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Fine-scale mapping of ocean user groups to support species and habitat spatial management

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A B S T R A C T

Context: Maritime vessel activity is pervasive in the world's oceans causing detrimental impacts on marine ecosystems. The management and monitoring of vessel activity has historically been focused on industrial vessels, however, and is often conducted only at large spatial scales and coarse resolutions. A more holistic approach is needed to understand where and when different maritime fleets are impacting the marine environment, particularly within protected areas.
Aims and methods: Here we explore fine-scale (50 m^2) spatiotemporal patterns of multi-fleet vessel activity using Satellite Automatic Identification System (S-AIS) data over a two-year period (2018 – 2019) within a network of marine protected areas (MPAs) and their conservation features, using the biologically distinct oceanic archipelago of the Isles of Scilly (UK) as a case study.
Key results: Vessel activity was widespread, affecting over 87 % of the study area. However, high-intensity activity was concentrated along key transit and shipping routes. Recreational and passenger vessels posed the greatest pressure within MPAs, particularly on conservation-critical features like European shag habitats and seagrass beds. Seagrass beds faced additional pressures from anchoring and mooring, with impact pressure up to four times higher than in other habitats.
Conclusions: These findings reveal the complexity of mapping vessel impacts within MPAs and underscore the value of high-resolution analyses. Further research is needed to understand the in-situ effects on marine communities, particularly in high-pressure areas. Ignoring these cumulative impacts in monitoring strategies may compromise the effectiveness of MPAs in achieving their conservation goals.

1. Introduction

The world's oceans support a diverse range of species and habitats [14,89] and provide humanity with ecosystem services including food provision, livelihoods and recreational opportunities [33,6]. Anthropogenic activities, however, are altering marine ecosystems leading to dramatic declines in biodiversity [10,56,80]. Quantifying the scale and development of human activities at sea has historically been challenging, however, over the last two decades, technological innovation and computational advances through the deployment of remote

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sensing technologies and establishment of national monitoring programmes have revealed the global footprint of human activities is widespread and expanding [32,34,59,69,86].

Maritime vessels dominate human activity at sea, encompassing a range of sectors from industry to recreation [63,69,79]. The environmental impacts and effects of these sectors vary but include release of ballast water containing aquatic invasive species, oil spills, underwater noise, ship strikes, contamination and habitat degradation [13,16,17,41,5,61,83]. Much of the focus to date has, however, been focused on: (1) mapping spatial patterns of vessel activity only [48]; (2) individual sectors such as fisheries [19,26,76], or commercial shipping [61,75]; and (3) conducted at large spatial scales (1 km – 10 km) [3].

Whilst these data have provided valuable insights to support conservation [15] and marine spatial planning (MSP) efforts [44,68], without taking a holistic approach by considering all maritime sectors and data at sensitive resolutions, accurately quantifying cumulative vessel impacts on the marine environment to support marine management remains difficult. Low-resolution analyses are often too coarse to accurately detect overlaps with spatially limited habitats [7] or mobile species [87]. Important temporal trends may also be masked in annual or multi-fleet composite analyses, failing to account for seasonally restricted life history events for species, such as migration, foraging or breeding [11,72]. Focus on individual sectors, such as fisheries and commercial shipping, may also fail to capture cumulative impacts or the more nuanced interactions between vulnerable ecosystems and other vessel sectors [49,66,82]. In English waters for example, this reflects the complexity of marine management and diversity of authorities responsible for management of different activities (i.e. Inshore Fisheries Conservation Authorities for fisheries, the Marine Management Organisation for recreation). Taking a more holistic approach to quantifying anthropogenic vessel activity is therefore essential to ensure the success of spatial management interventions.

To illustrate these issues, here we apply a suite of vessel tracking analysis methodologies to Satellite Automatic Identification System (S-AIS) data to map and explore fine-scale spatiotemporal patterns of multi-fleet vessel activity and cumulative impacts within an MPA network [86]. This study aims to provide insights into more complex spatial and seasonal trends in vessel activity across sectors, including specific interactions with habitats and species of conservation importance, to inform future targeted management interventions.

2. Methods

2.1. Study area

The Isles of Scilly are an oceanic archipelago, situated ~20 nautical miles into the Northeast Atlantic off the United Kingdom's Southwest coast (Fig. 1). At approximately 49°56′N latitude and 6°16'E longitude, the 300 islands and rocky outcrops are positioned on the shallow European continental shelf and are exposed to strong oceanic currents including the Gulf Stream. As a result of being situated in a transition zone between warm and cold temperate waters [94] the Isles of Scilly have a unique biogeography relative to wider western European seas and are considered a biodiversity hotspot [25], supporting a diverse range of coastal and pelagic, cold and warm temperate marine fauna and flora [27,54]. These include some of the largest seagrass beds in English waters [2,47], warm and cold-water structured kelp forests and sponge communities [22], regionally important populations of conservation priority crustaceans, fish, seabirds and marine mammals [24,39,52] as well as migratory megafauna including sharks, baleen whales and tunas [42,53].

To conserve and manage this diversity, a variety of marine designations have been implemented across the Isles of Scilly over the last two decades (Fig. 1). These include a Special Area of Conservation (SAC), a Special Protection Area (SPA) and Marine Conservation Zones (MCZs), which cover a variety of species and habitats of conservation importance (Table 1). These designations, coupled with limited point source pollution, effective fisheries management and few historical extractive activities (i.e. aggregate dredging) [4], have resulted in the archipelago's ecosystems being assumed to be in a relatively healthy condition [94] compared to the highly degraded Northeast Atlantic Ocean [34].

Whilst only five of the Islands are permanently inhabited by a small resident population of just over 2000 people, the archipelago experiences significant seasonal variations in visitor numbers during the boreal spring and summer months, with an estimated 100,000 visitors per annum [67]. To support this demand vessels ranging from large cruise liners (>70,000 Gross Tonnage; GT), small leisure craft, wildlife watching cruises, ferries and service vessels operate within a geographically constrained area, all competing for space and traversing shallow inshore waters. The archipelago is also located adjacent to major European shipping routes, that are some of the busiest in the

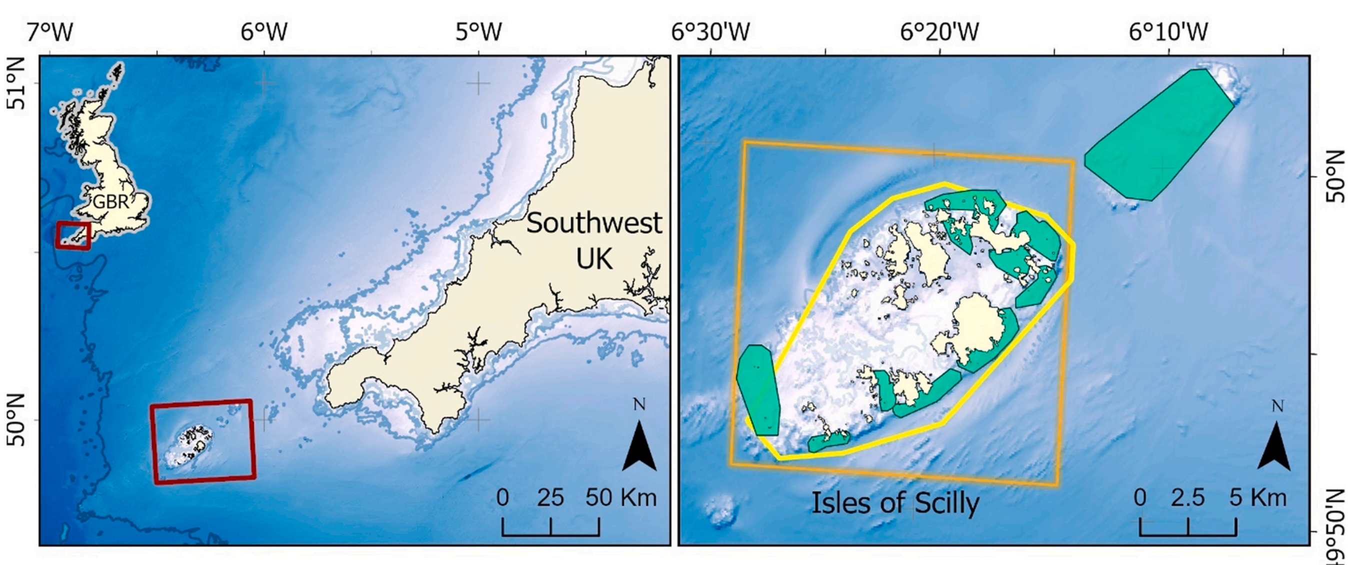

Fig. 1. Location of the Isles of Scilly archipelago and the Southwest UK coast. MPA designations Special Area of Conservation (orange outline), Special Protection Area (yellow outline) and Marine Conservation Zones (green polygons) shown.

Table 1
Marine Protected Area designations and features of the Isles of Scilly inshore (6 nm) zone.

Designation	Year implemented (updated)	Feature (sub-feature)
Special Protection Area	2001 (2020)	European storm petrel (*Hydrobates pelagicus*) European shags (*Phalacrocorax aristotelis*) Great black-backed gull (*Larus marinus*) Lesser black-backed gull (*Larus fuscus*) Seabird assemblage
Special Area of Conservation	2000	Subtidal sandbanks which are slightly covered by sea water all the time (Subtidal coarse sediment, Subtidal sand, Subtidal mixed sediments and Subtidal seagrass beds). Intertidal mudflats and sandflats not covered by seawater at low tide (Intertidal sand and muddy sand) Reefs (Intertidal rock, Infralittoral rock and Circalittoral rock) Atlantic grey seals (*Halichoerus grypus*) Shore dock (*Rumex rupestris*)
Marine Conservation Zones	2013 (2019)	Fragile sponge and anthozoan communities on subtidal rocky habitats Giant goby (*Gobius cobitis*) High energy circalittoral rock High energy intertidal rock Intertidal coarse sediment Intertidal mixed sediments Intertidal underboulder communities Intertidal sand and muddy sand Low energy intertidal rock Moderate energy circalittoral rock Moderate energy intertidal rock Pink sea-fan (*Eunicella verrucosa*) Spiny lobster (*Palinurus elephas*) Stalked jellyfish (*Calvadosia campanulata*) Stalked jellyfish (*Calvadosia cruxmelitensis*) Stalked jellyfish (*Haliclystus* species) Subtidal coarse sediment

world [59]. The surrounding waters (<6 nm) also experience some of the UK's highest fishing activity year-round due to rich fishing grounds [23] with inshore fishing vessels targeting high value crustacean species (i.e. Spiny lobster) from spring through to autumn [43]. Despite the ecological value of the archipelago, and important role tourism plays to local economies, there has been no fine-scale assessment of ocean user groups activities locally. All previous assessments have either relied on national data, which is inevitably coarse in nature, and focused on single fleets (i.e. recreation [77], fisheries [97] or only applied to study the impacts of certain vessel activities on specific protected features, rather than cumulative impacts at the whole-site level [30]. Without a detailed understanding of which sectors are present when, and which present the greatest source of pressure for protected habitats and species, the ability of MPAs to effectively manage human activities to meet their conservation objectives is likely to be reduced.

2.2. S-AIS data acquisition and preprocessing

All analyses were conducted in the software R (v 4.1.1) and R Studio (R [74]) unless otherwise stated.

Daily decoded S-AIS data were sourced from Spire (formerly exactEarth Ltd) in 2021 for the period 01/01/2018–31/12/2019 (n = 730 days). For the purposes of this study, only satellite acquired data were considered (as opposed to terrestrial-based AIS receivers). AIS is mandated on all vessels in excess of 300 GT in international waters, passenger vessels irrespective of size and on fishing vessels larger than 15 m in European waters. Recreational vessel are not currently mandated to operate AIS and therefore are likely underrepresented in the data [40]. These vessels are increasingly implementing the system for navigation and safety purposes [69], S-AIS therefore represents one of the most comprehensive sources of vessel tracking date available [59] for multi-fleet analyses. The years 2018 and 2019 were selected at the time to avoid temporary reductions in vessel activity associated with the COVID-19 pandemic [59]. Daily files consisted of high frequency (n = 1209,076, mean interval 12.8 min *SD* 25.7 min) vessel location point data (i.e. longitude, latitude WGS1984 (EPSG 4326); decimal degrees), along with accompanying vessel metadata including time (UTC), unique identifiers (i.e. Maritime Mobile Service Identifier (MMSI) numbers, vessel names, call signs), class (i.e. fishing, cargo), metrics (i.e. length in metres) and dynamic outputs generated from vessel sensors (i.e. heading in degrees) or activity states in the form of navigational codes (e.g. moored, underway). Positional and navigational errors are known to occur in S-AIS records due to equipment failure and human error, and so data were filtered [35,82], following the methods adapted from Metcalfe et al., [63] and based on procedures developed by the Marine Maritime Organisation [84] and the HELCOM Expert Group [38]. In summary, data were filtered to remove known spatial errors (i.e. on land), those without complete positional or temporal data, duplicated records and with invalid MMSI numbers (less than the requisite 9 digits and with codes <200000000 and >800000000). In contrast to other studies, distance threshold filters, which are often used to remove consecutive position reports that are considered close together (<100 m [63] or <50 m [38]) were not applied due to the high-resolution nature of subsequent analyses being conducted. Each vessel within the dataset was then assigned to one of six vessel categories (Table 2), using categorisation developed by the Marine Management Organisation [64] and adapted from Metcalfe et al., [63].

2.3. Vessel activity datasets – transits, mooring and anchoring

To characterise the footprint of vessel impacts two datasets were generated from the pre-processed S-AIS dataset: (1) 24-hour vessel transits which represent the trajectories of vessels making way; and (2) anchoring and mooring events which represent the movement of vessels not underway. These datasets are intended to represent the spatial distribution of moving vessels and their associated impacts (i.e. disturbance, noise pollution) and direct seabed abrasion from vessels deploying anchors or using fixed moorings. To generate 24-hour vessel transits, each vessel (i.e., identified by their unique MMSI), was assigned a unique identifier to all location data within a 24-hour period (00:00 a.

Table 2
Vessel categories within study location.

Group	Vessel types	Category
1	Bulk carrier, cement carrier, self-discharging bulk carrier, vehicles carrier, wood chips carrier, barge, cargo ship, container ship, deck cargo ship, dry cargo, general cargo ship, heavy lift ship, heavy load carrier, landing craft, roll on–roll off cargo ship, refrigerated (reefer) cargo ship	Cargo and bulk carriers
2	Fish carrier, fish factory ship, fishing vessel, trawler	Fishing vessels
3	Crew boats, ferries, cruise / passenger ships, surfer, high speed craft (fast passenger transports)	Passenger vessels
4	Search and rescue vessels, towing vessels, medical transports and hospital ships, resolution 18 ships, repair vessels, Tugs, pilot vessels, pollution control vessels, standby safety vessels, firefighting vessels, port/pilot tenders, and service vessels	Service craft
5	Pleasure craft, sailing vessels, yachts	Recreational vessels
6	Asphalt/bitumen tanker, bunkering tanker, chemical/oil products tanker, crude oil tanker, floating, production storage offloading (FPSO) tanker, liquefied natural gas (LNG) tanker, liquefied petroleum gas (LPG) tanker, shuttle tanker, tanker	Tankers

m. to 23:59 p.m.; UTC). To ensure transits represented only vessels making way, any S-AIS locations with navigation status codes 1 and 5 (anchored or at moorings) were excluded and only vessels with > 1 location per 24-hour period retained to enable conversion to transit lines. As metadata were not available on when vessel journeys begin or end; generating 24-h vessel transits represents an established method for quantifying daily patterns of vessel movements and may reflect a segment of a larger vessel journey [19,63].

For the anchoring and mooring dataset all vessel locations (i.e. including navigation status codes 1 and 5) within the SAC boundary (Fig. 1) were retained for further analyses. The SAC boundary was used due to the low number of estimated anchoring events outside of this area during data exploration ($n = 306$). To remove possible false positives (i.e. drifting vessels, or those briefly maintaining a position for navigational purposes) several steps were performed using methods adapted from Deter et al., [18]. These required filtering for speeds < 1 knot between consecutive locations and the number of points per anchoring or mooring event to ≥ 4 for each unique vessel in a 24-hour period. If two consecutive points for a unique vessel were greater then 200 m apart then they were treated as two separate anchoring events (assuming all subsequent filtering conditions were also met). This approach was adopted to account for vessels anchoring, departing then re-anchoring at another location within a 24-hour window. A lower total distance threshold was applied compared to other studies (i.e. 600 m [18]) given the limited number of vessels greater than 200 m (8 of 2240 unique vessels) found to be occurring within the SAC boundary.

2.4. Spatiotemporal trends in vessel activity - underway

To explore trends in vessel activity across years, months and between vessel types (Table 1), a raster grid with a cell resolution of 50 m^2 was generated for the study area (raster cells = 1295,040). This allowed fine-scale visualisations that are more representative of spatial patterns of activity and lead to more accurate estimates of vessels' spatial footprint and associated impacts [3]. For each year ($n = 2$, 2018 and 2019) the 24-hour vessel transit dataset was used to generate three metrics that have been established to explore spatiotemporal patterns of vessel activity [19,63]: (1) intensity, the sum of 24-hour transits per cell; (2) occupancy, the proportion of days per annum with one or more 24-hour transit per cell; and (3) pressure, derived by normalised the resulting intensity and occupancy outputs and scaling 0 and 1 for each cell as per Metcalfe et al., [63] (Equation 1). To account for temporal variability in intensity, occupancy and pressure, we averaged across the values for each cell for each year to create annual composites for each metric. This process was repeated for all vessel types combined and each vessel class individually ($n = 6$), and the entire process replicated for each month in a calendar year ($n = 12$).

$P_C = \ln(O_C * I_C)$

Equation (1) where P is the mean annual pressure per 50 m^2 cell (c) which equals the natural logarithm mean annual occupancy per cell (O_C) multiplied by the mean annual intensity per cell (I_C).

To identify where vessel pressures were most acute in time and space, the composite pressure rasters (see above) were spatially intersected to MPA boundaries and within designated feature extents. First, pressure rasters were converted to spatial points (longitude, latitude WGS1984; decimal degrees) using the centroid of each cell. These spatial points were then spatially filtered within individual MPA boundaries and within mapped features of conservation importance. A mean annual pressure score was then calculated for each MPA or feature by taking the mean pressure score from all intersecting points. This process was repeated using individual monthly pressure rasters to explore seasonality in vessel pressures. To determine the contribution of different fleets to pressure values, the mean annual pressure rasters for each vessel class were individually filtered to MPA and or feature extents following the above steps. The intersecting values for each vessel class were then summed, and the proportion of the total value contributed by each vessel class calculated.

MPA boundaries (i.e., SAC, SPA, MCZs) were obtained from the MAGIC data portal. Sites of Special Scientific Interest (SSSIs) and sites designated under the RAMSAR Convention were not considered for analysis as none contain fully marine features. For the SAC, fine-scale spatial data was provided for two of the designated habitat features under licence from Natural England (Marine Evidence Base (Internal) dataset 2021); and represented Reefs and Sandbanks which are slightly covered by sea water all the time. To account for variability within these habitats these were further divided into their sub-features. For reefs, this comprised 'Circalittoral rock' and 'Infralittoral rock'. For sandbanks, this comprised 'Subtidal seagrass beds' and a 'Subtidal sandbanks' which represented a combination of 'Subtidal coarse sediment', 'Subtidal mixed sediments' and 'Subtidal sand'. For the SPA, the only available fine-scale spatial data for designated features was for European shags that have been tracked using GPS tags [24]. Tracking data were provided by RSPB via the Seabird Tracking Database for 13 individuals from three breeding colonies (Annet, Samson, and the Gannicks) during the 2010–2012 breeding seasons (May-July). European shags consistently use key foraging areas across years [24,8] and are only partially migratory [31], exploiting similar locations year-round [65]. Therefore, these tracking data likely indicate the key European shag foraging sites within the Isles of Scilly Archipelago. We mapped the species-level home range (95 %) utilisation distribution using default smoothing parameters in the R package eks [21], which runs spatial processing in the R package *sf* [70,71].

2.5. Spatiotemporal trends in vessel activity - at mooring and anchor

To explore spatial patterns and intensity of anchoring and mooring, impact area polygons were generated from the processed locations for all vessels estimated to be at anchor or mooring in a 24-hour period. These polygons were intended to represent the likely extent of anchor or mooring chain abrasion for comparison against seabed habitat of conservation importance.

The 'seabed impact area' for each unique anchoring event was generated as a regression circle polygon and its centre position using the "lsfit.circle" function within the Circular v.0.4–7 package [1]. If the radius of the regression circle were > 200 m or if the generated centre position was found to be on land, then the centroid of the points rather than the centre of the regression circle was considered the anchoring or mooring position [18]. Impact area polygons were then reduced in area by one third using the QGIS (v. 3.20.3) 'Buffer by percentage' plugin [20] to remove the chain length placed in the water column [18,95]. This approach ensures that the size of impact areas reflected variation between large commercial vessels (with large anchors and long chain) vs smaller vessels with smaller anchors. Any final impact areas that intersected land were excluded from further analysis. To differentiate between vessels at anchor and those using fixed moorings, impact area polygons were assigned to either an 'anchoring' or 'mooring' category using the '*Recreational mooring areas*' layer from DEFRA's: '*Recreational anchoring and mooring in Marine Protected Areas (MPAs)*' dataset provided upon request [51]. If the centroid centre position (or centroid) of each impact area polygon intersected any of the designated mooring zones defined by this dataset, they were considered to be using existing moorings, however, if the centroid fell outside these zones, they were assumed to be at anchor.

All resulting impact areas were gridded at a 50 m^2 resolution to map anchoring and mooring intensity (mean number of events per annum) within the SAC. Impact area polygons were also intersected with SAC habitat features (described previously) to determine the number of events occurring per month and year, the total cumulative area (Ha) of anchoring or mooring occurring within a designated habitat (i.e. the sum of area for all intersecting polygons) and the percentage of novel area (Ha) impacted annually (i.e. dissolving all overlapping polygons). To further explore spatial variation in anchoring and mooring activity within seagrass beds and compare results with existing literature on extents and health, seagrass habitat data were assigned to the boundaries of pre-existing priority seagrass areas [58].

3. Results

3.1. Vessel categories

A total of 7748 unique vessels (identified by their unique MMSI) were detected as operating within the study zone, corresponding to 44,690 unique 24-hour transit events, with high similarity in vessel numbers (2018 n = 4828, 2019 n = 4969) and transits (2018 n = 22,825, 2019 n = 21,865), between years.

Across both years of data, cargo ships comprised the majority (39.7 %) of vessel activity with a total of 17,828 24-hour transits, followed by recreational craft (n = 8800, 19.6 %) and passenger vessels (5550, 12.3 %; Table 3). However, whilst these sectors were represented by thousands of unique vessels there were only 128 unique passenger vessels across both years of data, meaning individual passenger vessels were far more active (*Mean* ± *SD* transits per vessel: 43.0 ± 122.5) than either cargo or recreational vessels (Table 3). Passenger vessels were also more active across a smaller area (9.5 % of cells) compared to Cargo (41 %) and recreational vessels (51.7 %; Table 3).

3.2. Spatial patterns of vessel activity

Of the 7748 unique vessels operating within the study area 31.8 % (n = 2467) were active within the 6 nm inshore fisheries zone, and responsible for 41.9 % (n = 18,745) of the 24-hour transits (Table 4). A large proportion (70 %) of the transits within this zone were conducted by recreational 45.5 % (8537) and passenger vessels 24.5 % (4593), whereas cargo were the dominant fleet active in commercial shipping lanes outside of the fisheries zone (Table 4). In contrast to these sectors, activity by fishing vessels was consistent within and outside of the 6 nm inshore fisheries zone, conducting 11.0 % and 13.9 % of all transits, respectively (Table 4).

Analyses of all vessel data revealed that whilst vessel occupancy, was widespread throughout the study area with 87.5 % of cells subject to vessel transits each year (Fig. 2), mean pressure scores were generally found to be low (*M* ± *SD* 0.02 ± 0.04). However, spatially constrained zones of high mean annual occupancy (>0.5) and intensity (>100) were evident both inshore along inter-island transit routes and offshore within shipping lanes (Fig. 2). Seasonality in both occupancy (Figure S1) and intensity (Figure S2) was evident, with 79.6 % of cells experiencing vessel activity in summer months (June, July, August) compared to just 45.8 % in winter (December, January and February). However high levels (>90 %) of vessel occupancy within these inter-island transit routes and offshore within shipping lanes was still recorded even during winter months, suggesting certain areas of the archipelago experience sustained vessel activity regardless of season. Maximum intensity in any cells was 335.5 in winter (*M* ± *SD* 1.4 ± 4.3) compared with a summer maximum of 1272.5 (mean 3.5 + 11.9), again with highest intensity areas occurring on established transit and shipping routes. These high activity areas were driven by differing fleets, with inter-island routes dominated by recreational and passenger vessels, and offshore activity almost exclusively associated with cargo vessels (Figure S3).

Table 3
Summary of 2018 and 2019 S-AIS activity by vessel class.

Vessel class	Unique vessels	24-hour transits	Mean transits per vessel	SD transits per vessel	Proportion of cells occupied (%)
Cargo	3335	17,828	5.3	15.6	41.0
Recreational	1950	8800	4.4	10.2	51.7
Tanker	1398	4358	3.1	4.7	23.9
Fishing	271	5293	19.2	44.0	73.5
Service	220	860	3.8	13.7	13.4
Passenger	128	5550	43.0	122.5	9.5
Other	446	2001	4.4	10.0	28.5
Total	**7748**	**44,690**	**5.8**	**22.3**	**82.7**

Table 4
Summary of vessel activity (24-hour transits) by zone. Note some transit occur both inside and outside the 6 nm fisheries zone so totals are not comparable with actual total stated in Table 3.

Vessel class	6 nm fisheries zone transits (n.)	6 nm fisheries zone transits (%)	Outside 6 nm fisheries zone (n)	Outside 6 nm fisheries zone (%)
Cargo	1371	7.3	17,084	52.9
Recreational	8537	45.5	3807	11.8
Tanker	11	0.05	4351	13.5
Fishing	2064	11.0	4477	13.9
Service	468	2.5	506	1.6
Passenger	4593	24.5	1118	3.6
Other	1701	9.1	938	2.9
Total	**18,745**	**100**	**32,281**	**100**

3.3. Vessel pressure across MPAs and among fleets

Within the SAC and SPA, 98.5 % and 99.6 % of their respective areas were subject to vessel activity annually. However, mean annual pressure scores were relatively low (SAC: Mean ± SD 0.04 ± 0.07; SPA: Mean ± SD 0.06 ± 0.1) with only 2 % and 4 % of their total area experiencing pressure > 0.33 respectively. This shows vessel activity to be almost ubiquitous but at low levels across these designations. Pressure within these areas was primarily driven by recreational vessels (Fig. 3), contributing 38.9 % and 37.0 % of the cumulative pressure values respectively. All MCZ sites experienced vessel activity in > 90 % of their respective areas, however, there was greater variability in pressures across the network of MCZs, with remote MCZs such as Bishop to Crim (*M* ± *SD* <0.01 ± <0.01) and Bristows to the Stones (0.01 ± 0.01) experiencing low mean annual pressure, that was primarily driven by fishing vessels (Fig. 3). In contrast, MCZs situated close to islands such as Tean experienced the highest mean pressure of all MCZs (0.13 ± 0.11), which was primarily driven by passenger (47.9 %) and recreational craft (33.4 %).

3.4. Seasonal pressure within SAC and SPA designated features

Within the boundary of the SAC subtidal seagrass habitats were subject to greater vessel pressure across all months of the year compared to other designated habitat features (Table S1) and the SAC as a whole (Fig. 4). The most acute pressures facing seagrass were observed during the summer and early autumn months, peaking in August (Mean ± SD 0.52 ± 0.06). In comparison, the lowest overall monthly mean pressure values over circalittoral rock habitats were experienced in the month of February (Mean ± SD 0.02 ± 0.09). Within the boundary of the SPA core areas for European shag (as defined by their 95 % utilisation distribution) experienced marginally higher mean vessel pressure across all months than of the total SPA area (Fig. 4). However, pressure was greatest in July for both the tracked birds (Mean ± SD 0.49 ± 0.11) and the SPA as a whole (Mean ± SD 0.46 ± 0.14). As with occupancy and intensity, spatial patterns in pressure scores varied between winter and summer seasons (Figure S4), with large areas of both the SAC and SPA experiencing low or no vessel pressure in winter. Transit routes between St Mary's and St Agnes and St Mary's and Tresco Islands showed consistent spatial pressures (Figure S4), driving high variation in late autumn, winter and early spring pressure scores for features such as the European shag (Fig. 4).

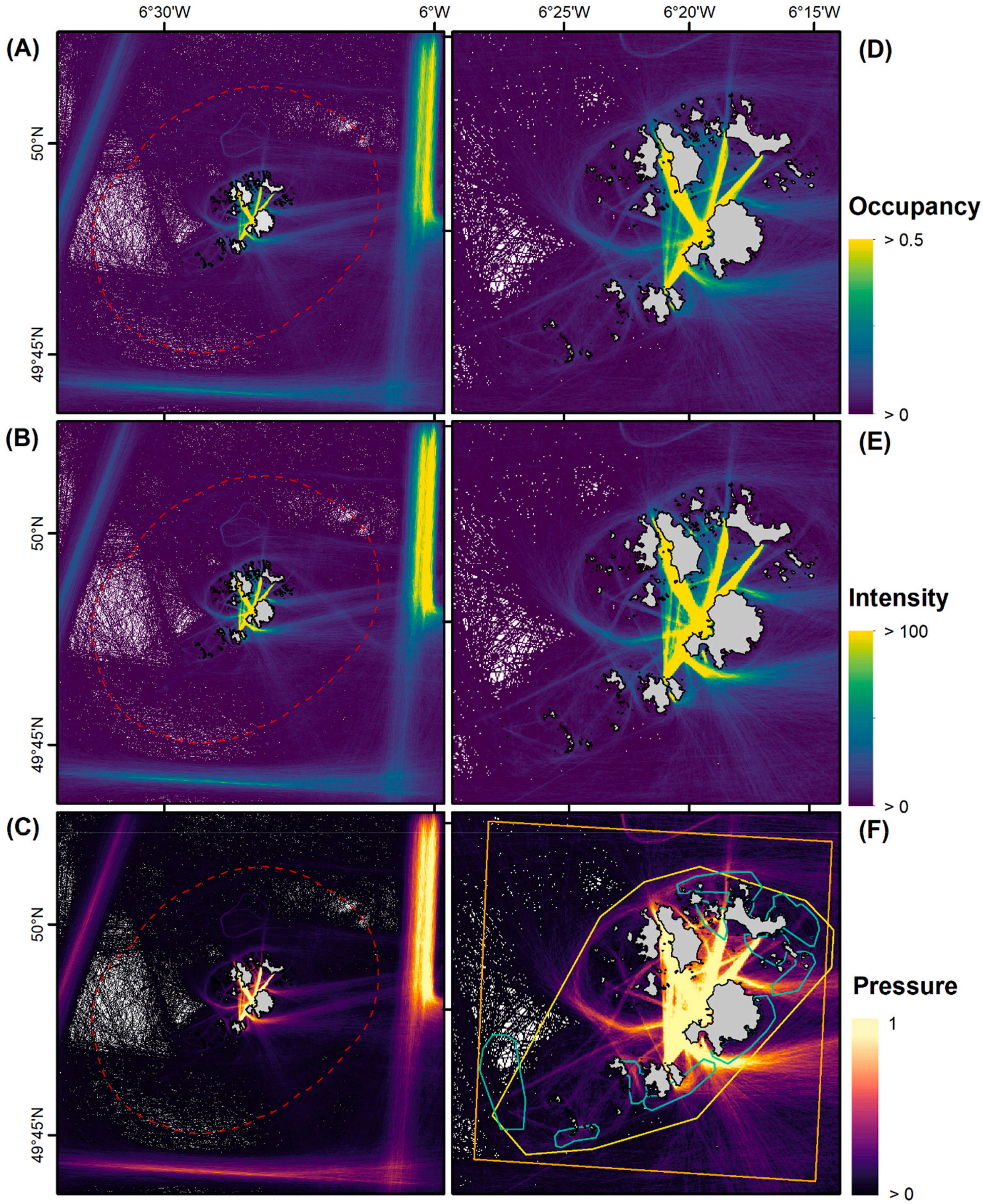

Fig. 2. Mean annual vessel (A) occupancy, (B) intensity and (C) pressure maps for the wider Isles of Scilly study site at a 50 m^2 resolution, with inshore fisheries zone highlighted (red dashed line). Pressure values displayed using a stretched standard deviation and percent clip (minimum and maximum of 2.5) colour ramp for visibility. Data (occupancy (D), intensity (E) and pressure (F)) also zoomed to the extent of the Isles of Scilly inshore MPA network with SAC (orange outline), SPA (yellow outline) and MCZs (green outline) shown.

3.5. Anchoring and mooring impact areas

Across the two years of data a total of 6119 distinct anchoring and mooring events were estimated to have occurred (2018 n = 3515, 2019 n = 2604). Of these, 57 % (n = 3371) were found to occur outside designated mooring zones, so were considered to be vessels deploying anchors, with the remaining (n = 2748) estimated to be using a fixed mooring chain (Table 5). When intersected with habitat data 45.0 % (n = 2754) of all impact areas partially overlapped within seagrass habitat, 32.5 % infralittoral rock, 12.2 % sediment habitats and 1.8 % circalittoral reef with 575 (9.5 %) events occurring over unmapped habitat within the SAC. However, most of the impact within seagrass beds was attributed to fixed moorings, with only 372 anchoring events found to occur. In comparison anchoring was found to occur more frequently than mooring in non-seagrass sediment habitats, circalittoral reefs and approximately evenly within infralittoral rocky ground (Table 5).

Whilst total cumulative impact areas were considerable, the novel

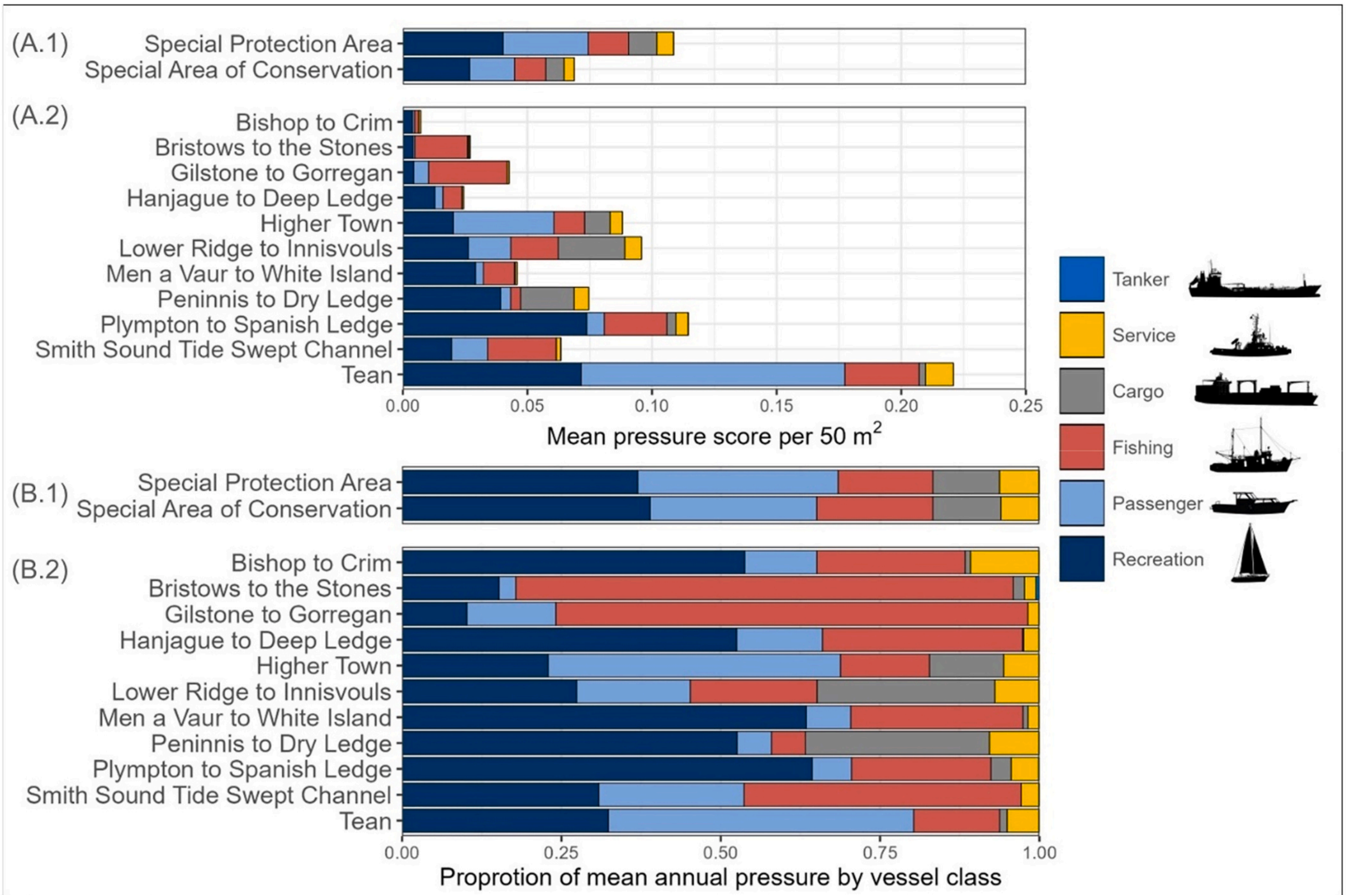

Fig. 3. Pressure score contribution by vessel class within marine protected area boundaries. (A) The mean pressure score value for all cells falling within each MPA boundary by vessel class and (B) the proportion of the summed mean annual pressure scores by each vessel class for (1) European Habitats Directive designations and (2) UK specific designations.

area of habitats affected was more limited, suggesting impacts were constrained to small areas that experienced intense repeat impacts. Total cumulative impact area across the two years of data was similar within seagrass and infralittoral rock habitats (163 Ha and 169 Ha) with subtidal sandbanks and circalittoral reef both receiving lower levels of impact (Table 5). Limited inter-annual variation between years was apparent, for example seagrass beds experienced only a 1.4 Ha change between 2018 and 2019 from 82.3 Ha of impact to 80.9 Ha. In terms of novel area impacted, however, only 4.5 % (22.4 Ha) of the total seagrass extent and 1.5 % (42.5 Ha) of infralittoral rock experienced impacts (Subtidal sandbanks and circalittoral rock both <1 %) across the two years of data, with inter-annual variation again limited, with a mean 3.0 % of all seagrass and 1.0 % infralittoral rock impacted per annum.

As with spatial pressures, recreational and passenger vessels were the dominant vessel classes for seabed impact events within the SAC (Table S2). Together these fleets contributed 88 % of all anchoring and mooring events. Fleet dynamics were similar within designated habitat features. Seagrass impact was driven primarily by passenger (58.4 %, n = 1609) and recreational vessels (28.6 %, n = 788), however, passenger vessels almost exclusively used existing moorings (n = 1530), as opposed to anchoring outside mooring zones (Table S2). Infralittoral rocky habitats displayed similar patterns for passenger (50.5 %, n = 1004) and recreational vessels (37.5 %, n = 746), with 32.8 % of all events occurring within infralittoral reefs attributed to recreational vessels deploying anchors.

Impact areas were distributed across the islands, with hotspots of activity evident in channels and sheltered bays (Fig. 5). For example, 73.3 % (2018 = 61.4 %, 2019 = 65.0 %) of the novel seagrass extent in St Mary's Harbour and 33.6 % (2018 = 10.7 %, 2019 = 25.5 %) in Old Grimsby Harbour, were subject to impact over the two years of data (Fig. 5), primarily due to the presence of designated mooring zones at these sites. In comparison only 5.4 % (2018 = 1.5 %, 2019 = 4.2 %) of the Broad Ledges, Tresco priority area experienced impact from anchoring at least once.

4. Discussion

Understanding where, when and how various maritime sectors impact the marine environment is crucial for achieving holistic marine management. Beyond fisheries related impacts, vessels are known to apply pressures on marine habitats and species through direct disturbance, noise pollution, oil spills, and physical damage to habitats through anchoring and mooring [13,16,49,61,83,91,95,96]. Combined, these cumulative impacts can disrupt ecosystems and compromise the effectiveness of protection measures [34]. By employing established methods for quantifying vessel behaviours [19,63] with higher spatio-temporal resolutions we can make more precise assessments of vessel impacts [3] and tailor management strategies for MSP, MPAs and their designated features accordingly [55]. Using the Isles of Scilly MPA network as a case study, our findings revealed near-ubiquitous vessel activity across the seascape, even at extremely sensitive resolutions (50 m^2), albeit generally at low intensities. While mean annual spatial pressures within MPAs appear low compared to local transit areas and wider studies on cumulative impacts on the Northeast Atlantic [34,59], specific designated features, such as subtidal seagrass beds and European shags, were subject to more acute levels of vessel pressure and anchoring impacts. Fleet dynamics and seasonal variations emerged as critical factors influencing distinct areas of high vessel pressure within

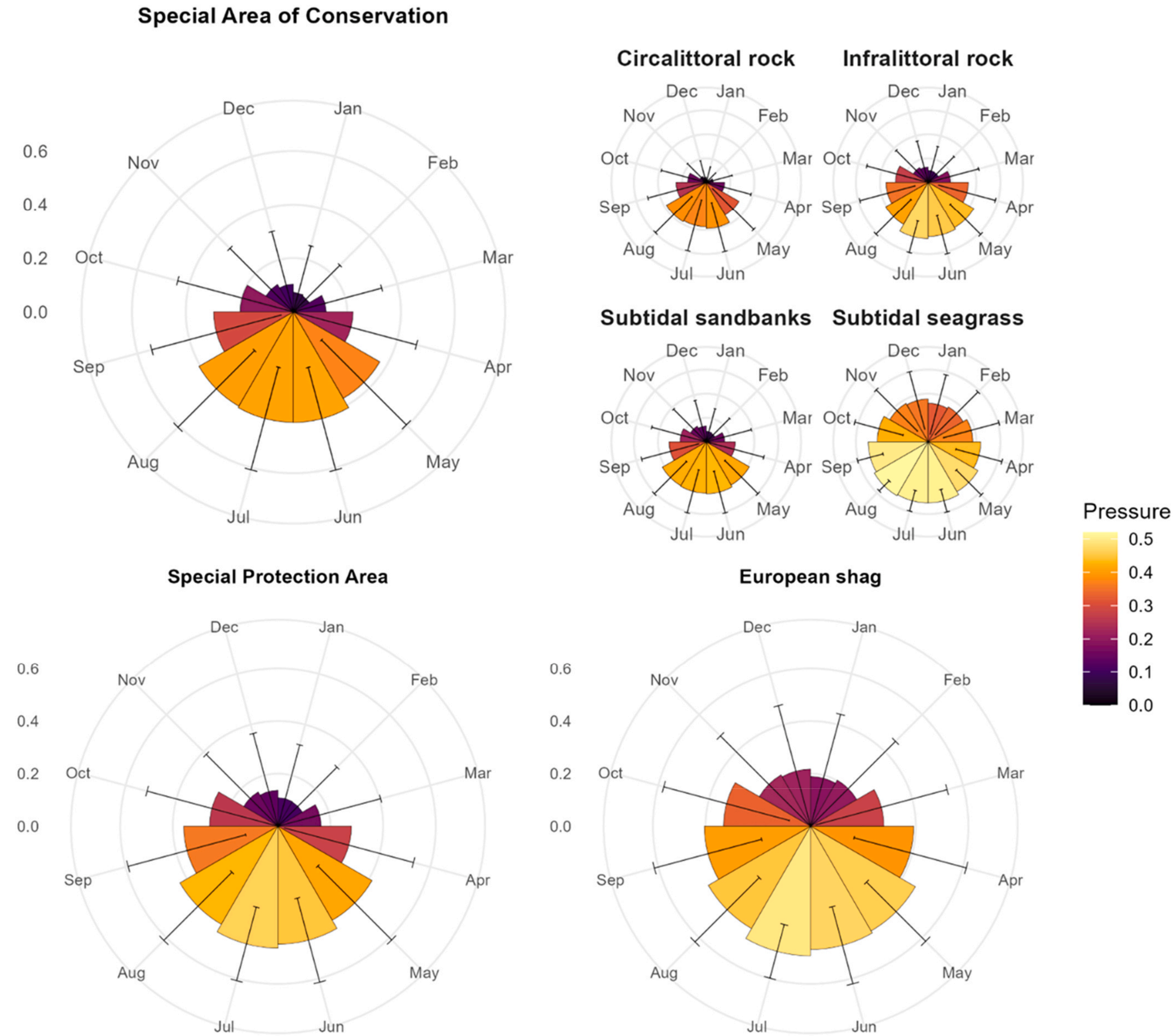

Fig. 4. Polar plot of mean monthly pressure scores experience by relevant Special Area of Conservation sub-features and the total mean monthly value for the entire Area of Conservation. Pressure legend applies to all habitat types and the Special Area of Conservation total.

Table 5
Summary of vessel activity (24-hour transits) by zone.

Habitat	Anchoring events (n.)	Mooring events (n.)	Total impact (Ha)	Novel impact (Ha)	Novel area of habitat extent impacted (%)
Subtidal seagrass	372	2382	163.0	22.4	4.46
Subtidal sandbanks	475	272	93.5	47.1	0.75
Infralittoral rock	918	1072	169.0	42.5	1.49
Circalittoral rock	114	0	13.5	9.75	0.13
Total	**3371**	**2748**	**438.9**	**121.8**	**0.70**

these features.

5. Application of high-resolution analysis for MPA management

Across the Isles of Scilly low annual intensity, occupancy, and pressure values at the MPA level can be attributed to various factors. These include remoteness (i.e. Bristows to the Stones MCZ), large size encompassing areas with minimal pressure, as observed in SAC and SPA, or low vessel activity levels in winter months, which mask seasonal peaks in mean annual values (Figure S1 and S2). In addition, inshore vessel activity appeared spatially constrained along narrow but intense transit routes, intersecting only defined sections of any single MPA (see Fig. 2). Coarser analyses, such as larger raster cell sizes, would have reduced the overall sensitivity of these results and potentially over-represented high-intensity transit routes in MPA mean annual pressure scores [3]. Whilst 50 m^2 analysis resolutions could still be considered coarse, particularly for smaller passenger vessels that likely follow narrow, defined routes, application of even finer resolutions may not result in higher accuracy due to known spatial error in S-AIS data [45]

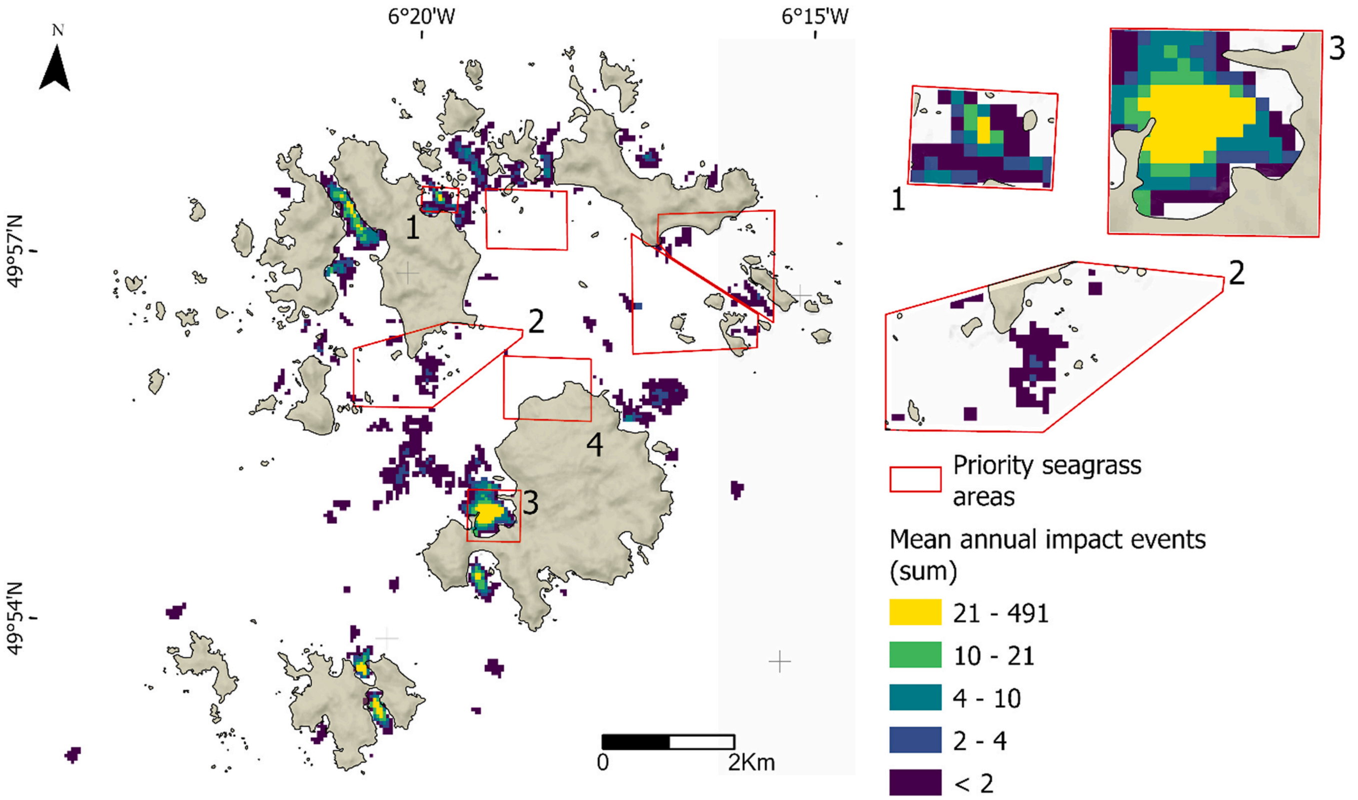

Fig. 5. Mean annual anchoring and mooring impact areas per 50 m^2 cell with priority seagrass areas overlaid (red outline). Colour ramp displayed using a quantile scale. Reference priority seagrass areas 1. Old Grimsby Harbour, 2. Broad Ledges Tresco, 3. St Mary's Harbour and 4. Bar Point. Note differing magnification scales for priority seagrass areas insets (Areas 1 and 3: 4 x magnification, area2: 2x magnification).

and the need to interpolate between AIS location points to reconstruct vessel transit paths [82]. Higher resolutions were only made possible due to significant increases in satellite assets in orbit as of 2018, resulting in more frequent positional data being recorded through higher daily overpasses.

The analysis of fleet dynamics as drivers of these trends is crucial for informing targeted management interventions. Fishing vessels (offshore) and recreational vessels (inshore) emerged as the primary contributors to ubiquitous yet low-level vessel pressures, resulting in the widest distribution of activity (Figure S3). Conversely, cargo, tanker, and passenger vessels exhibited more localised but highly intense activity, particularly in offshore and inshore zones, respectively. Notably, these high-intensity offshore commercial shipping routes directly intersected areas of regionally high abundance for common dolphins (*Delphinus delphis*), bottlenose dolphins (*Tursiops truncatus*), and harbour porpoises (*Phocoena phocoena*) [53]. Conversely, passenger and recreational craft were found to drive both anchoring and spatial pressures for inshore MPAs and their designated features.

Quantifying vessel pressures for dynamic and spatially complex MPA features would be similarly challenging without the application of higher spatiotemporal resolutions. Subtidal seagrass and shallow infralittoral rock habitats directly intersected inter-island transit routes and therefore experienced above average pressures compared to MPA totals or deepwater features such as circalittoral reefs. These pressures were particularly acute when broken down into monthly trends, with high average pressures experienced April through September – which corresponds with the tourism season. Relying solely on composite mean annual values would likely mask peaks in vessel pressure that occur in late summer and early autumn months. Breakdown of spatial patterns into monthly, or seasonal trends (i.e. Figure S4) is therefore essential when interpreting the annual outputs presented here (Fig. 2), and temporal rather than static spatial management interventions may be more appropriate in this context. This temporal variation is significant as it overlaps with seagrass flowering, a crucial time for bed expansion prior to winter storms [73] and when numerous teleost fish species migrate into seagrass beds to spawn [28]. The benefits of seasonal breakdown of the data were also apparent for European shags. While spatial data for other seabird species designated under the MPA network (Table 1) are currently unavailable, findings concerning European shags offer valuable insights into vessel pressure and potential disturbance for other species that comprise this internationally important seabird assemblage [37]. European shags are only partially migratory [31], so may remain in the archipelago year-round including months with low vessel activity levels. However, peaks in vessel pressure within shag home ranges during the summer breeding season [24] may have implications for their ability to forage and provide for young. Given the importance of the Isles of Scilly to European shag populations, coupled with a 36 % decline in breeding pairs between 2015 and 2023 within the archipelago [36], the impacts of vessel disturbance on foraging success and energy budgets could be considerable [98,92] and warrants further research. Whilst spatial data were only available for European shags, the seasonal peaks in vessel activity within the archipelago also coincide with breeding and chick rearing period for many other conservation concern migratory species that return to the Isles of Scilly to breed each year including Manx shearwater (*Puffinus puffinus*) and European storm petrel (*Hydrobates pelagicus*).

Quantifying the spatial distribution and intensity of anchoring and mooring impacts on seabed habitats is particularly important as their environmental footprint is rarely incorporated into current global compilations of human impacts in marine ecosystems [95]. This study was able incorporate fine-scale spatial habitat data derived from a combination of surveys and modelling (Marine Evidence Base (Internal) dataset 2021) for comparison against S-AIS data. However, due to the dynamic nature of certain marine habitats, and the difficulty in accurately mapping the marine environment an unquantified level of error is likely. As with vessel spatial pressures, subtidal seagrass beds were the most impacted MPA habitat feature for impact events from both fixed mooring chains and vessels deploying anchors. While abrasion impacts appear spatially confined, affecting only 4.3 % of the total seagrass extent, within these areas, impact was both intense and repetitive, attributed to the placement of mooring zones within sheltered bays that typically support *Zostera marina* beds. High frequency repeated abrasion is likely a significant contributor to the patchiness of seagrass beds, which has been linked to declines in habitat health locally [9,12], although natural processes and the dynamic nature of seagrass habitat also require acknowledging [93]. Spatial variation in impacts were also apparent within two of the seven priority seagrass areas within the Isles of Scilly [58] experiencing greater anchoring impacts. Over 30 % of the total seagrass area in Old Grimsby Harbour and over 60 % of St Mary's Harbour were subjected to impacts from vessels using fixed mooring between 2018 and 2019. These two sites have shown the greatest declines in patch occupancy (defined as the probability of occurrence in unit sample during surveys) from *in-situ* surveys, with a 65 % decline observed at Old Grimsby Harbour [9]. While annual increases in the number of anchoring events and the cumulative impacted areas were noted between 2018 and 2019, establishing long-term trends requires more sustained monitoring. The implementation of voluntary no-anchor zones within seagrass beds for recreational vessels and the adoption of low-impact mooring systems within harbours have been proven effective for reducing seagrass scouring and patchiness at other UK sites [57, 90]. Their application within high intensity mooring zones, as identified by this analysis, could help mitigate further declines in subtidal seagrass health. Shallow reef habitats experience reduced, but similar levels of anchoring impact with ~2000 intersecting events and ~153 Ha impacted between 2018 and 2019. Although vessel anchor and mooring chains would likely result in reduced impacts within hard benthic substrates, the epifaunal and algal communities that live on them are not immune to chain abrasion [30].

6. Limitations

Limited spatial data on MPA designated features prevented a more complete assessment of cumulative vessel impacts within the Isles of Scilly MPAs and their features. For mobile marine species that are likely sensitive to vessel disturbance [98,46,88,92], only spatial data on a sample of European shags were available for analysis. Spatial data on lesser and greater black-backed gulls, European storm petrels and Atlantic grey seals should therefore be prioritised to inform future MPA monitoring and assessments. This study is also unable to account for habituation behaviours when quantifying and discussing the spatial distribution of vessel pressures. Similarly, low intensity, but wide spread fishing vessel pressures in 'novel' areas may be more impactful due to their unpredictable nature [78] than high intensity, repeat activity of wildlife watching vessels and passenger ferries. For example, the Eastern Isles seal and seabird colonies may be less impacted by vessel activity due to exposure and habituation than the remote Western Rocks haul outs and seabird colonies, despite having far higher vessel pressures in surrounding waters, [78,85].

Whilst AIS is mandated on all vessels in excess of 300 GT in international waters, on all passenger vessels and on fishing vessels larger than 15 m in European waters, it is likely some small scale, recreational and fishing vessels are missing from the analysis [40,81]. For example, potential underestimates of recreational vessels in the anchoring spatial outputs were apparent as they contributed 45.5 % of inshore transits (Table 3), but only 39.6 % of anchoring events. This shortfall is likely due to recreational craft using AIS on a voluntary basis for navigation along busy transit routes but deactivating the system when safely at anchor. This limitation was more apparent spatially, with anchoring and mooring known to occur within the Bar Point priority seagrass area (Fig. 5), a location where no anchoring events were estimated from the S-AIS data. Similarly, none of the active fishing vessels that operate from Isles of Scilly harbours are mandated to operate AIS or VMS systems at present (due to a 11 m and 10 tonnes size limit, Fishing Gear Permit Byelaw 2013 [4]), however, the implementation of inshore VMS (iVMS) intends to fill this data gap [97]. Interpretations of the outputs of this study should therefore be used as an indicator that provides a snapshot of spatiotemporal pressures, rather than definitive, with the scale of anchoring in particularly likely underestimate of true impacts. Despite this issue, non-mandated vessels are increasingly carrying the system on a voluntary basis for safety and security [59] and the northeast Atlantic has been found to have higher AIS tracking rates for other sectors than other regions globally [69]. AIS therefore provides the most comprehensive source of maritime vessel activity data available for multi-fleet studies [60,63].

Whilst this study presents high-resolution spatiotemporal analyses of vessel activity, it is important to note considerable variation in the size and speed of vessels operating within the study area. Increased vessel size and speed amplify the impacts of vessel activity, notably through increased noise pollution levels [62]. The high-pressure areas identified here including offshore shipping lanes (large vessels) and transit routes (smaller but likely high-speed vessel) therefore likely experience acute levels of noise pollution. Future analyses incorporating vessel size and speed could therefore provide more refined spatial pressure metrics. In addition, *in situ* research to help ground-truth the results presented here and inform specific management measures for MPA features would be beneficial. For example, the application of low cost, passive acoustic devices [50] for monitoring variation in vessel noise pollution levels (i.e. between transit routes or in proximity to seal haul outs). More expensive but targeted research could include the use of animal borne passive acoustic sensors [29] to quantify actual disturbance for features including European Shags. These data would complement long-term monitoring of seagrass bed patchiness that have helped contextualise the impacts of anchoring activity presented here.

7. Conclusion

The results of this study have further reinforced the benefits of higher resolution application of S-AIS data for quantifying vessel impacts within MPAs and revealed the complex interactions different maritime sectors have in time and space within protected areas and the features they are designated to conserve. The variety of maritime sectors operating within the Isles of Scilly, the high seasonality in activity and the unique mosaic of habitats and species for the region therefore make it a useful case study location to quantify the cumulative spatial pressures of vessel activity within an MPA network. Combining techniques to comprehensively assess how these vessels interact with the MPA network will support more holistic marine management locally and establish how rarely unquantified vessel classes may contribute to the degradation of ecosystems that are otherwise perceived to be in a relatively pristine condition within a biodiversity hotspot.

Ethics statement

All research was subject to ethical approval by the University of Exeter Ethics Committee (Application ID: 492770).

Author statement

K.M., A.C.B. and O.E. conceived the study; O.E. conducted the spatial analyses and synthesised findings; O.E. wrote the first draft; and all authors contributed to the revision of the manuscript and gave approval for publication.

CRediT authorship contribution statement

Kate Sugar: Writing – review & editing. **Alice Trevail:** Writing –

review & editing, Methodology, Data curation. **Julie Webber:** Writing – review & editing. **Kristian Metcalfe:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Owen M. Exeter:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Julian Branscombe:** Writing – review & editing. **Annette C. Broderick:** Writing – review & editing, Supervision, Conceptualization. **Tom Hooper:** Writing – review & editing. **Jan Maclennan:** Writing – review & editing, Conceptualization. **Trudy Russell:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2025.106588.

Data availability

Derived data are available from the Zenodo repository (DOI: 10.5281/zenodo.13359119). All raw AIS, habitat data and species data subject to licences documented in the data availability section.

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