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Maritime traffic trends around the southern tip of Africa – did marine noise pollution contribute to the local penguins’ collapse?

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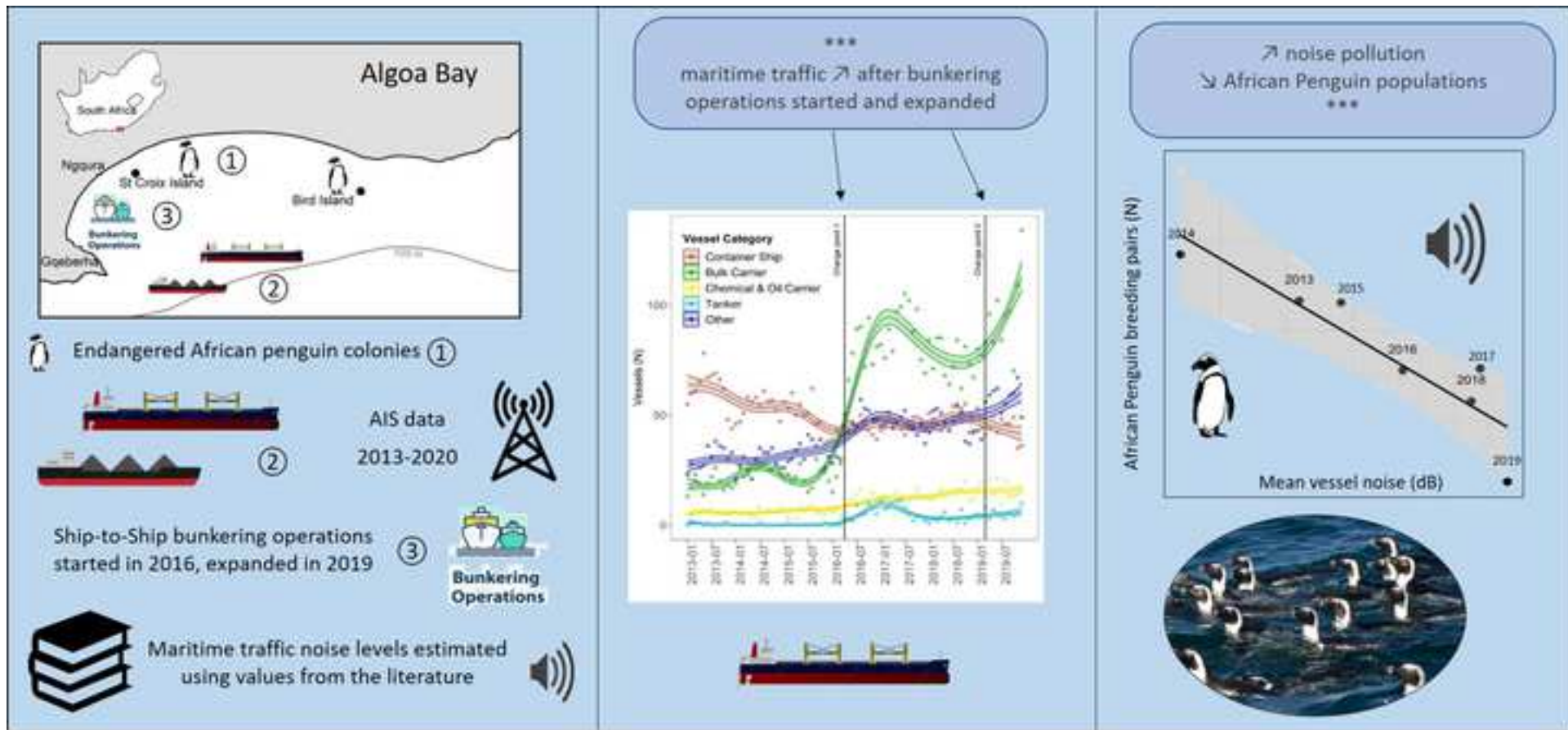
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Highlights

- Maritime traffic increases globally, with associated noise pollution
- Using AIS data, vessel noise emissions estimated in a marine biodiversity hotspot
- Vessel-derived noise increased after initiation of offshore ship-to-ship bunkering
- Local endangered African Penguin colony collapsed concomitantly
- First evidence of impact of maritime traffic noise pollution on seabirds

1 **Abstract**

2 The rapid increase in seaborne trade since the 1990s has resulted in an increase in vessel-derived
3 noise pollution, yet there is little evidence linking these activities to a decline in many marine taxa,
4 such as seabirds. Algoa Bay, South Africa, is a marine biodiversity hotspot, providing habitats for
5 the largest populations of endangered African Penguins (*Spheniscus demersus*), as well as other
6 endangered seabirds, cetaceans and seals. The bay is situated on a major shipping route and since
7 2016 has hosted the first offshore ship-to-ship (STS) bunkering operations in the country, i.e. the
8 supplying of fuel from one ship to another outside of harbours. Using Automatic Identification System
9 (AIS) data, we estimated noise emissions from vessels as a proxy for underwater ambient noise
10 levels within the core penguin utilisation area. Frequency of vessels using the bay doubled during
11 our study, with numbers of bulk carriers increasing ten-fold. Ambient underwater noise levels were
12 generally high in the bay (ca 140 dB re 1 μ Pa since 2015) but significantly increased by 2 dB SPL
13 after the initiation of STS bunkering in 2016, corresponding to double the underwater noise intensity.
14 This increase coincided with a significant and dramatic decline in penguin numbers from St Croix
15 Island. Algoa Bay is now one of the noisiest bays in the world. This is the first study to assess the
16 potential impact of vessel-derived underwater noise levels on a seabird population. Penguins, like
17 marine mammal species, are known to be sensitive to marine noise pollution and urgent
18 management interventions are required to mitigate this recent disturbance, to preserve the remaining
19 stronghold of the African penguin and the marine mammals' populations sharing the penguins'
20 habitat.

21

22 **Keywords**

23 Anthropophony, marine conservation, seabirds, shipping route, ship-to-ship bunkering, underwater
24 noise.

26 INTRODUCTION

27

28 Maritime traffic has increased exponentially since the end of the second world war (Malakoff,
29 2010) and currently incorporates over 90% of international trade in terms of volume (UNCTAD,
30 2019). In 2018, the total volume of merchandise transiting through the sea reached 11 billion tons
31 for a global fleet of almost 92 300 ships (UNCTAD, 2019). Maritime traffic is a major source of
32 pollution. The combustion of heavy fuel oil for maritime transport represents 15% of world sulphur
33 emissions (Qi et al., 2020), harmful to the health of human populations in ports and coastal cities
34 (Zhen et al., 2019). Oil spills (accidental or illegal discharges, e.g. Polinov et al., 2021) are perhaps
35 the most obvious and well-known pollution risks from sea-going vessels, being the most publicly
36 visual and with often large scale, long-lasting impacts on the environment and communities that
37 depend on healthy marine ecosystems (Chilvers et al., 2021). Less obvious to the public and with
38 infrequent reports recorded, vessel collisions with large marine animals have a clear significant
39 impact on cetacean populations worldwide (Schoeman et al., 2020). In addition, hull fouling and
40 ballast water, as major transport vectors for marine organisms, present a significant threat of
41 biological invasions to marine ecosystems (Sardain et al., 2019). The impacts of anthropogenic noise
42 pollution emitted from vessel activities on a wide range of taxa have only recently been given
43 recognition (Duarte et al., 2021). While environmental sustainability has started to become a major
44 policy concern in global maritime transport in more recent years (e.g., limits to the sulphur content
45 in fuel oil used by ships in 2016 (Lindstad et al., 2017), successful mitigation measures implemented
46 since the 1960s to reduced pollution from shipping and the offshore oil industry (Camphuysen, 2010;
47 Chilvers et al., 2021), and the creation of the International Convention for the Control and
48 Management of Ships' Ballast Water and Sediments in 2004 (see Ji et al., 2021)), mitigation of
49 marine noise pollution remains in its infancy. This is despite a range of guidelines for noise
50 measurement and ship design and engineering having been set by the International Maritime

51 Organisation (IMO) in 2014, with the aim of reducing the underwater noise produced by ships (IMO,
52 2014).

53 The reason for this lag is likely due to a paucity of research linking specific sources of sound
54 to animal taxa-specific sound thresholds (Popper et al., 2020). There is, however, an abundance of
55 literature linking various noise sources to a diversity of negative direct and indirect impacts
56 associated with a wide range of taxa (Duarte et al., 2021), although research of such impacts on
57 seabirds is limited. Overall low-frequency noise recorded below the surface in major shipping routes
58 has increased 32-fold over the past 50 years (Malakoff, 2010), doubling every decade (Weilgart,
59 2017) and transforming the underwater soundscape with added anthropophony to the existing
60 natural biophony and geophony (Pijanowski et al., 2011). In areas such as the Arctic, shipping
61 frequency has changed from an occasional disturbance to a dominant noise source, with the
62 potential to impact behavioural responses of animals using these areas (Aulanier et al., 2017). Most
63 marine species, from invertebrates to marine mammals, invariably use underwater auditory cues for
64 crucial biological functions such as foraging, orientation, communication, predator avoidance, mating
65 and care of their young (Au and Hastings, 2008). Anthropogenic noise can thus greatly impact these
66 animals' vital functions, with impacts ranging from low disturbance to lethal injuries (Chou et al.,
67 2021). Calls for measures to address this threat and establish policies to minimise the impacts of
68 marine noise pollution on marine ecosystems are growing world-wide, including by the governing
69 bodies of several conservation treaties such as the Convention on Biological Diversity (CBD,
70 Decision XII/23, 2014), the Convention on the Conservation of Migratory Species of Wild Animals
71 (CMS, Resolution 12.14), and several of the latter's ancillary Agreements.

72 In parallel with increased maritime traffic, the demand for refuelling options along major
73 shipping routes has seen a corresponding increase, to save time by avoiding berthing at port and
74 maximising economic profits from the voyage. Consequently, offshore ship-to-ship (STS) bunkering
75 activities, i.e., the supplying of fuel from one ship to another outside of harbours, are rapidly
76 expanding (Credence Research, 2019). STS bunkering operations involve the use of large tankers
77 (mother ships) which replenish the fuel stores of smaller tankers (daughter vessels) which in turn
78 dispense fuel to sea-going vessels at anchor. In addition to these activities presenting a clear risk of

79 oil pollution (Akyuz et al., 2018), with 7% of the annual global spills originating from bunkering
80 operations (ITOPF, 2020), they are also expected to induce high levels of underwater noise by
81 concentrating additional (and larger) vessels in a specific area, thereby compounding existing levels
82 of shipping and other sources of noise pollution. There is, however, no study to date that has
83 investigated the potential link between STS bunkering operations and underwater ambient noise
84 levels, with associated impacts on the environment.

85 Algoa Bay, off Gqeberha (formerly known as Port Elizabeth) in South Africa, is located on a
86 major global maritime route and offers since 2016 the first offshore STS bunkering services in the
87 country. It is the largest bay in South Africa providing shelter to anchored ships. The bay also hosts
88 two major commercial and industrial ports, the original port of Gqeberha and the deep-water port of
89 Ngqura, which opened in 2008 and which has since seen rapid development and operational
90 expansion. The location of these ports has facilitated the expansion of the ocean economy in this
91 region under the South African government's 'Operation Phakisa', which aims to unlock the marine
92 space for various initiatives, including oil and gas exploration, aquaculture, tourism, and marine
93 conservation (Holness et al., 2022). The bay is a hotspot of marine biodiversity, with large
94 populations of cetaceans and seals (e.g., Bouveroux et al., 2018) and two groups of islands in Algoa
95 Bay falling within a globally Important Bird and Biodiversity Area (Donald et al., 2019): the St Croix
96 Island group and the Bird Island group. These island groups together support globally important
97 populations of the endangered African Penguin (*Spheniscus demersus*) and Cape Gannet (*Morus
98 capensis*) (BirdLife International, 2020). Both species are endemic to southern Africa and have
99 undergone significant declines in their populations (Sherley et al., 2019; 2020) due to various threats,
100 from competition with fisheries, to degradation of their habitat and global climate change (Crawford
101 et al., 2011). As a Contracting Party to the Agreement on the Conservation of African-Eurasian
102 Migratory Waterbirds (AEWA), South Africa has committed to taking various measures to address
103 the threats facing these species (including both marine pollution and disturbance), with the aim of
104 restoring their populations to a favourable conservation status (AEWA, Annex 3). St Croix Island is
105 located within 5 – 15 km of the port of Ngqura, in close proximity to the anchorage areas where STS
106 bunkering activities take place (Fig. 1). Since the initiation of STS bunkering, four oil spills have

107 occurred (in 2016, 2019, 2021 and 2022), causing oiling of hundreds of seabirds (Ryan et al., 2019;
108 SANCCOB, 2020).

109 While an on-going scientific experiment is assessing the benefits of purse-seine fishing
110 exclusion for penguins in Algoa Bay (Pichegru et al., 2010; Sherley et al., 2018), no study has
111 investigated the level of underwater ambient noise in their habitat. African penguins are known to be
112 sensitive to noise disturbance (Pichegru et al., 2017) and have recently been shown to use acoustic
113 communication to increase group foraging efficiency (McInnes et al., 2020). Here, we studied the
114 recent trend (2013 - 2020) of maritime traffic in Algoa Bay and associated noise emissions using the
115 maritime very high frequency (VHF) Universal Automatic Identification System (AIS) data. The
116 system was originally designed for Vessel Traffic Systems (VTS), as a mandatory collision avoidance
117 measure (Robards et al., 2016), but the data are now increasingly used in research for maritime
118 traffic, gas emissions, pollution (oil spills and noise) or interactions with wildlife (Svanberg et al.,
119 2019). From the engine size associated with the different vessel types using data from the literature
120 (Veirs et al., 2016), and the vessel's daily location while transiting in the bay (speed >1 kn.), we
121 estimated the underwater ambient noise levels potentially received by African Penguins in their core
122 foraging area around St Croix Island. We related these noise levels to the penguin population trend
123 on St Croix Island over the same period. We hypothesised that underwater noise levels would
124 intensify after the initiation of STS bunkering operations, with a noticeable negative impact on
125 penguin numbers. This study is the first to explore the impact of maritime traffic noise pollution on a
126 seabird, and the consequence of offshore bunkering activities on underwater noise levels. The
127 outcomes are discussed in the context of South Africa's current legislative framework for ship-to-
128 ship bunkering authorisations.

129

130 **METHODS**

131 *Trends in vessel category and zone use in Algoa Bay*

132 AIS information was obtained for vessels transiting within or through Algoa Bay between
133 January 2013 and September 2020 from Clarksons Platou (H. Clarksons & Company Limited). AIS
134 autonomously and hourly transmits messages containing static data (vessel identification data such
135 as name, call sign, IMO number, type, and individual features) and dynamic navigation sensor data
136 (i.e., vessel GPS location, speed over ground, course over ground, heading and rate of turn). As
137 required under SOLAS (the International Convention for the Safety of Life at Sea) since 1 July 2008,
138 all ships ≥ 300 gross tonnage that undertake international voyages, all cargo ships ≥ 500 gross
139 tonnage irrespective of travel destination, tankers, and all passenger ships irrespective of size must
140 use AIS. AIS is not required on smaller fishing vessels, recreational boats, inland vessels, warships,
141 and naval auxiliary vessels. Due to the high number of vessel types in the AIS data ($N = 105$, see
142 Table S1), they were grouped for the purpose of this analysis into five categories: based on a monthly
143 median of ≥ 5 vessels and a non-zero % change in monthly median vessel numbers during the study
144 period – ‘Bulk Carrier’, ‘Container Ship’ and ‘Chemical and Oil Carriers’; based on $\geq 400\%$ increase
145 in monthly median vessels over the study period – ‘Tanker’; and, all the other vessel types – ‘Other’
146 (Table S1). The maritime areas considered in this study follow the Department of Transport’s
147 Transnet jurisdiction (Department of Transport, 2010), corresponding to the traffic and/or activities
148 herein: the two harbours (Gqeberha and Ngqura), anchorage areas 1 and 2 (where STS bunker
149 transfers occur), and shipping lanes used by vessels to enter or leave the harbour (Fig. 1). GPS
150 coordinates of each transiting vessel (with speed over ground >1 kn.) were extracted from the AIS
151 dataset and assigned to one of the five areas. Coordinates were extracted only once a day for each
152 vessel, between 12 pm and 1 pm, corresponding to the African Penguin peak foraging activity (see
153 below, van Eeden et al., 2016).

154 We used Generalised Additive Models (GAM, Wood, 2000) to assess change over time, at
155 monthly intervals, of the a) number of vessels per type within Algoa Bay (i.e., vessel category) and
156 b) number of vessels present per zone (i.e., vessel zone). GAMs were run separately for vessel
157 category and vessel zone. Due to unprecedented changes to vessel traffic trends in 2020 due to the
158 COVID-19 global pandemic, only data until December 2019 were used for these analyses.
159 Specifically, vessel count per month was set as the response variable and date (year-month) with

160 either vessel category or vessel zone included as a categorical variable (using the “by” argument in
161 the gam function in the mgcv R package, Wood 2017), thus allowing smooths to be generated for
162 each vessel category or zone. Smoothers were fitted to predictors using penalised regression splines
163 with the number of smoothing parameters selected using an Un-Biased Risk Estimator (UBRE). All
164 models were fitted with a Poisson distribution with a log link. Finally, to limit residual autocorrelation,
165 a temporal autoregressive correlation structure of order 1 (CorAR1) was implemented within each
166 model.

167 To obtain an unbiased estimate of significant change points in the number of vessels in the
168 bay at any given month during the study period, we applied a Bayesian change point analysis (BCPA)
169 using R package bcp (Erdman and Emerson, 2007) following the methods of Wang and Emerson
170 (2015). The BCPA uses the Markov chain Monte Carlo (MCMC) method to estimate the posterior
171 means of unknown data blocks partitioned in the data series and change points at any given location.
172 We applied the BCPA to a sequential time series of all vessels quantified per month using 500 MCMC
173 samples and discarded the first 50 as burn-in. Change points were selected with posterior probability
174 values > 0.5.

175 *Noise estimates in the African Penguin foraging area*

176 The at-sea distribution of African Penguins rearing chicks on St Croix Island was tracked with
177 GPS loggers as part of a long-term monitoring project (Pichegru et al., 2010; 2012), with relevant
178 ethics clearances (University of Cape Town 2009/V2/LP and Nelson Mandela Metropolitan
179 University NMMU-A15-SCI-ZOO-008) and permit approvals (South African National Parks
180 (PICL578), the South African Department of Forestry, Fishery and the Environment (res2013-05)).
181 Chick-rearing African Penguins were equipped with GPS loggers (earth & OCEAN Technologies™,
182 Germany, or CatTrack™, USA) recording locations every minute at an accuracy of <10 m and
183 weighing <2.5 % of adult body mass (see Pichegru et al., 2010 for details). To estimate the core
184 marine utilisation area for African Penguins breeding on St Croix Island, we used methods developed
185 by BirdLife International (Lascelles et al., 2016, Dias et al., 2018) to identify Marine Important Bird
186 and biodiversity Areas (mIBA). We used complete tracks (n = 46) recorded between 2015 and 2018

187 and the R package *track2KBA* (Beal et al. 2021) to generate the core marine utilisation areas. The
188 geometric centre of this foraging area was identified using the R package *sf* (Pebesma, 2018).

189 Due to a lack of referenced conversion factors for noise produced by ships at anchor,
190 underwater noise levels were estimated for transiting vessels only, i.e., for vessels with a speed over
191 ground >1 kn.. Estimating noise levels is a challenging and complex task, as vessel noise production
192 depends on intrinsic features (ship shape design, size, engine power, propeller type, etc) and
193 external factors (water depth, wave height, etc) (Abrahamsen, 2012; McKenna et al., 2013, Gaggero
194 et al. 2015). Nevertheless, for containerships for example, the speed as well as the size appear to
195 be the main variables in modelling the resulting noise emitted (Abrahamsen, 2012). We thus
196 estimated noise levels on main vessel types (Table 1) based on reference values (i.e., mean
197 broadband sound pressure levels between 20 to 40,000 Hz) from the literature (Veirs et al., 2016),
198 as the range of speed values of vessels transiting in Algoa Bay approximated the range of values
199 used in this study (Table 1).

200 While noise is produced throughout the day by vessels transiting the bay, hourly variation
201 was negligible (data not shown). We focused our analyses on the traffic occurring between 12pm
202 and 1pm daily, which corresponds to the peak of penguin foraging activity (van Eeden et al., 2016).
203 Therefore, each vessel present in the study area was considered only once daily in the following
204 analyses.

205 Considering only vessels transiting (speed >1 kn) between 12 pm and 1pm, we then
206 calculated (1) the noise received by penguins in the centre of their mIBA from each ship daily, (2)
207 the cumulative underwater noise level from all vessel traffic (with AIS) daily, and (3) the average
208 daily noise level received per month, following the equations below:

209 (1) The received sound level (RL, dB re 1 μ Pa), i.e., the level of noise received at the centre
210 of the penguin foraging area as emitted by each vessel, was calculated daily as per Eq.
211 1:

212

$$213 \quad RL = SL - TL \quad (\text{Eq. 1})$$

214

215 where SL = mean broadband (20-40 000 Hz) Source Level, i.e. the level of noise at 1 m produced
216 by the vessel depending on its type, as described from the literature (Veirs et al., 2016) (Table 1);
217 and TL = Transmission Loss, i.e., the reduction in noise level with distance (in m), estimated
218 based on the distance of the vessel to the centre of the mIBA following Eq. 2, taking into account the
219 shallow bathymetry of the study area (<50 m) and considering the seafloor characteristics of our
220 study area which is relatively uniform (Schoeman et al., 2022):

$$TL = 10 * \log_{10}(dist) \quad (\text{Eq. 2})$$

223

224 (2) The daily Received sound Level (RL_{day}) was then calculated as the cumulative noise level
225 received at the centre of the mIBA from all vessels between 12 pm and 1 pm on each day
226 (Eq. 3), where n is the number of vessels:

227

$$RL_{day} = 10 * \log_{10}(\sum_{i=1}^n 10^{\frac{RL}{10}}) \quad (\text{Eq. 3})$$

229

230 (3) and the monthly averaged daily Received sound Level (RL_{month}) was calculated following
231 (Eq. 4), where n is the number of days in the month.

232

$$RL_{month} = 10 * \log_{10}(\sum_{i=1}^n \frac{10^{\frac{RL_{day}}{10}}}{n}) \quad (\text{Eq. 4})$$

234

235 *African Penguin population trend and underwater noise levels*

236 We assessed the relationship between annual vessel-derived noise estimates and the annual
237 counts of African Penguin breeding pairs using standard linear regression. Annual vessel-derived
238 noise estimates were averaged across the 12 months of data using the equation 4 (replacing RL_{day}
239 for RL_{month} and $n = 12$ months). Penguin counts were extracted from the annual count conducted

240 by the Department of Forestry, Fishery and the Environment (DFFE) following a standard method
241 (see Sherley et al., 2020 for details). All data analyses were performed in the R statistical
242 environment (R version 3.6.1; R Core Team, 2019).

243

244 **RESULTS**

245 *Trends in vessel category and zone use in Algoa Bay*

246 Vessel traffic in Algoa Bay more than doubled between 2013 and 2019, from 96 vessels on
247 average per month in early 2013 to 245 vessels per month in 2019, with two significant change points
248 identified in April 2016 and in March 2019 (Fig 2, Table S2). This trend was strongly influenced by
249 vessel category (Fig. 2a) and zone use (Fig. 2b), with the majority of explanatory smooth terms
250 (Vessel Category: all terms except s(nYM): Chemical and Oil Carrier; Zone: all terms except s(nYM))
251 in the GAM outputs fitting well to the data and being highly significant ($P < 0.001$, Table S2).

252 Bulk carriers were the vessel types that increased the most during our study period, with a
253 ten-fold increase from 13 vessels per month in January 2013 to 134 in December 2019 (Fig. 2a).
254 This increase was largely driven by two periods of significant changes in vessel numbers, around
255 the two significant change points: from 22 ± 6 vessels (median \pm Inter Quartile Range, IQR) before
256 April 2016, to 81 ± 16 and 96 ± 18 vessels after change points 1 and 2 respectively (Fig. 2a). The
257 average number of container ships in the bay remained fairly constant over time, averaging close to
258 50 ships per month, but Chemical and Oil Carriers, as well as Tankers, increased by 200 to 400%
259 during our study period (from 1-3 to 11-21 per month, Table S1). All other vessel types remained in
260 low numbers (1-4), with little change over time (Table S1).

261 Most of the increases in vessel traffic occurred in the shipping lanes and in anchorage area
262 1 (Fig. 2b, Fig. S1). Vessels in shipping lanes increased from 108 ± 16 vessels before April 2016 to
263 184 ± 18 and 214 ± 16 vessels after change points 1 and 2 respectively. Vessels in anchorage area
264 1 increased from 22 ± 6 vessels before April 2016 to 84 ± 22 and 115 ± 25 vessels after change

265 points 1 and 2 respectively (Fig. 2b). The use of anchorage area 2 also increased sharply after 2016,
266 but not after March 2019, while the vessel traffic in Ngqura harbour increased relatively slowly and
267 constantly during the study period. By contrast, the use of Gqeberha harbour varied more over time
268 but remained relatively constant when compared to vessel trends in the anchorage areas and
269 shipping lanes (Fig. 2b).

270 *Noise estimates in the African Penguin foraging area*

271 The annual mean ambient underwater noise level estimates received at the centre of the
272 penguin foraging area have been constantly high since 2013. Noise estimates increased from <140
273 dB re 1 μ Pa in 2013 to >142 dB re 1 μ Pa from 2016 onward (Fig. 3, Table S3), which corresponds
274 to double the noise intensity from before to after 2016.

275 Importantly, the variability within years of noise levels decreased since 2016. Prior to 2016,
276 monthly variations were apparent throughout the year with monthly noise levels ranging from 137 to
277 143 dB re 1 μ Pa during this period. Highest noise levels estimated occurred in the summer months
278 (Fig. 3, Table S3). From 2017 onwards, this variability decreased (<2 dB re 1 μ Pa between months;
279 Table S3), with received noise levels being higher and more constant throughout the year (between
280 141 and 143 dB, Fig. 3).

281 In 2020, due to the national lockdown implemented during the global pandemic, underwater
282 noise levels dropped drastically from >140 dB re 1 μ Pa to ca. **133** dB re 1 μ Pa in just a few weeks
283 (Fig. 3).

284 *African Penguin population trend*

285 There was a strong negative relationship ($R^2 = 0.83$, linear regression model estimates: $t = -$
286 4.9 , $P = 0.005$) between the annual number of African Penguin breeding pairs on St Croix Island and
287 annual estimates of vessel-derived noise received levels at the centre of the penguins' foraging area
288 in Algoa Bay during the study period (Fig. 4). Increase in annual estimates of vessel noise
289 corresponded to a significant average decrease of 976 ± 285 (mean \pm SE) penguin pairs per year
290 during our study period (Fig. 4). It is worth noting from Fig. 4 that the lowest recorded numbers of

291 penguins' breeding pairs correspond to the period after the initiation of STS bunkering in 2016 (2016
292 – 2019).

293

294 **DISCUSSION**

295

296 The impacts of vessel-derived noise pollution on ecosystems are difficult to estimate, partly
297 because of a limited knowledge of taxa specific sound thresholds, and partly because spatial data
298 for global maritime traffic has, until recently, remained sparse. AIS data has only been generalised
299 to vessels for just over a decade, and its use to understand the impacts of maritime vessel activities
300 on marine biota and ecosystems is in its infancy (Robards et al., 2016). These data are, however,
301 essential to monitor changes following for example the expansion of maritime activities such as
302 offshore STS bunkering, which has been forecast to become one of the most rapidly expanding
303 maritime industries in the near future (Credence Research 2019).

304 In this study, we observed a rapid 10-fold increase in the number of bulk carriers and a
305 significant increase in vessel activity in shipping lanes and anchorage areas, both linked to significant
306 temporal change points, which corresponded to first the initiation of STS bunkering in 2016 and the
307 subsequent expansion of its operations in early 2019, with the operationalisation of the third STS
308 bunkering company. Changes in areas used overtime also reflect STS activity patterns as STS
309 bunkering operations were first established in anchorage area 2 in April 2016, as shown by the rapid
310 increase in vessel use of the area after 2016, but were subsequently transferred to anchorage area
311 1 in early 2017 after the first oil spill that occurred in August 2016 (Fig. 2b). Noise levels emitted by
312 maritime traffic in the bay consequently rose and the estimated average received underwater noise
313 levels at the centre of the core utilisation area of African Penguins breeding on St Croix Island
314 steadily increased from <140 dB to a plateau at around 142 dB re 1 μ Pa (broadband source level
315 estimation) since 2017, placing Algoa Bay among the noisiest bays in the world (Duarte et al., 2021).
316 For example, the bays with the busiest maritime traffic in Brazil had noise levels reaching up to 110
317 dB re 1 μ Pa for the 200-700 Hz frequency band (Bittencourt et al., 2014). At various sites in United

318 Kingdom waters, median noise levels were measured between 81.5–95.5 dB re 1 μ Pa for one-third
319 octave bands from 63–500 Hz (Merchant et al., 2016). Broadband received levels (11.5–40.000 Hz)
320 near the shoreline in Haro Strait (United States of America), a transiting area for the shipping port of
321 Vancouver, were 110 ± 7 dB re 1 μ Pa on average (Veirs et al., 2016), while chronic anthropogenic
322 noise in Saguenay–St. Lawrence Marine Park, Canada, reached 112.6 dB re 1 μ Pa (broadband
323 noise, 0.01-23.3 kHz) (Gervaise et al. 2012).

324 Estimation of vessel traffic noise is complex and depends on but is not limited to, vessel size,
325 speed and frequency (Abrahamsen, 2012; Gaggero et al., 2015). Speed can vary during the course
326 of the day or between usage zones (e.g., anchorage areas versus shipping lanes), which we did not
327 take into account in the present study, as we only considered average values (Table 1). We also did
328 not consider the cumulative impact of biophony, from wind for example (Schoeman et al., 2022), on
329 overall ambient underwater noise levels. However, a recent assessment of the soundscape of Algoa
330 Bay in 2015 using *in-situ* hydrophones revealed the significant contribution of maritime traffic,
331 especially of large vessels in shipping lanes (Schoeman et al., 2022). The authors predicted an
332 increase of this contribution in the near future due to the planned development of the national ocean
333 economy (Schoeman et al., 2022). Our results, focusing on the relative change over time of
334 estimated noise levels from maritime traffic, validate the authors' concerns.

335 It is important to note that, while AIS data is mandatory for vessels larger than 65 ft, it is not
336 required for fishing or recreational vessels, vessels <300 t Gross Tonnage, tankers and passenger
337 vessels <150 t Gross Tonnage (NEMA, 2010). Recreational vessels are known to be responsible for
338 a substantial proportion of ambient underwater noise, especially in shallow coastal waters
339 (Hermannsen et al., 2019). For example, in a study conducted in Denmark, recreational vessels (i.e.,
340 non-AIS vessels) caused more noise than AIS-vessels as they are predominant in Danish shallow
341 coastal waters, and these motorised vessels can elevate third-octave band noise centred at 0.125,
342 2 and 16kHz by 47–51 dB (Hermannsen et al., 2019). Similarly, a study conducted in the Wilmington,
343 North Carolina Intracoastal Waterway, showed that the recreational boat traffic in this area produced
344 mean underwater noise received levels ranging from 109 to ~ 118 dB re 1 μ Pa within a day
345 (Haviland-Howell et al., 2007). Underwater noise levels in Algoa Bay are thus very likely to be

346 significantly higher if recorded from acoustic stations (e.g., Merchant et al., 2014, Schoeman et al.,
347 2022) compared to the present estimates using sound proxies, only for vessels that are legally
348 required to have AIS. In addition, our estimation only considered transiting vessels and not vessels
349 at anchor or undergoing STS bunkering operations. Anchored vessels can be an important source
350 of noise (Abrahamsen, 2012; Baltzer et al., 2020), depending on the type of vessels, with anchor
351 vibrations potentially affecting marine mammals or fish up to 700 m away from the vessels (Baltzer
352 et al., 2020). No published data exist on noise emissions during STS bunkering operations, and this
353 information is crucial for a full picture of the potential underwater noise pollution derived from this
354 activity, not only from the attraction of maritime traffic but also from the activity itself.

355 Importantly, the increase of 3 dB in noise level estimates measured during our study period
356 corresponds to a doubling of the noise intensity in seven years. This is among the fastest increase
357 in sound (0.38 dB p.a.) measured to date from the literature, due to maritime traffic. For example,
358 Ross (1993) estimated an increase of 0.55 dB per year between 1950 and 1975 in the East Pacific,
359 East and West Atlantic oceans, while other studies using different methods showed increased
360 ambient noise levels in the past decades of 0.3 dB per year off the Californian coast (Andrew et al.,
361 2002) or 2.5-3.0 dB per decade in the Northern Pacific Ocean (McDonald et al., 2006). Such rapid
362 doubling of noise intensity in an area is likely to significantly affect resident wildlife.

363 High levels of underwater noise levels can directly affect individual animals by decreasing
364 their foraging success, impacting their sensory abilities (e.g. hearing, orientation) and inducing higher
365 stress levels (see Kight and Swaddle, 2011 for a review; Committee on the Assessment of the
366 Cumulative Effects of Anthropogenic Stressors on Marine Mammals, 2017; Putland et al., 2019)),
367 thereby directly influencing adult survival. While little is known on the hearing range of African
368 Penguins (e.g., Wever et al., 1969), Gentoo Penguins (*Pygoscelis papua*) have demonstrated a
369 strong directional avoidance reaction to underwater noise at received levels between 110 to 120 dB
370 re 1 μ Pa RMS, while no behavioural response was observed with received levels at
371 100 dB re 1 μ Pa RMS (Sørensen et al., 2020). Similar behavioural avoidance responses were noted
372 for the common murre (*Uria aalge*), with received noise levels varying from 110 to
373 137 dB re 1 μ Pa RMS (Hansen et al., 2020). It is thus highly likely that constant anthropogenic noise

374 levels averaging 142 dB re 1 μ Pa around St Croix Island have directly affected penguins. African
375 Penguins are known to be sensitive to underwater noise levels and avoid areas closer to seismic
376 survey activities (Pichegru et al., 2017). In addition, recent findings revealed the importance of
377 acoustic communication in group foraging in African Penguins (McInnes et al., 2020). Thus,
378 increased ambient underwater noise levels could exacerbate inferred Allee Effects currently
379 impacting the foraging performance of this species (Ryan et al., 2012), and contribute to the
380 cumulative threats that impact African Penguins and their prey availability, such as competition with
381 fisheries and climate change (Pichegru et al., 2010; Sherley et al., 2018; IPCC 2022). Indeed, during
382 the short period of our study, a population which at the onset of the study was the world's largest
383 remaining African Penguin colony (ca 8500 breeding pairs, Sherley et al., 2020), located within 5 –
384 15 km of the most intense maritime traffic activities in the bay, more than halved which significantly
385 correlated with the concurrent underwater noise levels in the bay associated with maritime traffic.
386 High mortality of adult penguins was also observed during monthly beach surveys conducted in the
387 bay during the study period (Pichegru et al., 2020, unpubl. report). As far as we are aware this is
388 the greatest short-term decrease of an African Penguin colony on record. As of 2022, this population
389 has now decreased by 85% (ca 1200 pairs; Pichegru, unpubl data).

390 Increases in maritime traffic in Algoa Bay, and subsequent noise levels emitted, are
391 correlated with the establishment and expansion of STS bunkering operations in the bay, with an
392 average of 82 vessels being bunkered every month in Algoa Bay between April 2016 and January
393 2019 (Fig. S1). STS bunkering mainly attracts bulk carriers (Fig. 2), which are among the noisiest
394 vessels in transit (Table 1, Veirs et al., 2016). It is therefore clear that this activity is a major
395 contributor to the altered anthropophony of the bay. In addition to globally significant seabird
396 populations, Algoa Bay is home to high population densities of dolphins and whales (Reisinger and
397 Karczmarski, 2009; Bouveroux et al., 2018; Melly et al., 2018) and Cape fur seals (*Arctocephalus*
398 *pusillus pusillus*), which are all sensitive to underwater noise levels (Duarte et al., 2021). The impact
399 of STS bunkering activities in terms of noise pollution should, therefore, be assessed before
400 authorisation is granted to operate. Indeed, South Africa is a Contracting Party to the Convention on
401 Biological Diversity (CBD), and as such has been encouraged to, *inter alia*, conduct impact

402 assessments for activities that may have significant adverse impacts on noise-sensitive species,
403 combine acoustic mapping with habitat mapping to identify areas where these species may be
404 exposed to noise impacts, mitigate underwater noise through the spatio-temporal management of
405 activities, and consider thresholds as a tool to protect noise-sensitive species (CBD Decision XII/23).
406 Similarly, Parties to the Convention on the Conservation of Migratory Species of Wild Animals (CMS)
407 have also been urged to undertake 'relevant environmental assessments on the introduction of
408 activities that may lead to noise-associated risks for CMS-listed marine species and their prey', to
409 prevent adverse effects on these species and their prey by restricting the emission of underwater
410 noise, and – where noise cannot be avoided – 'to develop an appropriate regulatory framework or
411 implement relevant measures to ensure a reduction or mitigation of anthropogenic marine noise'.
412 The necessity for a precautionary approach has been emphasised in this context (CMS Resolution
413 12.14). As a Contracting Party to these and other relevant environmental treaties (such as AEWA),
414 South Africa should clearly be taking measures to assess and address the impacts of anthropogenic
415 underwater noise on African Penguins and other species – whether through project-level impact
416 assessments or broader planning processes, and taking into account the precautionary principle.
417 This includes the underwater noise induced by STS bunkering through associated increases in
418 vessel traffic. The current working plan for the AEWA Benguela Coastal Seabirds International
419 Working Group highlights concerns regarding the potential impacts of ship-to-ship bunkering and
420 associated vessel traffic and recognises the need for these impacts to be properly assessed and for
421 noise pollution to be reduced (AEWA Benguela Coastal Seabirds International Working Group 2021).

422 However, to date, Ship-to-Ship bunkering is not listed as an activity requiring environmental
423 authorisation in terms of South Africa's National Environmental Management Act 107 of 1998. As
424 such, the 2014 Environmental Impact Assessment (EIA) Regulations are not applicable. STS
425 bunkering operations require permission from the South African Maritime Safety Authority (SAMSA)
426 in terms of the Marine Pollution (Control and Civil Liability) Act 6 of 1981 and a licence from the
427 Transnet National Port Authority (TNPA) in terms of the 2009 Port Rules. Neither of these
428 instruments provides a comprehensive framework (comparable to the EIA Regulations) for
429 assessing the full range of direct, indirect, and cumulative impacts associated with STS bunkering.

430 A Bunkering Code of Practice is currently being developed with a view to improving the management
431 of STS bunkering in South Africa. However, it remains to be seen how effectively this will address
432 gaps in the existing regulatory framework.

433 This local context contrasts sharply with the international efforts that are currently underway
434 to explore avenues to decrease commercial ships' noise emissions, including the development of
435 standard measurement protocols by the International Organization for Standardization (ISO 2016,
436 2019). The IMO's Marine Environment Protection Committee also approved guidelines on reducing
437 underwater noise from commercial shipping in 2014, which are currently being reviewed (IMO,
438 2021). Noise reduction measures may include reducing the speed of vessels underway or limiting
439 time periods of ships' activities, including bunkering, in biologically important areas (e.g., Veirs et al.,
440 2018; Williams et al., 2019). The use of quieting technologies (Simmonds et al., 2014), like new
441 propeller designs ("Battling noise pollution, underwater | Hellenic Shipping News Worldwide," 2019)
442 or four-strokes engines rather than two-strokes (Chahouri et al., 2022 and references therein), would
443 also rapidly decrease noise levels emitted. International and trans-disciplinary and trans-institutional
444 collaborations are required to effectively implement the necessary noise level reduction measures
445 (Southall et al., 2017). Marine Protected Areas with spatial and temporal exclusions of noise emitting
446 sources probably remain the most efficient way to protect marine life from the negative impacts of
447 underwater sound (e.g., Simmonds et al., 2014).

448

449 **CONCLUSION**

450 The intensification of underwater noise levels in the African Penguin's foraging habitat was linked to
451 the initiation and expansion of ship-to-ship bunkering activities which intensified the maritime traffic
452 in the area. Noise levels were significantly related to the collapse of what had been the world's largest
453 remaining colony of endangered African Penguins. The underwater soundscape of Algoa Bay, a
454 hotspot of biodiversity, has now been profoundly modified. The situation is likely to worsen in the
455 near future as global maritime traffic is predicted to increase by 240–1,209% by 2050 (Sardain et
456 al., 2019) due to anticipated increased demands for goods associated with a projected increase in

457 the global human population compounded by a general push for expansion of the Blue Economy in
458 many countries. Unless mitigated against, underwater ambient noise levels will also increase and
459 these will be exacerbated in regions where vessels congregate, such as in ports and sheltered bays
460 that provide maritime and refuelling services, with likely ecosystem-wide impacts.

461

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715 List of Tables and Figs

716

717 Table 1. Sample size and speed values (mean \pm SD, in knot) from AIS data for vessels transiting
718 (speed >1 kn) in Algoa Bay between 2013 and 2020, in comparison with speed values considered
719 in Veirs et al., (2016), as well as mean Source Level (SL) values (dB re 1 μ Pa @ 1m) emitted by
720 various passing vessel types described in Veirs et al., (2016) and used in the estimate of
721 underwater noise levels in Algoa Bay.

722

723 Fig 1. Map of the study area, showing Ngqura (light blue) and Gqeberha (dark blue) harbours,
724 anchorage areas 1 and 2, shipping lanes, as well as the main African penguin foraging area (dotted
725 line) from St Croix Island and its centre (back cross).

726

727 Fig. 2. Trend (smooths from generalized additive mixed models and SE) in monthly number of
728 vessels in Algoa Bay per type (a) and area of use (b) between January 2013 and December 2019.
729 The two black vertical lines show the significant change points from the Bayesian change point
730 analysis (BCPA).

731

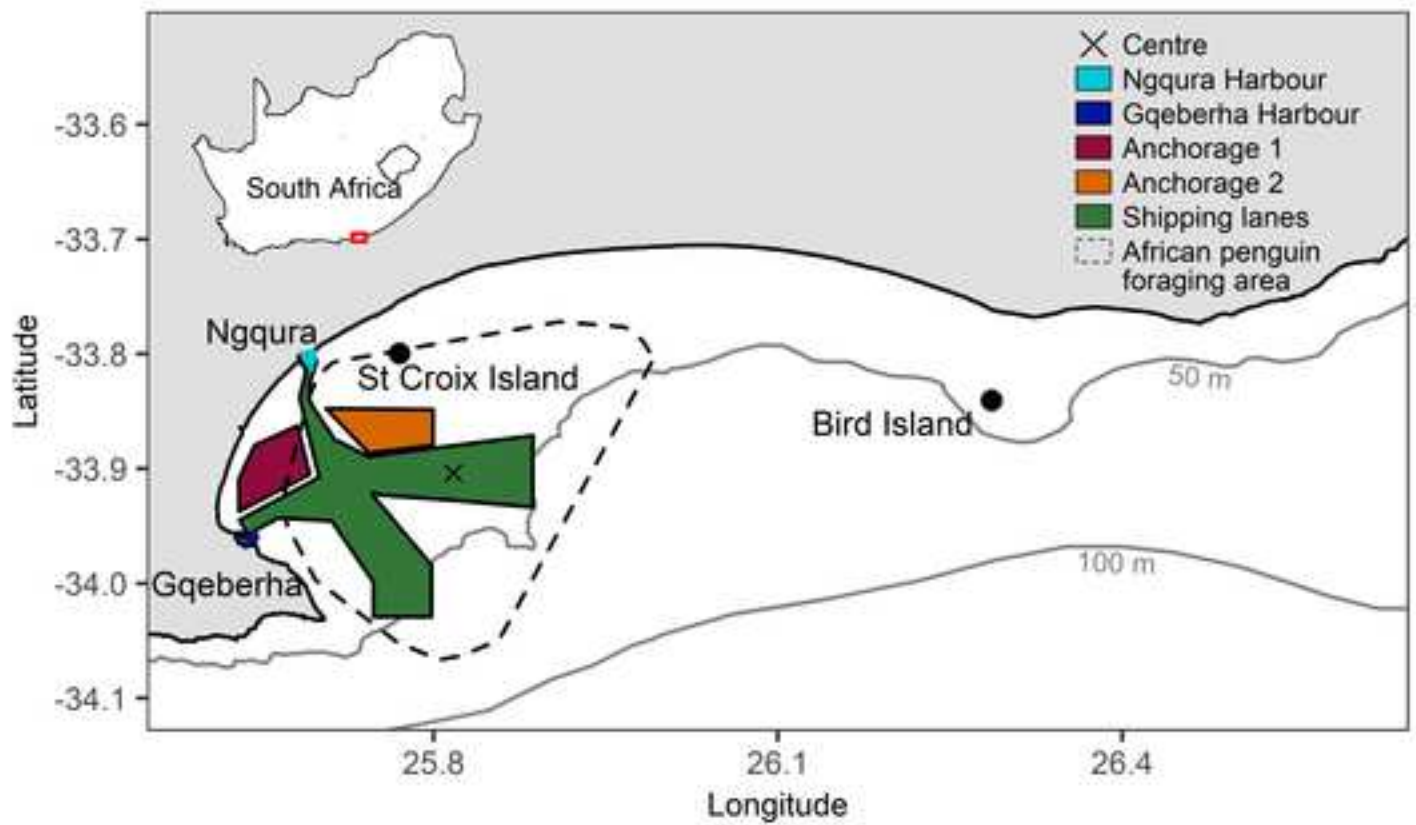
732 Fig 3. Mean (\pm SD) annual underwater vessel noise levels (in dB re 1 μ Pa) received between 2013
733 and 2020 at the centre of the St Croix Island African penguin foraging area. Monthly averages are
734 also shown (grey dots).

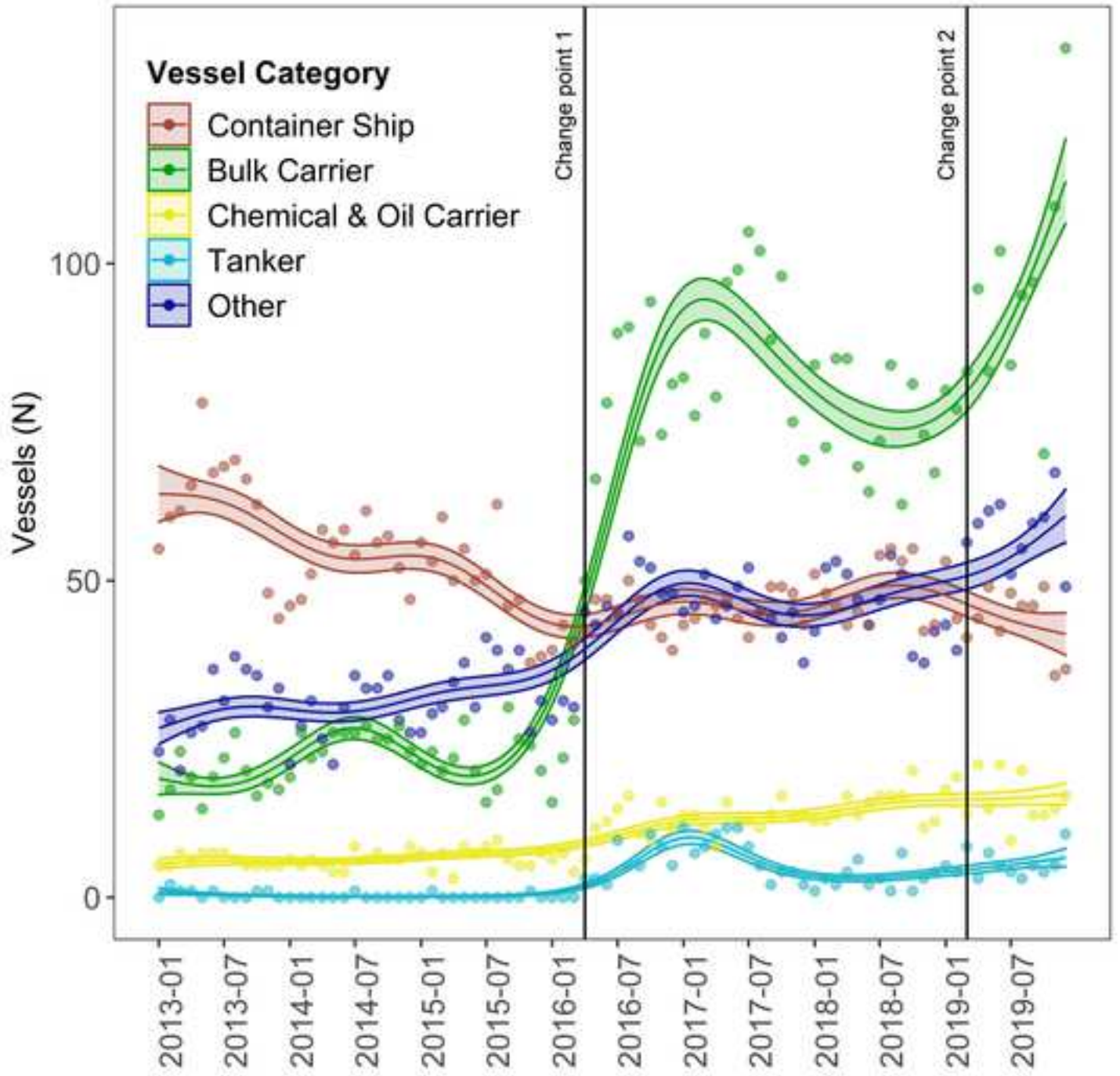
735

736 Fig 4. Linear regression (and 95% confidence interval) between the mean annual underwater vessel
737 noise levels (in dB re 1 μ Pa) received at the centre of the St Croix Island African penguin foraging
738 area and corresponding annual breeding pairs of African penguins recorded on St Croix Island
739 between 2013 and 2019.

Table 1. Sample size and speed values (mean \pm SD, in knot) from AIS data for vessels transiting (speed >1 kn) in Algoa Bay between 2013 and 2020, in comparison with speed values considered in Veirs et al., (2016), as well as mean Source Level (SL) values (dB re 1 μ Pa @ 1m) emitted by various passing vessel types described in Veirs et al., (2016) and used in the estimate of underwater noise levels in Algoa Bay.

Vessel category	N Algoa Bay	Speed (kn) Algoa Bay	Speed (kn)	Mean SL
			Veirs et al., 2016	(Veirs et al., 2016)
Bulk carrier	82 788	9.96 \pm 3.19	13.7 \pm 1.5	173
Containership	46 185	9.73 \pm 5.47	19.2 \pm 1.9	178
Tug	1 629	5.81 \pm 3.72	8.2 \pm 2.3	170
Cargo	9 256	10.80 \pm 4.12	14.4 \pm 2.3	175
Vehicle carrier	8 804	10.10 \pm 5.53	16.9 \pm 1.8	176
Tanker	25 793	7.03 \pm 4.49	13.8 \pm 1.4	174
Military vessel	142	10.10 \pm 3.62	11.1 \pm 3.1	161
Fishing vessel	8 734	6.65 \pm 3.03	9.1 \pm 2.2	164
Passenger vessel	833	12.1 \pm 4.41	14.4 \pm 4.	166
Others	6 969	7.62 \pm 3.96	11.2 \pm 5.8	163
Leisure craft	70	9.25 \pm 3.39	12.4 \pm 4.9	159
Research boat	498	7.32 \pm 3.48	11.1 \pm 1.8	167





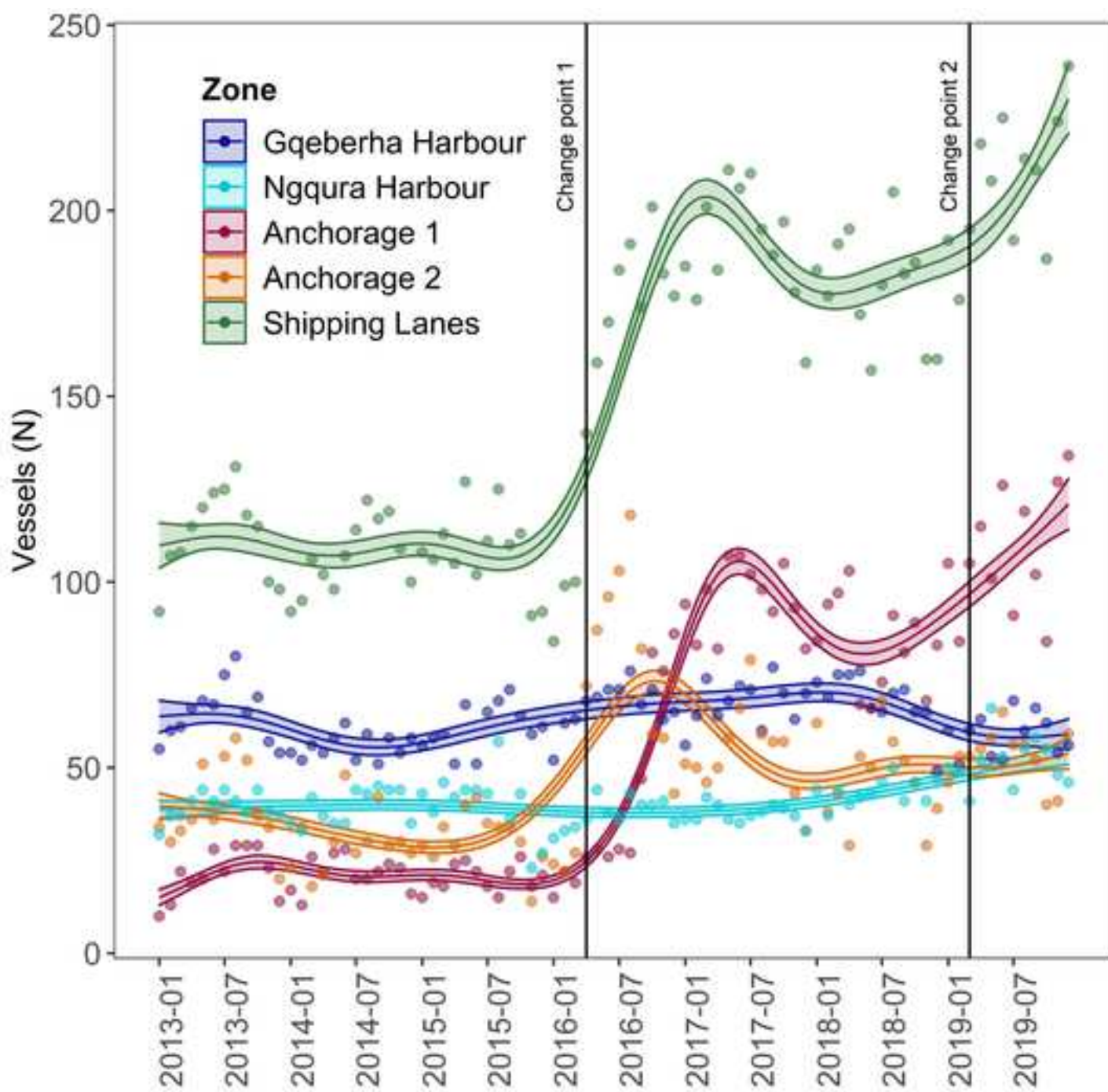
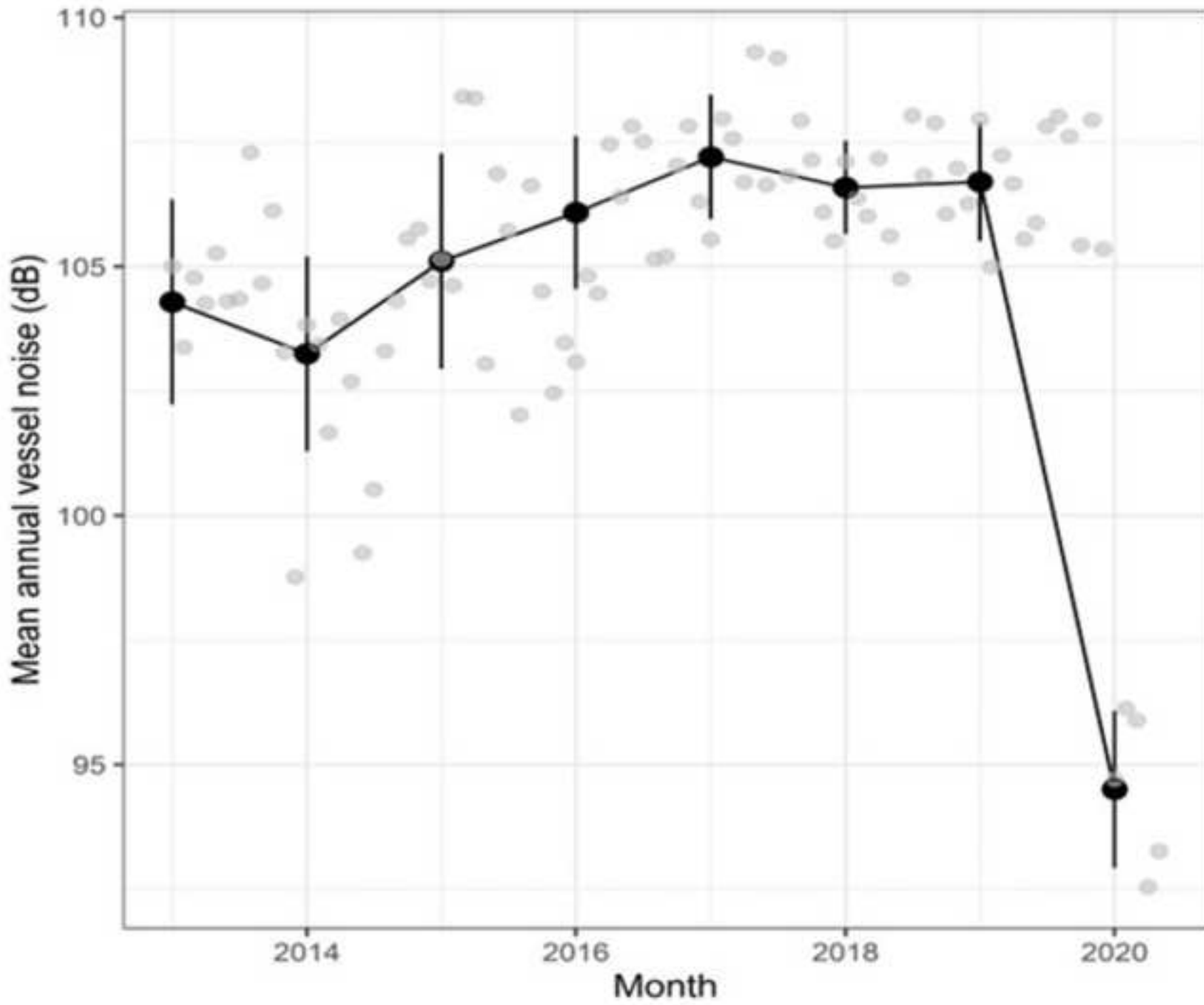
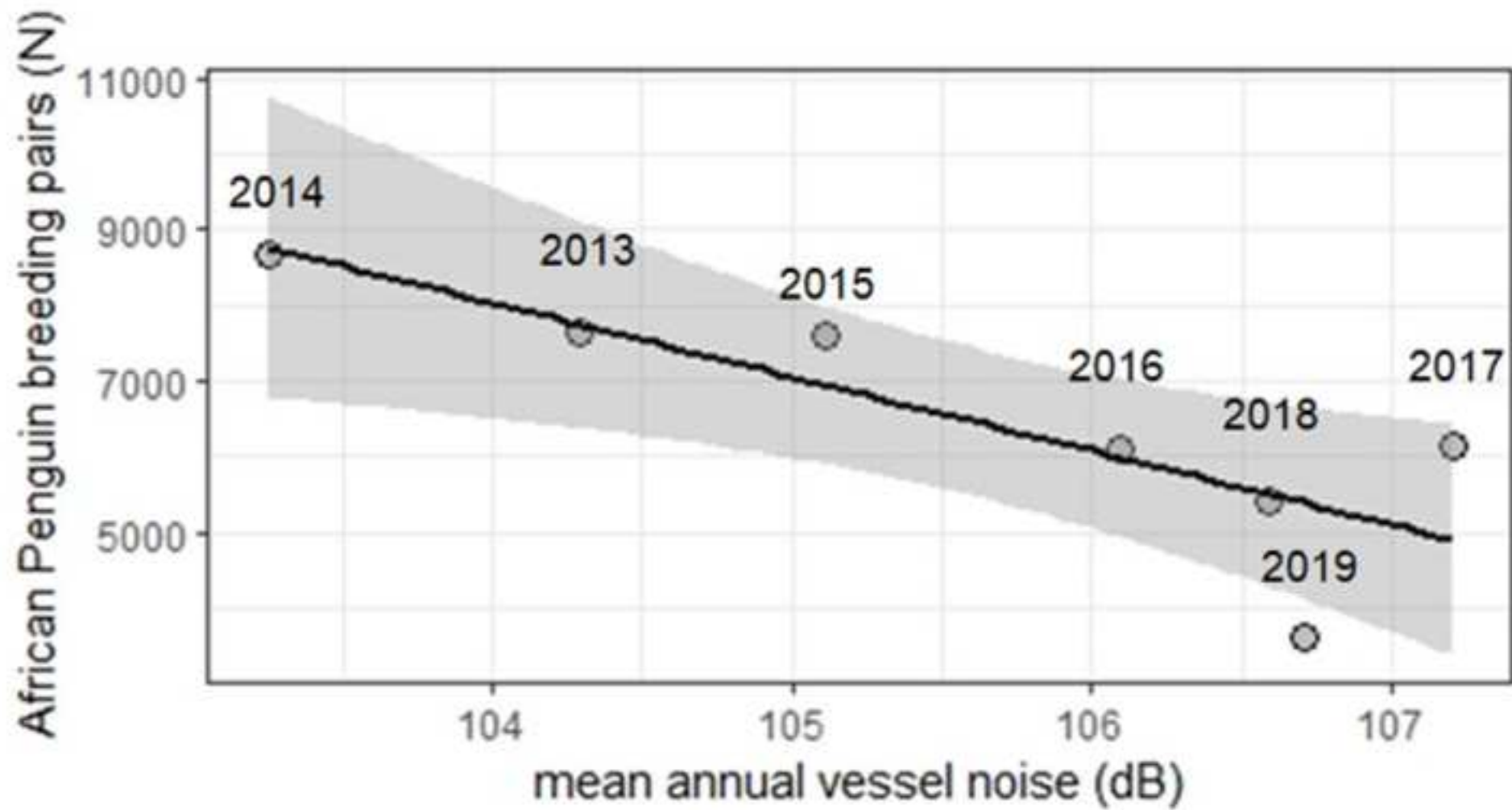


Figure 3







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Supplementary Material

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Declaration of interests

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author contributions

LP: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Roles/Writing - original draft.

LV: Data curation; Formal analysis; Writing - original draft

AT: Formal analysis; Methodology; Writing - review & editing

IC: Methodology; Writing - review & editing

NS: Writing - review & editing;

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TK-C: Formal analysis; Methodology; Writing - review & editing;

AM: Conceptualization; Data curation; Formal analysis; Methodology; Writing - review & editing