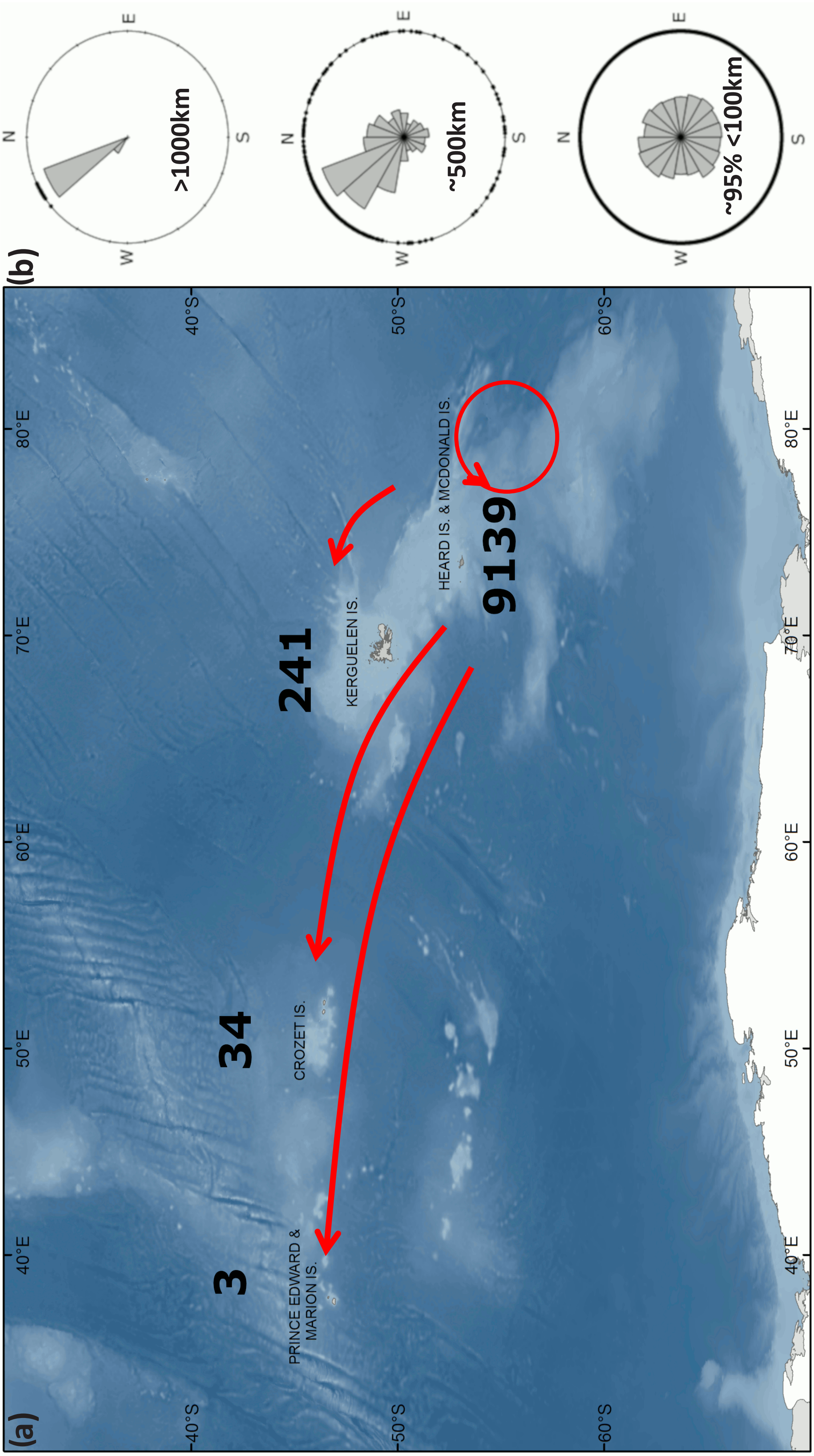

Figure 6: Movement of Patagonian toothfish tagged in the HIMI EEZ: (a) numbers represent numbers of individuals recaptured between 1998 and 2017, (b) rose frequency diagrams indicate the direction of fish movements.

on board Australian and French fishing vessels for their hard work. We thank the Australian Fisheries Management Authority (AFMA) for their financial supports. We are also very grateful to the skippers, crews and ship owners of the Australian vessels for their cooperation in data collection during commercial fishing operations, and particularly the crew and owners of FV *Southern Champion* and FV *Austral* for their support during the scientific surveys.

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