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

Lorien Pichegru[1,ǂ,*], Laetitia Vibert[1, ǂ], Andrea Thiebault[1,2], Isabelle Charrier[2], Nicky Stander[3], Katta Ludynia[3,4], Melissa Lewis[5], Tegan Carpenter-Kling[1,5] and Alistair McInnes[5,6]

[1] Institute for Coastal and Marine Research, Nelson Mandela University, Gqeberha, South Africa, 6001

[2] Université Paris-Saclay, CNRS UMR 9197, Institut des Neurosciences Paris-Saclay, 91400 Saclay, France

[3] Southern African Foundation for the Conservation of Coastal Birds, Cape Town, South Africa, 7441

[4] Department of Biological Sciences, University of Cape Town, South Africa, 7700

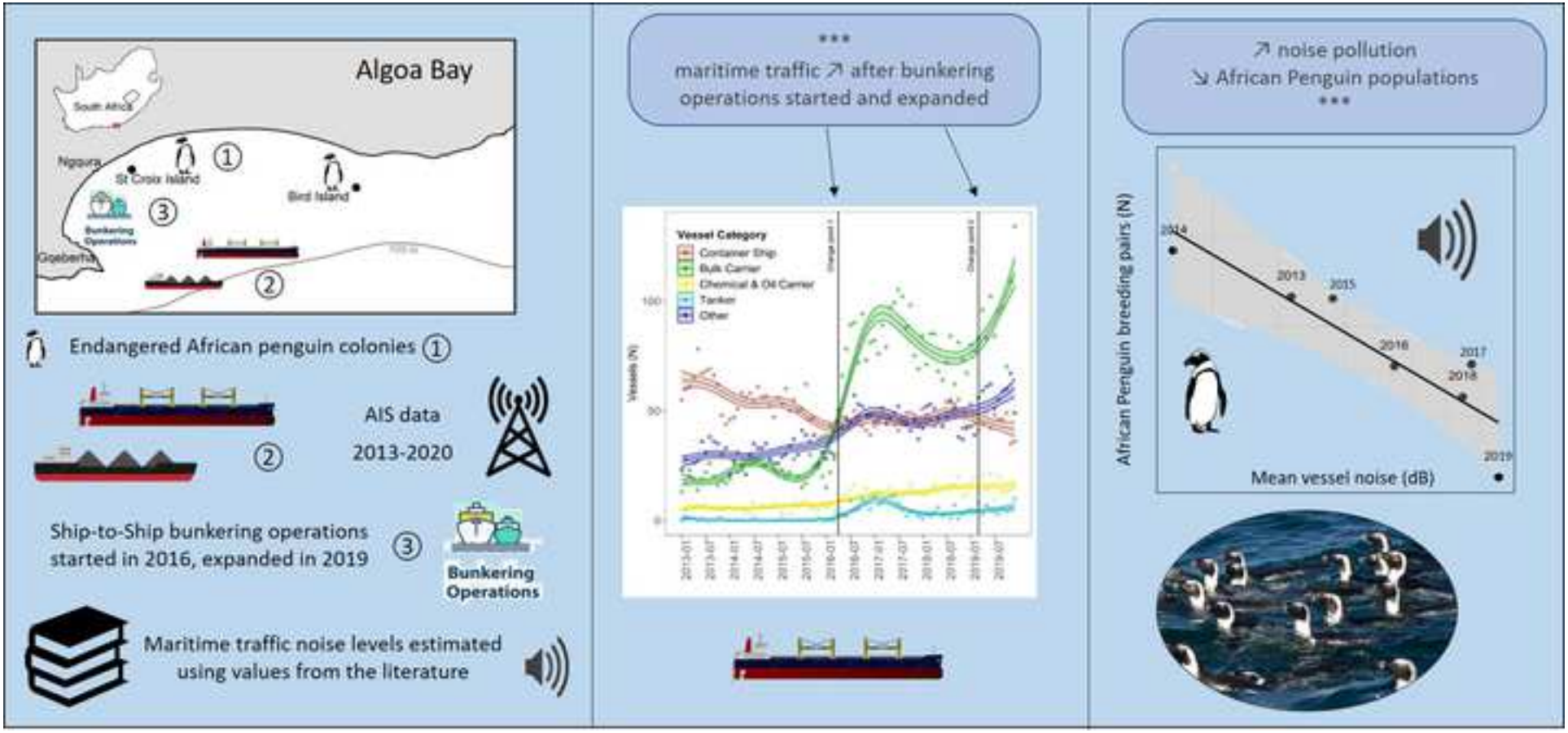
[5] BirdLife South Africa, Cape Town, South Africa, 8001

[6] FitzPatrick Institute of African Ornithology, University of Cape Town, South Africa, 7700

[ǂ] These authors contributed equally to the work.

*Author for correspondence: lorien.pichegru@mandela.ac.za

Graphical Abstract



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

Manuscript (double-spaced and continuously LINE and PAGE numbered)-for final publication

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Abstract

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

Keywords

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

INTRODUCTION

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

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

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

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

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

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

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

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

METHODS

Trends in vessel category and zone use in Algoa Bay

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

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

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

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

Noise estimates in the African Penguin foraging area

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

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

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

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

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

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

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

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

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

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

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

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

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

African Penguin population trend and underwater noise levels

We assessed the relationship between annual vessel-derived noise estimates and the annual counts of African Penguin breeding pairs using standard linear regression. Annual vessel-derived noise estimates were averaged across the 12 months of data using the equation 4 (replacing RLday for RLmonth and n = 12 months). Penguin counts were extracted from the annual count conducted

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

RESULTS

Trends in vessel category and zone use in Algoa Bay

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

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

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

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

Noise estimates in the African Penguin foraging area

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

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

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

African Penguin population trend

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

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

DISCUSSION

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

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

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

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

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

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

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

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

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

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

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

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

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

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

CONCLUSION

The intensification of underwater noise levels in the African Penguin's foraging habitat was linked to the initiation and expansion of ship-to-ship bunkering activities which intensified the maritime traffic in the area. Noise levels were significantly related to the collapse of what had been the world's largest remaining colony of endangered African Penguins. The underwater soundscape of Algoa Bay, a hotspot of biodiversity, has now been profoundly modified. The situation is likely to worsen in the near future as global maritime traffic is predicted to increase by 240–1,209% by 2050 (Sardain et 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

462 ## Acknowledgments

463 We would like to thank Clarksons Platou (H. Clarksons & Company Limited) for providing the AIS
464 data, the South African Maritime Safety Authority (SAMSA) for providing information on bunkering
465 activities in Algoa Bay, and the Department of Forestry, Fishery and the Environment for penguin
466 counts. We thank Dr E. Vermeulen for the shapefiles of the harbours as well as for earlier comments
467 on this study. We also thank Dr R.P. Schoeman for constructive discussions on the earlier phase of
468 this research. SANCCOB is supported by a wide range of donors.

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List of Tables and Figs

Table 1. Sample size and speed values (mean ± 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 µPa @ 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.

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

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

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

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

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

Figure 1

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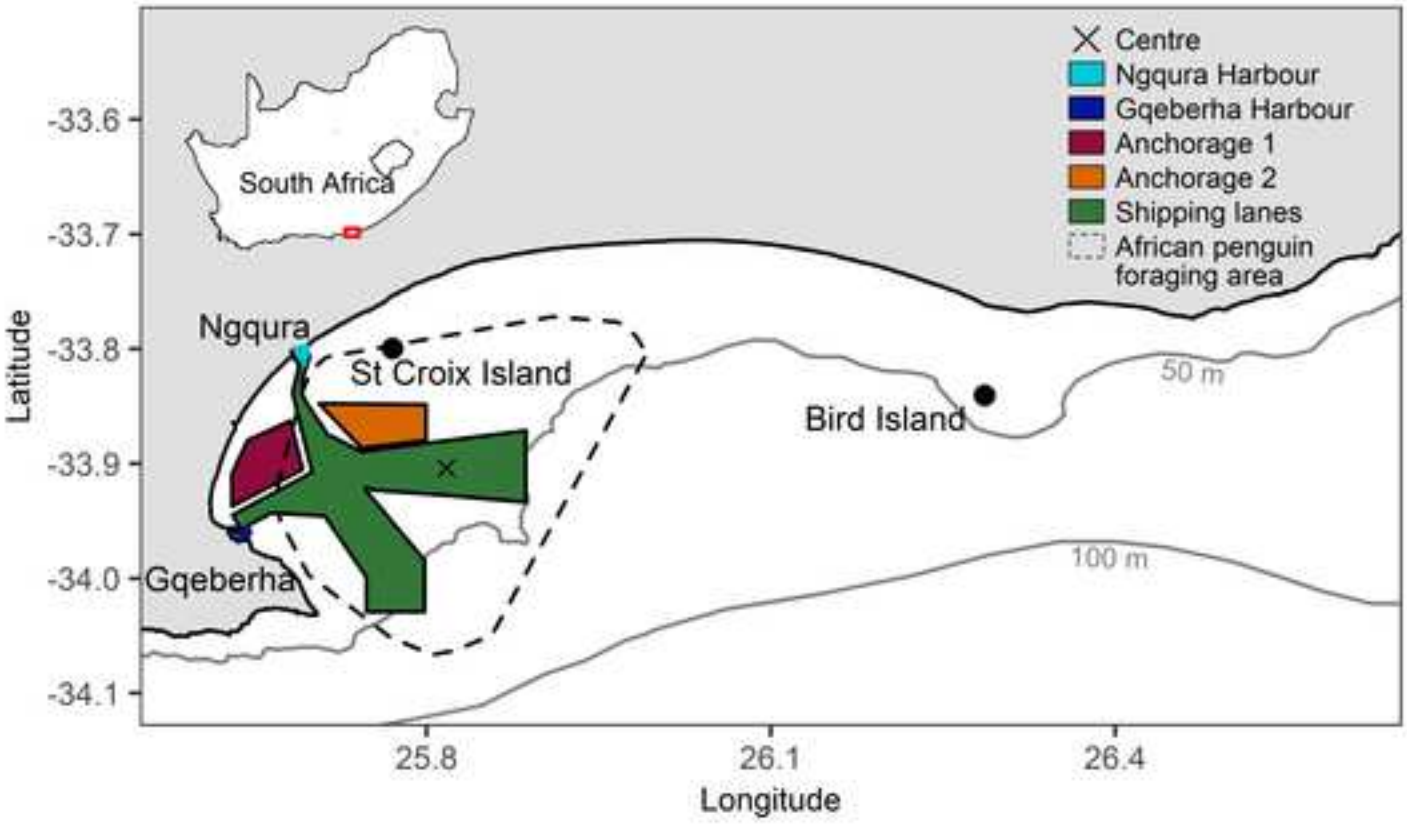


Figure 2a

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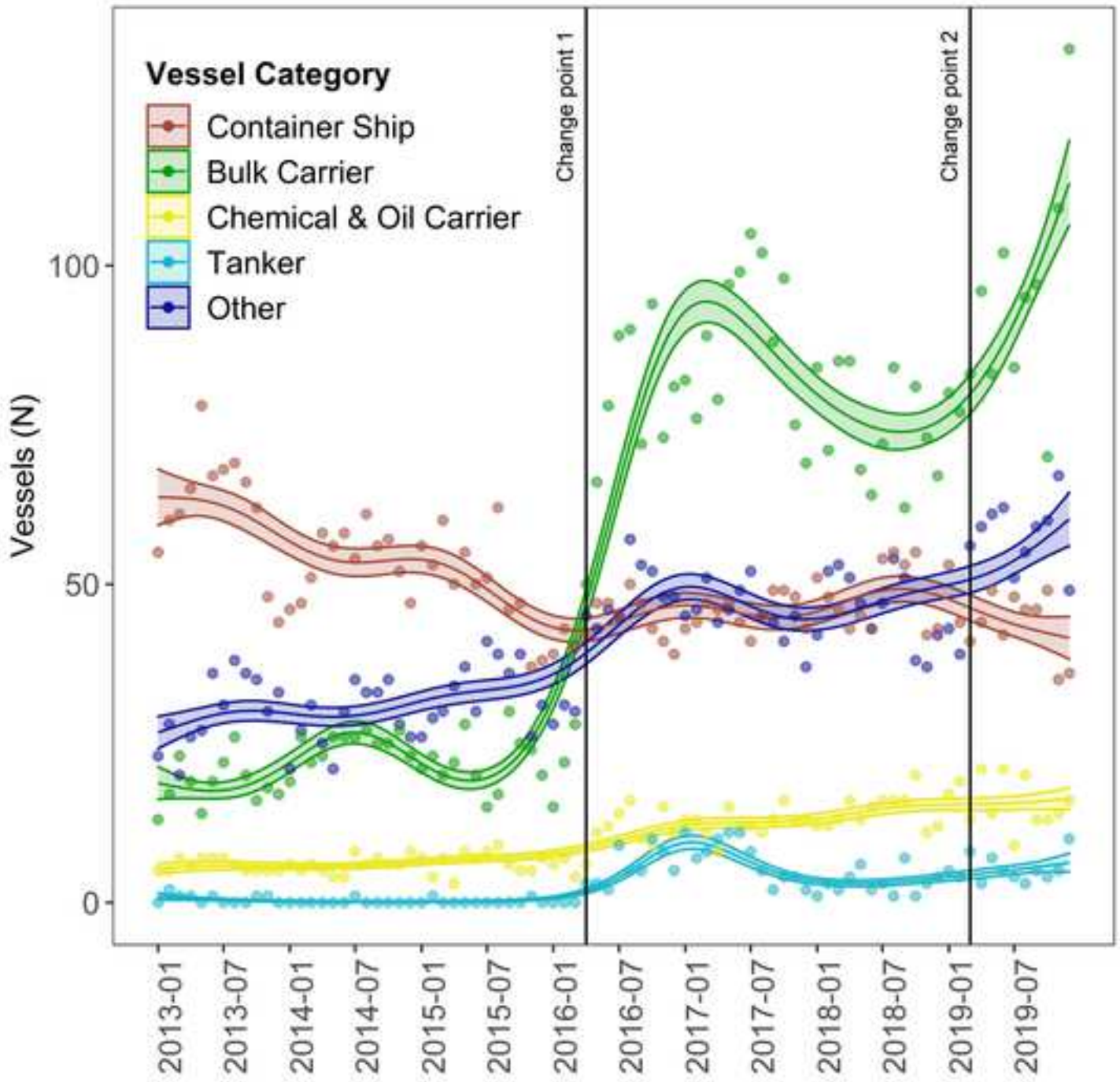


Figure 2b

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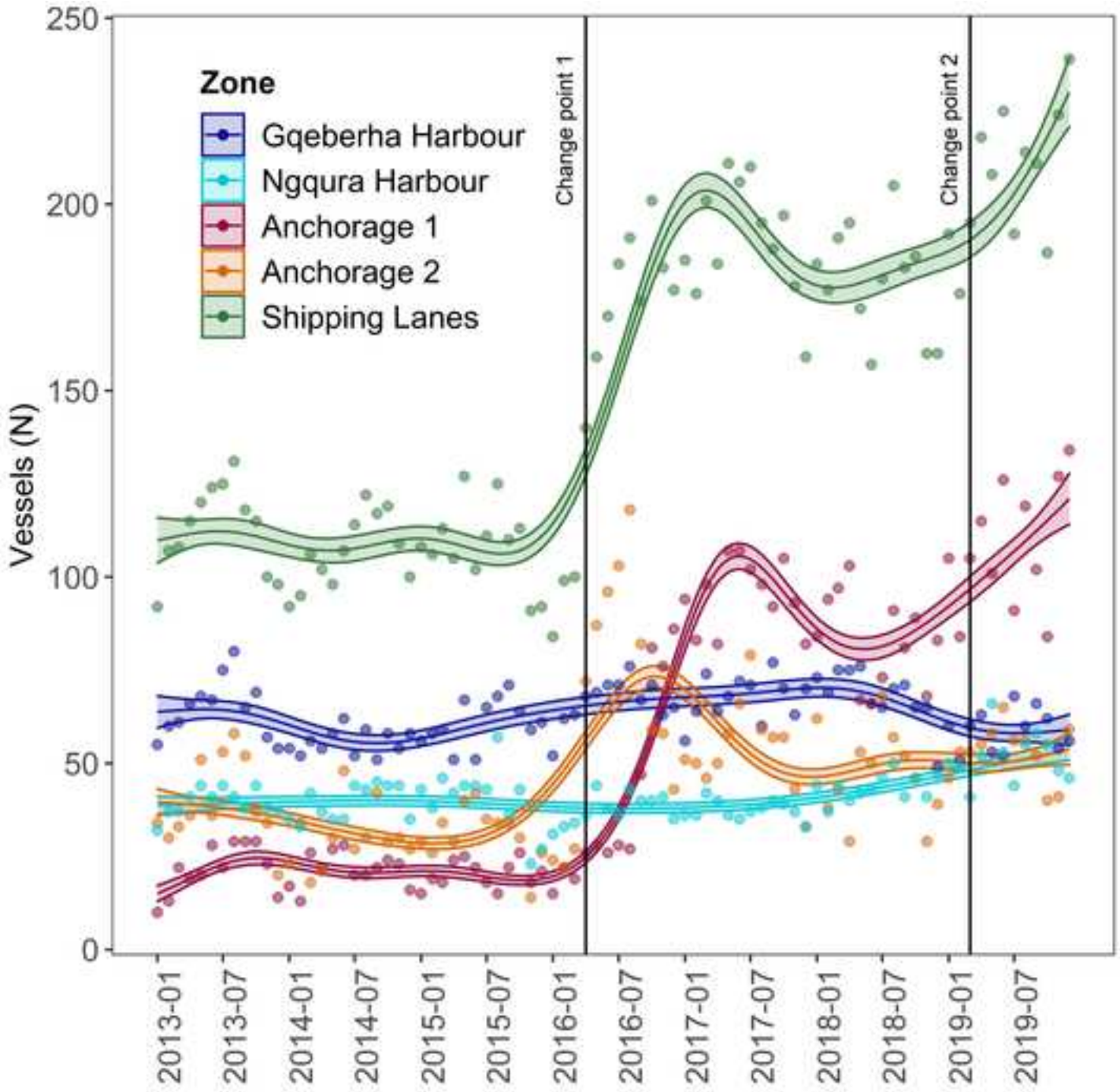


Figure 3

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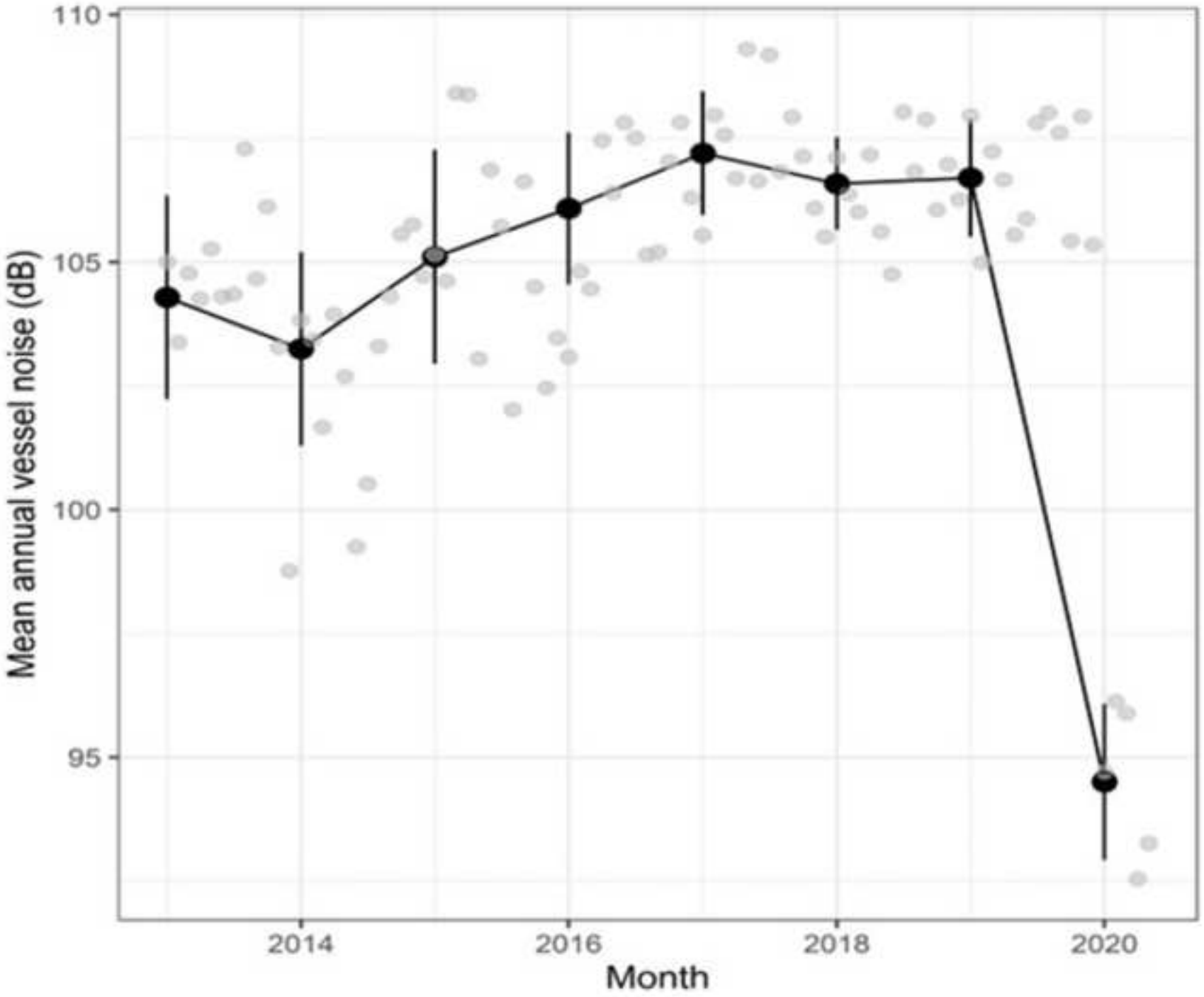
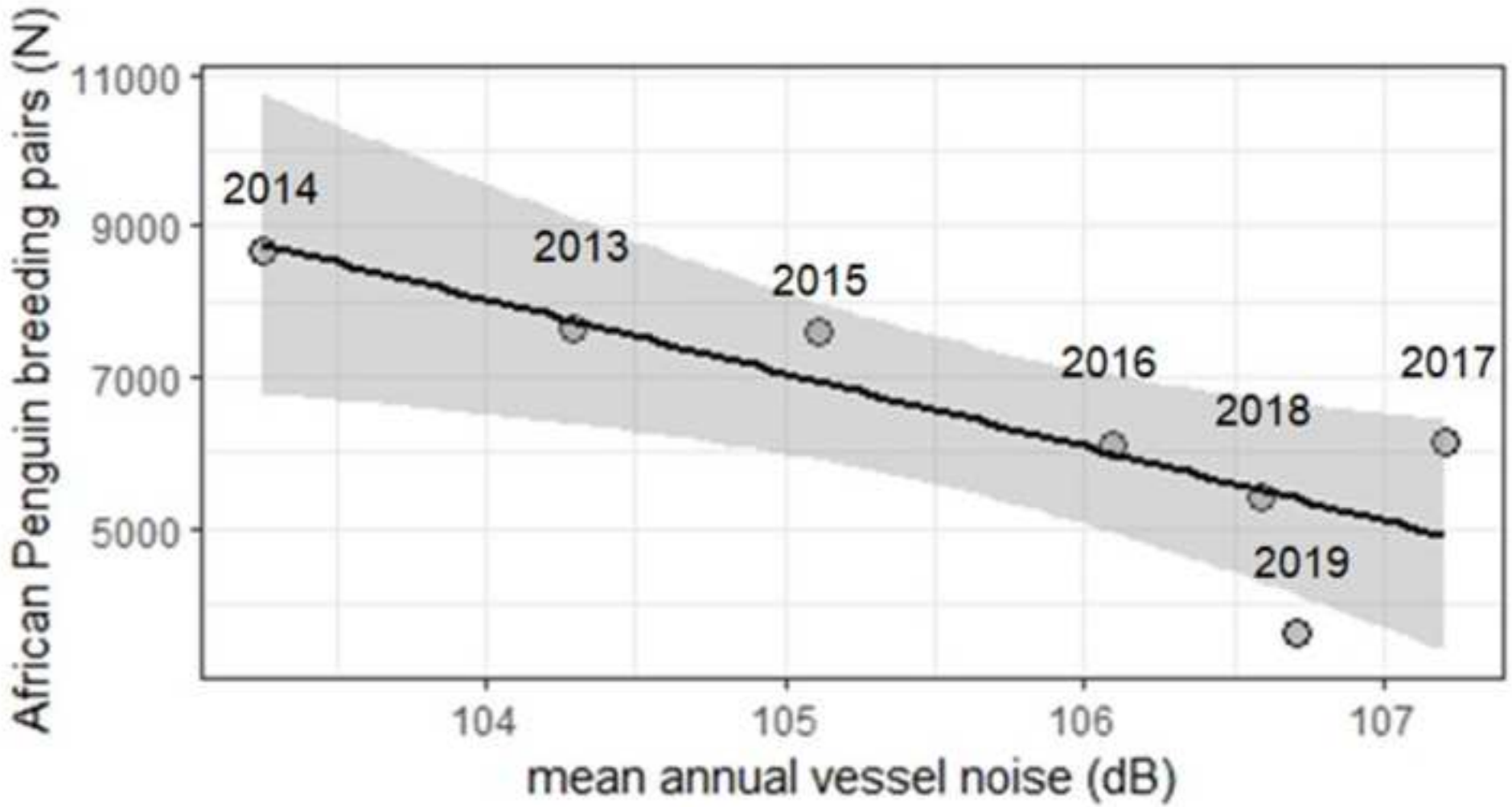


Figure 4

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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;

KL: Writing - review & editing;

ML: Writing - review & editing;

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

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