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Research article

Effectiveness of marine protected areas in safeguarding important migratory megafauna habitat

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ABSTRACT

Marine protected areas (MPAs) are a commonly used management tool to safeguard marine life from anthropogenic impacts, yet their efficacy often remains untested. Evaluating how highly dynamic marine species use static MPAs is challenging but becoming more feasible with the advancement of telemetry data. Here, we focus on southern right whales (*Eubalaena australis*, SRWs) in the waters off Aotearoa/New Zealand, which declined from 30,000 whales to fewer than 40 mature females due to whaling. Now numbering in the low thousands, the key socializing and nursery areas for this population in the remote subantarctic islands are under the protection of different types of MPAs. However, the effectiveness of these MPAs in encompassing important whale habitat and protecting the whales from vessel traffic has not been investigated. To address this, we analyzed telemetry data from 29 SRWs tagged at the Auckland Islands between 2009 and 2022. We identified two previously unknown and currently unprotected areas that were used by the whales for important behaviors such as foraging, socializing, or resting. Additionally, by combining whale locations and vessel tracking data (2020–2022) during peak breeding period (June to October), we found high spatiotemporal overlap between whales and vessels within several MPAs, suggesting the whales could still be vulnerable to multiple anthropogenic stressors even when within areas designated for protection. Our results identify areas to be prioritized for future monitoring and investigation to support the ongoing recovery of this SRW population, as well as highlight the overarching importance of assessing MPA effectiveness post-implementation, especially in a changing climate.

1. Introduction

Anthropogenic activities are increasingly affecting marine megafauna through a variety of mechanisms, including entanglement in fishing gear, direct collision with ships, plastic and noise pollution, and climate change (O'Hara et al., 2021; McCauley, 2023). In the face of these growing threats, marine protected areas (MPAs) are one widely used biodiversity conservation tool intended to reduce anthropogenic pressures, particularly fishing activities, on marine ecosystems (Grorud-Colvert et al., 2021). There is currently a worldwide initiative to protect 30% of the global ocean in a network of well-managed MPAs by 2030 (the '30 by 30' initiative; Convention of Biological Diversity, 2022). It follows on from a 10-fold increase in global MPAs since 2005 (United Nations Environment Programme & International Union for

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Conservation of Nature, 2021), including over one million square kilometers of ocean sanctuaries and marine parks declared in large open ocean areas, such as the Cook Islands' Marae Moana, Hawaiian Islands Papahānaumokuākea Marine National Monument, and the Ross Sea Region MPA (Maestro et al., 2019).

While protecting large sections of remote ocean regions may be beneficial to many marine animals, the effectiveness of MPAs in achieving their intended conservation goals are rarely evaluated, or they are found to provide insufficient or only partial protection from threats such as fisheries interactions (Pomeroy et al., 2005; Rodríguez-Rodríguez et al., 2016; Turnbull et al., 2021). Furthermore, MPA boundaries are sometimes defined by socio-economic or political constraints, rather than the ecological needs of the species being protected (De Santo, 2020; Allan et al., 2021). A key challenge faced by static area-based management approaches is that most marine megafauna are highly dynamic and regularly move hundreds to thousands of kilometers beyond stationary MPA boundaries (Gilmour et al., 2022; Pereira et al., 2023). Therefore, a common first step in the efforts to design an effective MPA is to identify areas that are important to marine megafauna, such as areas used seasonally for feeding and breeding (Maxwell et al., 2011; Schofield et al., 2013; Hindell et al., 2020). Yet, even after significant efforts have been made to identify ecologically important habitats, over weeks to seasons or years, these areas can be displaced from static MPAs due to climate change or changing population dynamics in species recovering from exploitation (Bruno et al., 2018; Maxwell et al., 2020; Weir and Stanworth, 2020). If regular assessments of MPA effectiveness are not made, this mismatch might go unnoticed by marine managers.

Migratory baleen whales are an interesting case study for the assessment of MPAs as many species need distinct habitats at different parts of their migratory and life cycles (Bannister, 2009; Tyack, 2022). In addition, thanks to various conservation measures, many populations of baleen whales are now increasing (Bejder et al., 2016; Tulloch et al., 2019), or have even recovered (Magera et al., 2013) from past whaling exploitation. Today, the greatest threats to whales are from entanglement in fishing gear, noise pollution and ship-strike (Erbe et al., 2019; Moore, 2019; Schoeman et al., 2020), as well as climate change and prey driven fluctuation in population sizes (e.g., gray whales (*Eschrichtius robustus*), Stewart et al., 2023) and habitat use patterns (e.g., North Atlantic right whales (*Eubalaena glacialis*), Meyer-Gutbrod et al., 2023). Evaluating the effectiveness of MPAs on baleen whales can be challenging as many of these animals have large home ranges, sometime spanning entire ocean basins (Bailey et al., 2009; Riekkola et al., 2018; Lydersen et al., 2020), therefore obtaining direct observations is all but impossible. However, we can now use new approaches and technologies to overcome this challenge. Satellite tracking can provide information on the important, high-use areas (or hotspots) across wide regions (e.g., Hoover et al., 2019), and when combined with modern statistical methods (e.g., Jonsen et al., 2023), behavioral states of animals can be

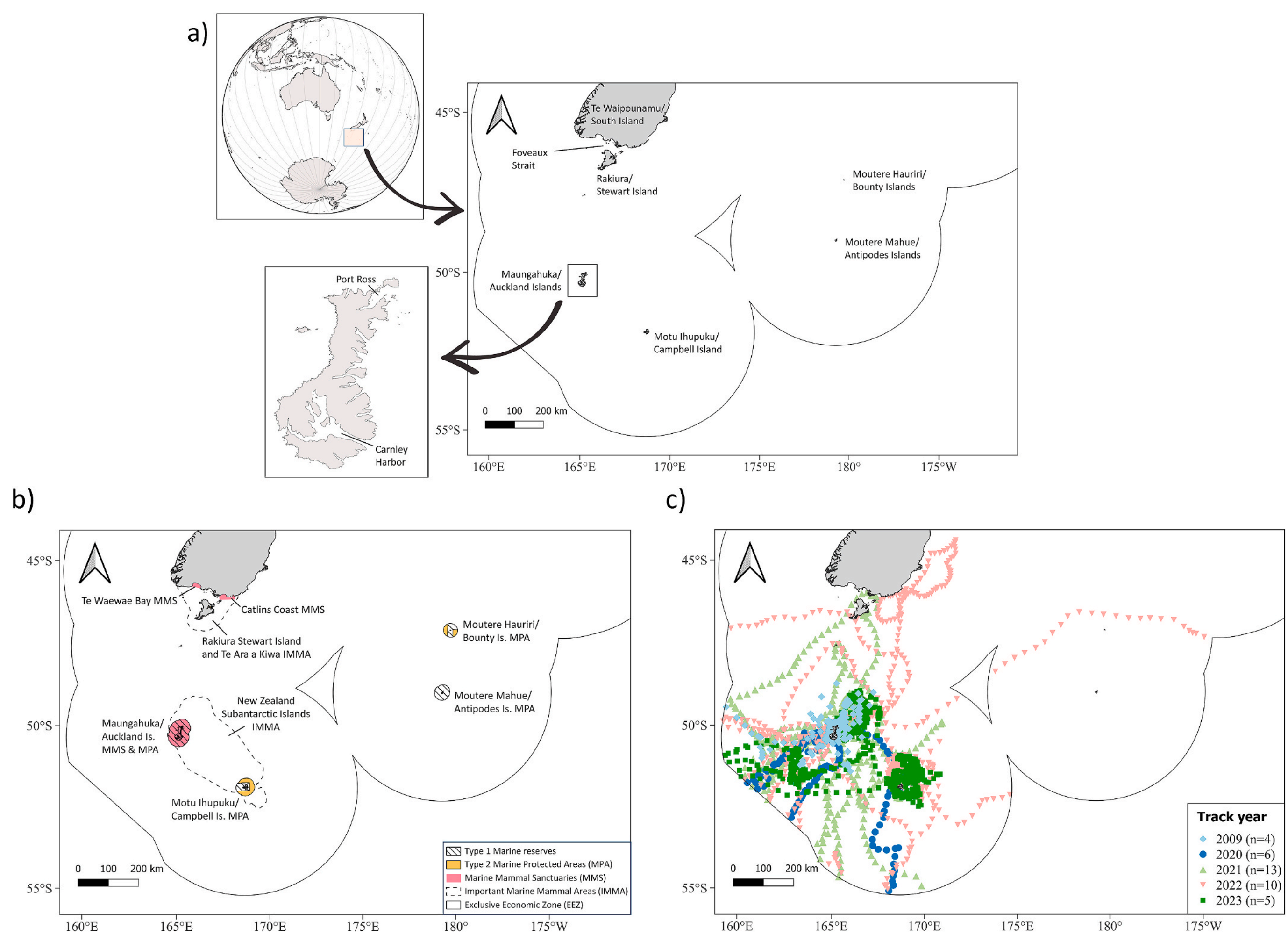

Fig. 1. a) The study area, New Zealand Exclusive Economic Zone (EEZ), with the top left inset map showing the location of the subantarctic region (in pink), b) different types of marine protected areas in southern New Zealand, and c) SSM-filtered locations of 29 southern right whales in New Zealand's EEZ color-coded by the year the locations were recorded (*n* denotes the number of tags that transmitted during a given year. Note that this may not be the same as the year of tagging as tracks for a given tag can span across years). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

inferred. Such information on animal habitat use patterns could ultimately help inform MPA design and their effectiveness (Hays et al., 2019; Hindell et al., 2020; Gilmour et al., 2022).

Here we consider the case of the Aotearoa/New Zealand (NZ) southern right whale/tohorā (SRW, *Eubalaena australis*), a genetically distinct SRW population which was once broadly distributed around NZ waters (Richards, 2009). Commercial whaling in the early 19th century decimated the population from approximately 30,000 whales to an estimated 30–40 mature females around 1920 (Jackson et al., 2016). In 2009, this population of SRWs was estimated at ~2000 individuals, <10% of their pre-whaling abundance (Carroll et al., 2013; Jackson et al., 2016). One of the further consequences of whaling was that this population has now retreated to the high-latitude NZ subantarctic region for breeding during the austral winter. Habitat modeling and visual surveys have indicated that SRWs from all age groups, in particular cow-calf pairs, strongly favor the subantarctic Maungahuka/Auckland Islands (Fig. 1a) for calving and socializing (Patenaude et al., 1998; Rayment et al., 2014; Carroll et al., 2022). Sub-adult and solitary SRWs frequent Motu Ihupuku/Campbell Island (Fig. 1a), an important socializing habitat (Stewart and Todd, 2001; Torres et al., 2017). Occasional sightings are also reported around Rakiura/Stewart Island and mainland NZ (Fig. 1a) as the population slowly recolonizes its former wintering habitats (Carroll et al., 2014; Cranswick et al., 2022). However, Auckland Islands remain the most important wintering habitats for the NZ population since it is the only known consistent contemporary calving ground where whales from all age groups regularly visit.

Currently, there are four types of MPAs in southern NZ waters (i.e., south of 45° S; Fig. 1a): (i) type 1 no-take marine reserves, prohibiting any resource extracting activities up to 12 nm offshore, (ii) type 2 MPAs prohibiting some fishing methods, such as bottom trawling, Danish seining, and dredging (Davies et al., 2018), (iii) Marine Mammal Sanctuaries (MMS) restricting or prohibiting activities such as seismic surveys, seabed mining, commercial fishing, recreational fishing and whale and dolphin tourism (up to 12 nm), and (iv) Important Marine Mammal Areas (IMMAs; Hoyt and di Sciara, 2021). The first three types of MPAs are legally binding in NZ and managed by Te Papa Atawhai/Department of Conservation (DOC). In contrast, an IMMA is advised by the International Union for Conservation of Nature (IUCN) because of a region's ecological importance to marine mammals and has no national legal standing (Tetley et al., 2022). For migratory SRWs, the effectiveness of these static boundary protected areas still requires thorough examination due to the limited spatial information available on whale distribution in relation to the MPAs in this region.

In this study, we assessed the effectiveness of current MPAs within southern NZ in providing protection to the local SRW population. To do this, we first used satellite telemetry data to (i) identify SRW core use areas based on temporal and behavioral habitat use indices, and (ii) quantify how well existing MPAs captured SRW core use areas. We then overlaid core whale habitat during their peak breeding period (June–October) with marine traffic data to investigate the level of spatio-temporal overlap between SRWs and vessels within NZ's Exclusive Economic Zone (EEZ) and within current MPAs. Through this comprehensive spatial analysis, we aim to support future management efforts to mitigate anthropogenic disturbances on marine megafauna, on both local and global scales, by highlighting the importance of evaluating MPA designs.

2. Methods

2.1. SRW habitat use in NZ's EEZ

2.1.1. Satellite telemetry data collection

We compiled a satellite tracking dataset for 31 SRWs tagged in Port Ross, Auckland Islands, NZ (Fig. 1a), in the austral winters of 2009 (Childerhouse et al., 2010; Mackay et al., 2020) and 2020–2022. In 2009 (n = 6 used here), SPOT 5 location-only Argos satellite transmitters (Wildlife Computers Ltd, Redmond, Washington, USA) were deployed in strict accordance with the approvals and conditions set by the Australian Antarctic Division (The Environment Protection and Biodiversity Conservation Permit, 2007–007; AgResearch Animal Ethics Committee approval 2941–09/10), and programmed with a duty cycle of 6 h on and 18 h off (see Childerhouse et al., 2010; Mackay et al., 2020 for further details). In 2020–2022 the deployment of 22 location-only SPOT-372A tags and three location and dive profile SPLASH-10 Argos satellite tags was conducted under University of Auckland Animal Ethics approved protocol 002,072. All tags used in this study were Type-C (consolidated) tags which are non-retrievable (Andrews et al., 2019). Instead, the tags transmit messages to Argos satellites and the tags' location is calculated using the Doppler Effect on transmission frequency (Collecte Localisation Satellites, 2016). Tag duty cycling was optimized to balance battery life and Argos satellite transmission opportunities across the Indo-Pacific region. Specifically, the tags were programmed to transmit every 45 s between 00:00–03:00, 06:00–09:00 and 14:00–21:00 UTC, with up to 17 uplinks per hour. We used a custom-modified pneumatic line thrower (Air Rocket Transmitter System; Heide-Jørgensen et al., 2001) set at a pressure of 14 bars to deploy tags from the bow of a rigid-hulled inflatable boat at distances ranging from 1 to 5 m. All tags were deployed on mature individuals judged to have excellent body condition (Pettis et al., 2004). Tags stop transmitting data when they run out of battery, are naturally shed, damaged or experience sensor fouling.

2.1.2. Quantifying whale movement and core use areas

Raw Argos location data were quality controlled using several steps. First, we filtered positions using the *Speed-Distance-Angle* function (SDA) from the R package *argosfilter* (Freitas et al., 2008; R Core Team, 2022) to remove implausible locations based on swimming speeds. Second, we removed all duplicate whale locations (i.e., with the same timestamp), retaining the higher quality Argos location class where applicable. To avoid over-interpolating, we split individual tracks into track segments, with new segments added if a transmission gap exceeded 24 h. Track segments with fewer than 10 observations, and therefore insufficient data for modeling, were removed from further analyses (n = 2 from the 2009 tagging data). Finally, we applied a continuous-time correlated random walk state-space model (SSM) to the track segments using the *fit_ssm* function from the R package *aniMotum* (Jonsen et al., 2023). The model accounts for the location error associated with Argos satellite data and estimates new locations at regular intervals based on the step lengths and turning angles in the raw location data (Jonsen et al., 2023). Different time steps (i.e., the duration between successive locations generated by the SSM) were applied to the 2009 tracks and one individual tagged in 2021 (Appendix S1) based on the programmed duty cycle and the average time differences between consecutive locations in the raw data (Thums et al., 2022).

A move persistence model (*fit_mpm* function from the package *aniMotum*; Jonsen et al., 2023) was then fitted to generate behavioral state estimates for each state-space filtered location. The move persistence index (Gamma, γ) captures autocorrelation between speed and directionality. It is represented by a continuous value between 0 and 1, with smaller γ values indicating decreasing speed and directionality, and vice versa. For instance, low move persistence generally means slower, tortuous movements referred to as area-restricted search (ARS) behavior that could indicate foraging, socializing, or breeding. In contrast, high move persistence is associated with high-speed direct travel, such as migration and direct travel (Jonsen et al., 2023).

To identify ocean areas that formed core use area for SRWs, we followed a similar methodology to Thums et al. (2022), creating a 0.35 × 0.35° (approximately 39 km × 39 km) time spent grid using all SSM-filtered locations between 160° E and 170° W and between 45° and 55° S (hereafter referred to as the study area) with the functions *GridTopology* and *TripGrid* from the R package *trip* (Sumner et al., 2020). We used a relatively large grid size for this analysis to avoid grid cells with very few whale locations. We initially identified areas of highest use by

SRWs by calculating a measure of occupancy, equal to the total time spent for all tagged whales across all years in each grid cell (in days; *TripGrid* function). Following this, we ranked grid cells from highest to lowest time spent and calculated the top 50% of cumulative frequency distribution, following Soanes et al. (2013) and Thums et al. (2022). Hereafter referred to as 'core use areas,' this is similar to the 50% utilization distribution which represents the minimum area where the tagged whale had a 50% probability of being found. By using a larger gridded area than just the EEZ, and including location points outside of the EEZ in the core use area calculation we prevented the overestimation of time spent along the edge of the EEZ. This also accounted for whales that traveled outside the EEZ but then returned to the EEZ during the peak breeding period (Appendix S2).

To identify areas used by SRWs for ARS behaviors, we calculated the average move persistence (γ) value for all grid cells inside the EEZ. We differentiated between ARS and transit behaviors by using a cutoff value, which was the average γ for all locations inside the EEZ. Grid cells with an average $\gamma <$ the average overall γ value were classified as areas with ARS behaviors, whereas $\gamma \geq$ the average overall γ value was classified as transit areas.

2.2. Whale-vessel overlap during peak breeding period

2.2.1. Peak breeding period core use areas

We focused our analysis of whale-vessel overlap to the peak breeding period for SRWs in NZ in the austral winter, between June and October, when the whales gather in high numbers in the NZ EEZ, specifically around Auckland Islands (Carroll et al., 2022). We applied a 20 × 20 km grid, and calculated the time spent (in days) for whales in each grid cell between June and October following the methods described above. We used a smaller grid size for this analysis to gain a more fine-scale, accurate measure of whale-vessel overlap. As above, the gridded area extended beyond the boundary of the EEZ to prevent the overestimation of time spent along the edge of the EEZ and we employed the top 50% of cumulative time spent frequency distribution to identify core use areas during the peak breeding season.

2.2.2. Vessel traffic data and analysis

The Automatic Identification System (AIS) is an automated vessel tracking system that provides information on a vessel's unique identity, vessel type, location, speed, and bearing (Tetreault, 2005). The International Maritime Organization (IMO) requires international sailing vessels heavier than 300 tons to carry AIS, although many smaller vessels also have AIS for safety concerns (Silber et al., 2012). AIS data used in this study were sourced through DOC.

The volume and distribution of vessel traffic in southern NZ was obtained for March 2020 to December 2022 to temporally match the SRW tagging data (data for 2009 were not available). Vessel data were filtered to the study area, and only data that included vessel length and width information were included in the analysis. We recognize that factors such as vessel speed (e.g., Laist et al., 2014), draft depth (Crum et al., 2019), time of day (Calambokidis et al., 2019), and the behavioral responses of individual whales (e.g., McKenna et al., 2015) could substantially affect the risk of collision. However, considering the comparatively low density of vessel traffic in the study region (Appendix S3), and as the goal of this study was to characterize the spatiotemporal overlap between vessel traffic and whales, vessel data were not removed based on specific speeds or sizes.

To examine the movement patterns for various vessel types, we made five vessel categories: Cargo, Tanker, Passenger, Fishing, and Other. 'Cargo' included all "Cargo-Hazard A″ and "Cargo-Unknown" ships. 'Passenger' included commercial cruise ships. 'Other' included anti-pollution vessels, motorized pleasure craft and sailing vessels. Duplicate AIS locations (i.e., with the same timestamp) and vessels with fewer than 10 location fixes during the entire tracking period were removed from further analysis.

The processed AIS data were filtered to SRW peak breeding period months (June–October) and summarized into the same 20 × 20 km grid (see above). For each grid cell, the cumulative amount of time (in days) that each unique vessel spent in that given cell was calculated using the *TripGrid* function. We used Jenks Natural Break (Jenks) Classification in QGIS (QGIS Development Team, 2022) to classify peak SRW breeding season vessel traffic density into three classes (low, medium, and high). This classification method creates maximum variations between the classes while minimizing differences within the same class (Jenks, 1967). The breakpoints differed to reflect unique movement patterns for each vessel type.

2.2.3. Estimating overlap between whales and vessel traffic

Assessments of the tagged SRWs exposure to vessel traffic during the peak breeding season were performed by comparing the time-spent density of each vessel type within grid cells classified as whale core use area. Subsequently, we counted the number of overlapping cells (i.e., if a cell was identified as SRW core area and also had any recorded vessel time spent). This was then divided by the total number of whale core area grid cells within the study area EEZ to calculate the percentage of overlap between whale core use areas and vessel traffic in peak breeding season. To characterize the spatial use patterns of whales and vessels within different MPAs, we sourced MPA shapefiles from DOC and the Marine Mammal Protected Areas Task Force (www.marinemammalhabitat.org). We applied the *Clip* tool in QGIS to extract vessels and whale use grids during whale peak breeding season within protected areas shapefiles. Next, we used the *Identify Features* tool in QGIS to calculate the area (in square kilometers) of the clipped grid cells occupied by whales and each vessel type. Lastly, we compared these areas with the total area (in square kilometers) of MPAs to determine the percentage of areas used by whales and vessels. The sizes of the MPAs were derived from the relevant polygon shapefile under the NZGD 2000 (EPSG: 3851) projection.

3. Results

3.1. Whale movement models

The movements of 29 SRWs in southern NZ were tracked and modeled (Fig. 1b, Appendix S2). After applying the SDA filter and removing duplicate locations, an average of 1825 ± 1535 (standard deviation, SD) Argos locations per individual were used to run the state space and movement models (Appendix S1). Within NZ's EEZ the whales were tracked from five to 182 days, averaging 49 ± 41 days (Appendix S2). The SSM locations indicated that tagged whales, on average, traveled 1775 ± 1243 km (range: 400 km–5246 km) within the EEZ (Fig. 1c, Appendix S2).

3.2. Whale behavior and core use areas within the EEZ

Analysis of the satellite tracking data revealed that across all years, most SRWs core use areas within NZ's EEZ were located in the subantarctic region, especially around the Auckland and Campbell Islands (between 47° and 53° S; Fig. 2a). In contrast, only a few grid cells in the eastern portion of the study area (east of 170° E) were determined as SRW core use areas (Fig. 2a). Some grid cells adjacent to the coastal waters of Stewart Island and the NZ South Island were also identified as core use areas (Fig. 2a), however these were not contiguous, and were only used by three of the tagged SRWs (~10% of tagged whales, Fig. 1c). Only 1.9% of SRW core use areas within the EEZ were captured by Auckland and Campbell Islands MPAs, whereas the IMMAs collectively captured 26.7% of core use areas (Fig. 2a). Within this core area of SRW distribution, grid cells with a lower average γ than the average overall move persistence index within the EEZ ($\gamma = 0.51$) were identified as ARS areas, which could indicate foraging, resting or breeding behaviors. These primarily occurred in four locations: (1) Auckland Islands, (2)

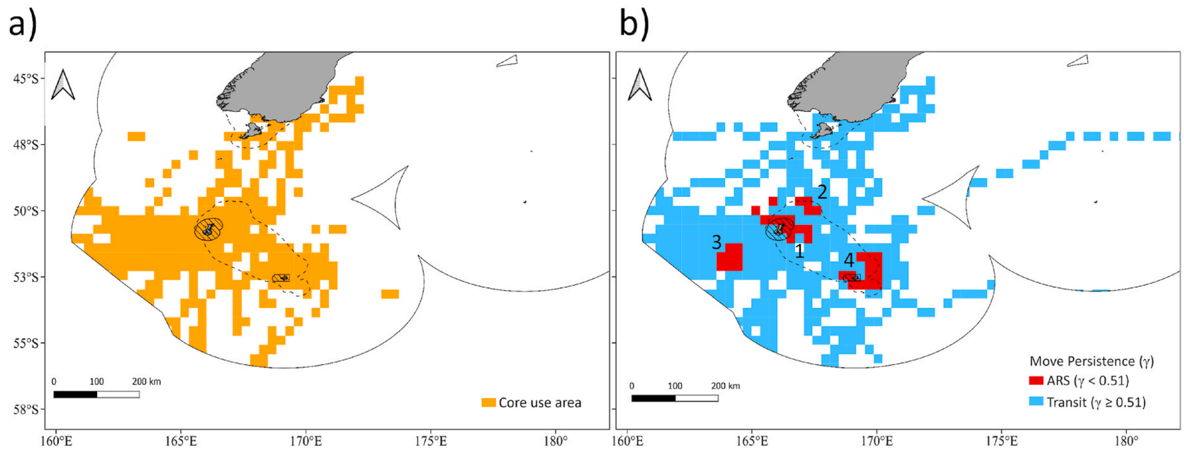

Fig. 2. a) Southern right whale (SRW) core use area, represented by 50% utilization distribution calculated using time spent (occupancy), and b) the behavioral estimates of the 29 tagged SRWs with low move persistence ($\gamma < 0.51$) indicating area-restricted search behavior (ARS; foraging/socializing/calving; in red) and high move persistence ($\gamma \geq 0.51$) indicating migration/transiting (blue). Numbers 1–4 denote four distinct ARS areas. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

northeast/east of Auckland Islands, (3) southwest of Auckland Islands, and (4) Campbell Island (Fig. 2b). In contrast, SRWs habitat use outside of these areas was predominantly relatively fast and directed (i.e., high move persistence values; Fig. 2b), indicating that the whales were only transiting through them. Only ~10.3% of ARS areas occurred inside of current MPAs, while ~56.7% were encompassed by the NZ Subantarctic IMMA (NZS-IMMA), however ARS area '3' occurred completely outside of any MPA (Fig. 2b).

3.3. Whale-vessel overlap during peak SRW breeding season

The SRW breeding season (June–October) core areas were distributed broadly but were concentrated west of 170° E and south of 48° S (Fig. 3). As vessel traffic was widespread across the study area during this time, whales' overlap with overall vessel traffic was common (apart from Passenger vessels that did not operate in winter and are therefore not shown, Fig. 3). Nevertheless, the relative degree of overlap with whales differed spatially depending on vessel type (Fig. 3). Although the density of vessel traffic was generally consistent between June and

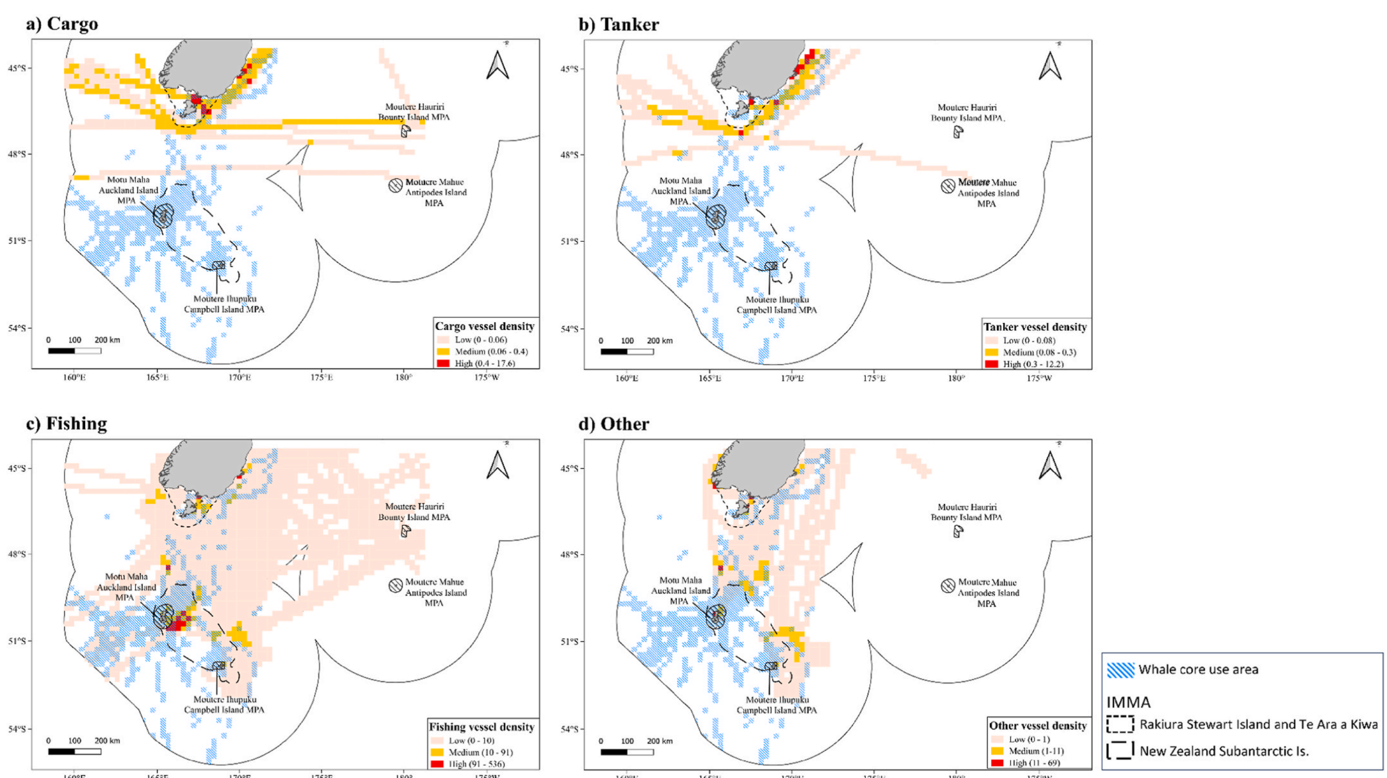

Fig. 3. Southern right whales (SRWs) and vessel density distribution in the whale breeding season (June–October), including (a) Cargo, (b) Tanker, (c) Fishing, and (d) Other vessel types. The whale breeding season core use area was represented by 50% utilization distribution based on cumulative time spent per grid cell (in days). Vessel density (in days) was measured by low, medium, and high using the Jenks Classification in QGIS. Passenger vessels were excluded from the figure as they were operational only between January and March. The solid black line represents New Zealand Exclusive Economic Zone, dashed lines represent two Important Marine Mammal Areas (IMMA), and the hatched areas around the subantarctic islands represent the four marine protected areas (MPAs).

October, the potential exposure to vessel traffic differed temporally as a result of the shifting movements of tagged whales (Fig. 4). The distribution of whale breeding season core use area peaked between July and September, with an average of 169 grid cells (range: 140–195) identified as core use areas (Fig. 4a). As a result, the core whale habitat that overlapped with any vessel activity increased from 30 grid cells (17.4% of whale core use area) in July to 132 grid cells (67.7%) in September (Figs. 3 and 4b).

Fishing vessels (which represented the majority of vessel traffic in the study region, Appendix S3) had the greatest overlap with the tagged SRWs primarily due to the commercial fishing operations to the east of Auckland Islands and north of Campbell Island (Fig. 3c). Fishing vessels were also prevalent west of 165° E and south of 48° S, an important migration corridor used by SRWs to travel to the southwest for summer foraging (Fig. 3c). Fishing and Other vessels had the highest percentage of overlap with whale breeding season core use areas from July to September, averaging 37.4% and 14.6% of overlap (Fig. 4b). While the number of grid cells classified as “high density” Fishing was relatively low ($n = 13$; Fig. 3c), the majority of these cells ($n = 10$) were located to the east of the Auckland Islands where they created a high level of overlap with the SRW core use area throughout most of the peak breeding season (Figs. 3c and 4b). Moreover, “high density” Fishing grid cells had a broad range of time spent per grid cell (range: 91–536 days; Fig. 3c), suggesting that fishing vessels spend a large number of days in any given grid cell (compared to e.g., Cargo and Tanker vessels).

Cargo and Tanker vessels had less overlap with the SRW core use areas in the subantarctic region, as vessel traffic was scarce south of 48° S (Fig. 3a–b, Fig. 4b). However, the tagged SRWs faced the highest level of overlap with these vessel types near the east coast of South Island and around Stewart Island, where Cargo and Tanker vessels were mainly concentrated (Fig. 3a–b). This occurred between September and October when three tagged whales traveled northward from the Auckland Islands toward the South Island (Fig. 1b), thereby increasing the potential for overlap with Cargo and Tanker vessels (Fig. 3a–b, Fig. 4b). Overall, the overlap between whale core use area and vessel traffic existed throughout the peak breeding season, with September and October being the two months when whale and vessel overlap was most likely to occur (specifically with Fishing vessels, Fig. 4b).

3.4. *Whale-vessel overlap within marine protected areas*

During the peak breeding period, the space use of tagged whales and vessel types across the different MPA types (Table 1) was consistent with the results from the spatiotemporal analysis (Figs. 3c and 4b). The breeding season core use area for tagged whales occupied almost the entire area of the Auckland Islands and Campbell Island Marine Reserves (Table 1). Fishing and Other vessel types showed high area use in both of these reserves, overlapping with tagged whales throughout the protected areas to a high degree (Table 1, Fig. 3c–d). There was no overlap between whales and Cargo or Tanker vessels within the Auckland and Campbell Islands Marine Reserves (Table 1), as these vessel types were absent from the areas from June to October (Fig. 3a–b).

The NZS-IMMA is the largest MPA in the study area as it includes the Auckland Islands Marine Reserve and Marine Mammal Sanctuary, the Campbell Island Marine Reserve, and the waters that connect them (Fig. 1a). During the peak breeding period the percent overlap between SRW core use area and vessel traffic within the NZS-IMMA was generally speaking lower than in other MPAs (Table 1) as relatively few tagged whales traveled southeast to Campbell Island and spent little time between Auckland and Campbell Island (Fig. 3). Only Fishing and Other vessel types were present within the IMMA during the peak breeding period (Table 1).

The Rakiura Stewart Island Te Ara a Kiwa IMMA (RS-IMMA) covers the southern coast of the South Island and the waters around Stewart Island (Fig. 1a). All vessel types were present within this MPA, and the area coverage of vessel space use was high (>68%, Table 1, Fig. 3), except for Tankers (18%, Table 1, Fig. 3b). Although the RS-IMMA had the smallest relative amount of whale breeding season core use area of all the MPAs (only 29% of IMMA identified as core use area, Table 1), this largely overlapped with Fishing, Cargo, and Other vessels (Table 1, Fig. 3). The high level of overlap was a result of these waters being the most direct transit route to large ports throughout the region, thereby increasing vessel activity compared to the subantarctic region.

4. Discussion

With the expansion in global vessel fleets, the spatiotemporal overlap between vessels and recovering populations of large, slow-swimming baleen whales is projected to increase (Pirotta et al., 2019; Silber et al., 2021; Halliday et al., 2022), resulting in an urgent need to

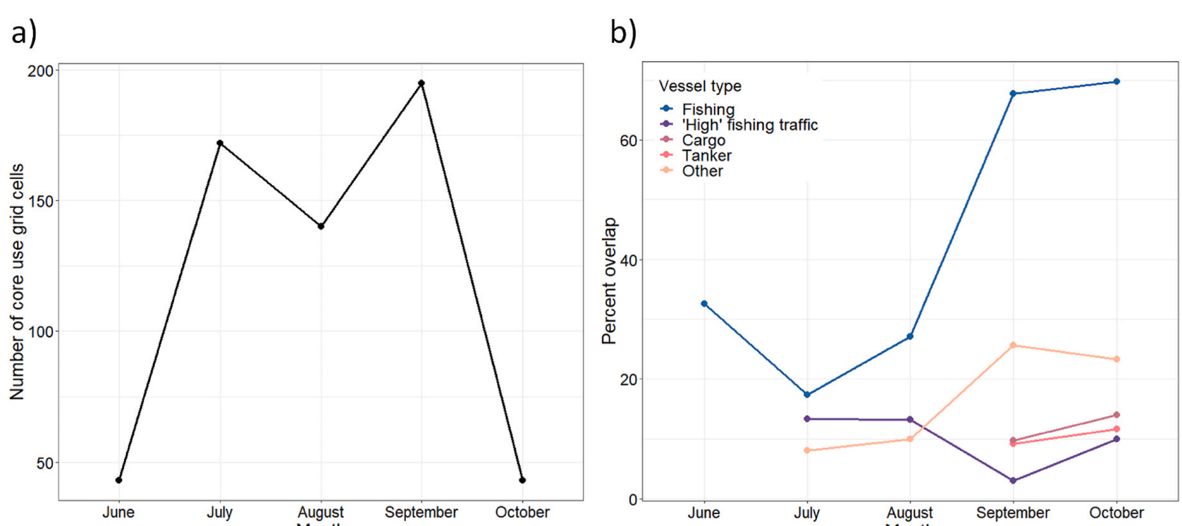

Fig. 4. a) The number of whale core use grids (represented by 50% utilization distribution calculated using time spent/occupancy) within the New Zealand Exclusive Economic Zone, and b) the percentage of core use grids that overlapped with vessel traffic during the peak breeding period (June–October). ‘High’ fishing traffic refers to grid cells used by fishing vessels where the time spent within the grid was greater than 91.4 days (see Fig. 3c). Passenger vessels were not included as they were not operational during June–October.

Table 1
Summary of southern right whale (SRW) core use area and vessel space use in various marine protected areas (MPAs) in southern New Zealand waters during SRW peak breeding period (June–October). The whale breeding season core use area was represented by 50% utilization distribution based on cumulative time spent per grid cell (in days). Whale core use area, vessel space use, and whale-vessel overlap are represented as km^2 and as a percentage of MPA area. The marine reserves and Important Marine Mammal Area (IMMA) shapefiles were acquired from the Department of Conservation and from the Marine Mammal Protected Areas Task Force, respectively.

		Whale core use area within MPA (km^2/%)	Vessel space use within MPA (km^2/%)				Overlap between whale core use areas and individual vessel types within MPA (km^2/%)			
MPA	Sea area (km^2)		Cargo	Tanker	Fishing	Other	Cargo	Tanker	Fishing	Other
Auckland Islands Marine Reserve	5167	4991/96.6	NA	NA	3557/68.8	1773/34.3	NA	NA	3382/65.5	1773/34.3
Campbell Island Marine Reserve	1176	1176/100	NA	NA	592/50.3	451/38.4	NA	NA	592/50.3	451/38.4
New Zealand Subantarctic Islands IMMA	68,315	38,343/56.1	NA	NA	46,587/68.2	23,244/34.0	NA	NA	26,936/39.4	14,038/20.5
Rakiura Stewart Island IMMA	17,319	5030/29.0	11,795/68.1	3120/18.0	15,439/89.1	11,785/68.0	3962/22.9	1073/6.2	4761/27.5	4363/25.2

mitigate negative vessel impacts. Various types of MPAs, whose fundamental goal is to provide a certain level of protection from harmful anthropogenic interactions to marine animals and their habitat, are a common tool for doing so (Halpern et al., 2010). However, after implementation, it is also important to assess whether MPAs fit the needs of the highly mobile marine animals they have been designed to protect, especially in a rapidly changing climate. While there are increasing efforts to designate 30% of the world's ocean as MPAs by 2030, if poorly designed or managed these efforts may not provide their intended conservation outcomes. Here, we assessed whether the current MPAs in southern NZ were effective in safeguarding the migratory southern right whale. We found that the different types of MPAs currently in place (both those that are legally binding by NZ law, and those advised by the IUCN) captured some, but not all the areas that are important to the whales. Furthermore, when assessing the level of overlap between whales and vessels during the whales' peak breeding period, we identified high levels of overlap within the MPAs as well as a shifting risk profile based on space, time, and vessel type.

4.1. How well do MPAs in southern NZ protect key SRW habitats?

Similar to previous work (Hays et al., 2019; Hindell et al., 2020; Gilmour et al., 2022) we showed that satellite tracking data can be an effective tool for examining how well MPAs protect the habitats of dynamic marine species. While the core use area was identified using satellite tracks from 29 individuals, we are confident that these data represent the range of movement patterns by the broader population of ~2000 whales in NZ waters (Carroll et al., 2013). The results confirmed that the Auckland and Campbell Islands are key regions for behaviors consistent with socializing and breeding (i.e., low move persistence, Fig. 2b; Stewart and Todd, 2001; Torres et al., 2017; Carroll et al., 2022). In addition, we identified two previously unknown areas used by SRWs for important behaviors northeast and southwest of Auckland Islands (labels '2' and '3' in Fig. 2b). Further work is now required to understand whether these regions are offshore socializing or foraging grounds for a specific portion of the population. For example, density-related changes have altered the distribution of right whales in South Africa, Australia, and Argentina, with increasing numbers of cow-calf pairs displacing whales without calves to nearby habitats (Harcourt et al., 2019). Additionally, long-term monitoring using techniques such as passive acoustics (e.g., Webster et al., 2019) and satellite imagery (e.g., Fretwell et al., 2014) could be used to confirm whether these areas represent long-term key habitats or are only temporary, opportunistic ones. Understanding the importance of these areas is especially important given they are not protected by current MPAs.

Within the Auckland Islands, SRWs are protected by the Auckland Islands Marine Reserve and Marine Mammal Sanctuary throughout the territorial sea region (up to 12 nm from the coast; Fig. 1a). In contrast, only 39% of the territorial seas around Campbell Island are protected by the Campbell Island Marine Reserve, with the rest (~1767 km^2) being protected by a type 2 MPA (Fig. 1a) as the region has the potential to be used for new fisheries (DOC, 2020). Although there are some restrictions on fishing, the type 2 MPA may not offer sufficient protection for SRWs given that fishing vessels can still operate within this area. Considering SRWs showed relatively extensive use of the waters around Campbell Island and beyond the territorial seas (Fig. 2), the importance of the broader area may currently be underestimated. To protect a higher proportion of the ARS areas to the north/northeast of Campbell Island, the Campbell Island Marine Reserve could be increased to cover its territorial seas. Alternatively, IMMAs clearly delineate the most important habitats for marine mammals (Hoyt and di Sciara, 2021; Tetley et al., 2022). Compared with the current subantarctic marine reserves, the NZS-IMMA effectively captured the majority (~56.7%) of the ARS areas identified in our study (Fig. 2b) by focusing on the ecological needs of the whales and other marine mammals, rather than being defined by legal or political constraints.

No large MPA is currently established in the waters surrounding Stewart Island, with only two small MMS in Te Waewae Bay and the Catlins on the southern coast of the South Island (Fig. 1a). The MMSs are designated to protect Hector's dolphins (*Cephalorhynchus hectori*), and they would only provide protection to SRWs if the whales were close inshore. The southern South Island region is much more industrialized than the offshore subantarctic islands, with the potential of establishing additional activities such as oil and gas exploration (e.g., Hollis et al., 2014), aquaculture (e.g., Camara and Symonds, 2014), and offshore wind farms (e.g., Beca, 2023). These developments could potentially increase the frequency of overlap between whales and vessels, leading to an increased risk of vessel-related injuries and more underwater noise (e.g., Popper et al., 2020; Redfern et al., 2020). Marine spatial planning tools, such as the RS-IMMA, could address the current management gap. Alternatively, measures such as speed regulations (e.g., Constantine et al., 2015; Leaper, 2019) or temporally defining areas to be avoided (e.g., Redfern et al., 2019) could be applied individually or in combination to further reduce negative vessel impacts in this area.

Attempting to increase the size of the MPAs in southern NZ would likely involve substantial discussions with all stakeholders (e.g., Rees et al., 2013; Giakoumi et al., 2018). Moreover, as a highly mobile species, which may also show individual preferences for establishing potentially new socializing or nursing grounds (Weir and Stanworth, 2020), small, static marine reserves may not be sufficient to support SRWs in the future, particularly if their distribution expands with the growing population or shifts in response to climate change (Bruno et al., 2018; Maxwell et al., 2020). More complex approaches for managing anthropogenic impacts, such as time-dependent area closures or dynamic MPA networks, have been gaining popularity in recent years (Lewison et al., 2015; Allan et al., 2021; Zemah-Shamir et al., 2023).

Here, a dynamic management option could potentially provide a compromise between human and animal interests as SRWs are mainly present in NZ waters during winter (Rayment et al., 2014; Carroll et al., 2022; Cranswick et al., 2022), and MPAs may not need to be in effect year-round. Therefore, our second analysis focused specifically on understanding the effectiveness of the current MPAs during the whales' breeding season.

4.2. How well do MPAs protect SRWs during the breeding season?

During the peak breeding period (June–October), large portions of the MPAs were identified as SRW core use areas (Table 1). However, there was also a high level of overlap between whales and vessel traffic, highlighting the potential for vessel-whale encounters inside the MPAs (Table 1, Fig. 3). Specifically, our analyses highlighted a shifting risk profile based on location and timing and identified the following regions of overlap: (1) waters in between and around the subantarctic Auckland and Campbell Islands ('subantarctic region') from June to October and (2) waters along the southeast coast of South Island and Foveaux Strait ('South Island and Stewart Island region') from September to October (Fig. 3).

4.2.1. The subantarctic region

In the subantarctic region, vessel-whale overlap was high during winter due to the high density of whales in the SRW wintering grounds; Port Ross, northeast Auckland Island (see Carroll et al., 2022) and Northwest Bay, Campbell Island (Stewart and Todd, 2001; Torres et al., 2017). The socializing, breeding and nursing behaviors often mean whales spend a substantial amount of time near the ocean surface (Patenaude et al., 1998), and therefore within the depth range of vessels. Fishing vessels spend high amounts of time around the subantarctic islands, in waters important for southern arrow squid (*Nototodarus sloanii*) and southern blue whiting (*Micromesistius australis*) trawl fisheries (Large et al., 2019), but they sometimes also enter the nearshore waters to seek shelter in rough weather. The use of the subantarctic MPAs for emergency sheltering is managed under the Regional Coastal Plan (DOC, 2017) which is currently under review (Sarah Hucker DOC, pers. comm.). Fishing vessels typically use Carnley Harbour, at the southern end of Auckland Islands (Fig. 1a), but some also enter Port Ross. This poses a risk to SRWs in their key breeding habitat, as demonstrated by observations of fresh propellor wounds after a fishing vessel transited Port Ross in the dark (Carroll et al., 2022). Other vessels, including recreational vessels and yachts used for research purposes, also visit the Auckland Islands during winter. As stipulated by the Regional Coastal Plan (DOC, 2017), Passenger vessels and commercial whale-watch operators are not allowed in the Auckland Islands' MMS to protect the whales during the peak breeding season as they have the potential to cause vessel strikes and entanglements (Fishing vessels) in the offshore waters, and increase the risk of vessel strikes, noise pollution, oil spills and exposure to vessel engine exhaust within the sheltered parts of the MPAs (e.g., Lachmuth et al., 2011; Chilvers et al., 2021; Carroll et al., 2022).

4.2.2. The South Island and Stewart Island region

All four vessel types were widespread in the waters along the southeast coast of South Island and in the Foveaux Strait (Fig. 1a), with larger vessels (Cargo and Tankers) more likely to be found in medium and high densities (Fig. 3). However, the absolute time-spent values were noticeably lower than for other vessel types, indicating that Cargo vessels and Tankers traveled quickly through the region instead of spending considerable time in one place (Fig. 3). For SRWs, these vessel movement patterns may pose a high risk as they are generally larger and faster than small Fishing and Other vessels (Appendix S3), increasing the probability of lethal ship strikes (Vanderlaan and Taggart, 2007; Wiley et al., 2011; Laist et al., 2014). North Atlantic right whales which have physical and biological similarities with SRWs have a limited ability to perform quick descents, ascents or horizontal movements to avoid vessel collisions, and they have shown little advantageous behavioral response to ships (Nowacek et al., 2004; Parks et al., 2011). Given the species' similarities, it is likely that SRWs would struggle to avoid fast-approaching ships. With the increasing abundance of SRWs, more whales are expected to use mainland NZ waters as they slowly recolonize their former wintering habitats (Carroll et al., 2014; Cranswick et al., 2022). Hence, it is reasonable to expect higher levels of vessel-whale overlap in the South Island and Stewart Island region, increasing the potential risk of vessel-related injuries and mortality in this region.

Besides physical injuries, concern about the potential effects of ship noise is growing, as underwater noise increases the stress level of right whales and other baleen whales (Pallin et al., 2022; Rolland et al., 2012). As with most baleen whales, SRWs produce a wide range of pulsive and tonal vocalizations, primarily in the low-frequency range (Webster et al., 2019). Anthropogenic noises such as shipping and seismic sources dominate the low-frequency band, which could mask SRW vocalizations, leading to acoustic interference and reduced communication space (Erbe et al., 2019; Duarte et al., 2021). Previous studies focusing on the effect of noise pollution on other cetaceans have reported behavioral disturbance (e.g., Sprogis et al., 2020), displacement from areas of high noise (e.g., Morton and Symonds, 2002), and masking of vocalizations (e.g., Putland et al., 2018). For SRWs, noise pollution in both regions of whale-vessel overlap identified here could negatively affect the population.

5. Conclusions and implications for management

An important step in assessing the effectiveness of MPAs is to confirm whether they encompass and protect key habitats. Here, we provided new information on the habitat use patterns of SRWs in southern NZ, adding to the growing literature on the use of satellite tracking as a tool for informing MPA development and assessing their effectiveness. Our results confirmed previous findings on the nearshore habitat use patterns and revealed that out of the four areas used by SRWs for important behaviors, two were partially protected by current MPAs while the other two were not. Additionally, we found high spatiotemporal overlap between whales and vessels during the peak breeding season (June to October) within several MPAs and IMMAs, suggesting the whales could still be vulnerable to multiple anthropogenic stressors even when within areas designated for protection. This highlights that marine animals may still be subject to anthropogenic risks even within the MPAs themselves, and it is therefore not enough to merely assess whether MPAs sufficiently capture key habitats. Both the areas important to SRWs not currently protected by MPAs and the regions with high levels of whale-vessel overlap should be prioritized for future monitoring and investigation to support the ongoing recovery of this SRW population. In cases such as here, when whales and vessels cannot be fully separated in space and time, the appropriate approach may be to combine MPAs with additional measures, such as speed restrictions or posting watches during transit of high-density whale areas (Constantine et al., 2015; Leaper, 2019; Flynn and Calambokidis, 2019). However, similarly to the need to assess the effectiveness of MPAs post-implementation, measures such as speed limits or the posting of observers must be monitored and enforced for them to be effective (e.g., Ebdon et al., 2020).

CRediT authorship contribution statement

Xuelei Zhang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Emma L. Carroll:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Rochelle Constantine:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization. **Virginia Andrews-Goff:** Writing – review

& editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation. **Simon Childerhouse:** Writing – review & editing, Resources, Investigation, Conceptualization. **Rosalind Cole:** Writing – review & editing, Resources, Investigation. **Kimberly T. Goetz:** Writing – review & editing, Resources, Methodology, Investigation. **Catherine Meyer:** Writing – review & editing, Resources, Investigation. **Mike Ogle:** Writing – review & editing, Resources, Investigation. **Robert Harcourt:** Writing – review & editing, Resources, Investigation, Conceptualization. **Esther Stuck:** Writing – review & editing, Resources, Investigation. **Alexandre N. Zerbini:** Writing – review & editing, Resources, Investigation, Data curation, Conceptualization. **Leena Riekkola:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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