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Population ecology and juvenile density hotspots of thornback ray (*Raja clavata*) around the Shetland Islands, Scotland

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Abstract

Elasmobranchs are facing global decline, and so there is a pressing need for research into their populations to inform effective conservation and management strategies. Little information exists on the population ecology of skate species around the British Isles, presenting an important knowledge gap that this study aimed to reduce. The population ecology of thornback ray (*Raja clavata*) around the Shetland Islands, Scotland, was investigated in two habitats: inshore (50–150 m deep) and shallow coastal (20–50 m deep), from 2011 to 2022, and 2017 to 2022, respectively. Using trawl survey data from the annual Shetland Inshore Fish Survey, the size composition of *R. clavata* catches was compared between shallow and inshore habitats across 157 trawl sets, and 885 individuals, over the years 2017–2022. Catch per unit effort (CPUE) of *R. clavata* was significantly higher in shallow than that in inshore areas (ANOVA, $F = 72.52$, $df = 1, 5$, $p < 0.001$). Size composition also significantly differed between the two habitats (analysis of similarities, $R = 0.96$, $p = 0.002$), with *R. clavata* being smaller in shallow areas and juveniles (<60 cm) occurring more frequently. Spatial distribution maps confirmed density hotspots of juveniles in shallow habitats, with repeated use of certain locations consistent over time. The results of this study provide the first evidence for *R. clavata* using shallow areas for potential nurseries in Shetland, which can inform the IUCN's Important Shark and Ray Area process. Furthermore, this study provides important new population ecology information for *R. clavata* around Shetland, which may have important conservation implications and be valuable for informing species and fisheries stock assessments in this region.

KEYWORDS
elasmobranchs, fisheries, nurseries, Rajidae, Shetland Islands, thornback ray

1 | INTRODUCTION

1.1 | Skates (class, Elasmobranchii; order, Rajiformes)

Elasmobranchs (sharks, skates, and rays) face many global threats, including habitat loss and destruction (Lyons et al., 2019), climate change (Santos et al., 2021), and exposure to marine pollutants (Tiktak et al., 2020), but the group is especially vulnerable to fisheries overexploitation and by-catch (Dulvy et al., 2021). Skates (order: Rajiformes) can be very vulnerable to threats associated with fishing due to some species being k-strategy species—large size, slow growth, late maturation, production of few young, and long reproductive cycles in some species (McCully et al., 2012). Furthermore, their cryptic diversity makes identifications at sea difficult, which can lead to confusing datasets (OSPAR, 2021), all of which leads to difficulties in accurately identifying their distribution and life-history habitats.

1.1.1 | Thornback ray, *Raja clavata*, Linnaeus, 1758

Thornback ray (*Raja clavata*; order: Rajiformes) are widespread in the eastern Atlantic Ocean from Iceland to the west coast of Africa (Ebert & Stehmann, 2013) where they are demersal on mud, sand, and coarse ground substrates. They occur from 10 to 300 m, thought to be most abundant from 10 to 60 m (Ebert & Stehmann, 2013; Ellis, 2016).

R. clavata females in British waters are estimated to produce between 60 and 150 egg cases per year (Ebert & Stehmann, 2013; Holden, 1975) and are known to aggregate in certain areas, which could make it easier to identify and delineate areas for future management (Ebert & Stehmann, 2013). Due to their large body sizes, adult *R. clavata* are very sensitive to fisheries pressure (Walker & Hilsop, 1998), where they are targeted by longline and gillnet fisheries, and commonly occur as by-catch in mixed demersal fisheries (Ebert & Stehmann, 2013).

1.2 | Elasmobranch nurseries

For conservation purposes, nurseries are important areas to identify and protect as they help ensure successful recruitment of juvenile individuals into the population (Hoff, 2016), while also conferring potential benefits for embryo development and increased juvenile survival (Jirik & Lowe, 2012). Shallow nursery areas, in sheltered locations, are important for providing an environment with stable conditions (Drymon et al., 2020) and may also offer protection from predation and fishing. Elasmobranch nurseries can be located in shallower, coastal areas that are protected and highly productive (Enajjar et al., 2015). For example, shallow nursery areas have been identified in school sharks (*Galeorhinus galeus*), where the young-of-the-year (YOY) preferred shallow areas <10 m (McAllister et al., 2015).

To aid delineation of nurseries by using scientific and technical definitions, Heupel et al. (2007) established a set of three criteria to robustly evaluate whether an area could be classified as a nursery. For individual elasmobranchs <1 year old (newborn or YOY), (i) the density in that area must exceed mean density over all areas, (ii) individuals tend to remain or return for extended periods (weeks or months), and (iii) the area or habitat is repeatedly used across years whereas adjacent areas are not.

Evidence for areas meeting the nursery criteria (Heupel et al., 2007) is mounting for many elasmobranchs, for example, smalltooth sawfish (*Pristis pectinta*) and bull shark (*Carcharinhus leucas*; Scharer et al., 2017). In British waters, evidence for egg-laying/spawning nurseries is growing. Much existing knowledge on elasmobranchs in Scottish waters is focused around the critically endangered flapper skate (*Dipturus intermedius*), where there is evidence for site fidelity (Lavender et al., 2022) and egg-laying nurseries (Dodd et al., 2022) within the Loch Sunart to the Sound of Jura Marine Protected Area (MPA).

In British waters, potential juvenile *R. clavata* nurseries have been highlighted in the Greater Thames Estuary, Bristol Channel, Cardigan Bay, and the eastern and western Irish Sea (Ellis et al., 2012). However, for most skate species found in Scottish waters such studies are lacking, and thus the potential for these waters to serve as nursery habitats for *R. clavata* is not known.

1.3 | Evidence-based frameworks for elasmobranch conservation and management

Understanding existing frameworks for elasmobranch conservation and management is vital for appreciating the context and wider implications of population ecology studies.

The IUCN's Species Survival Commission (SSC) Shark Specialist Group (SSG) recently launched its Important Shark and Ray Area (ISRA) process (Hyde et al., 2022). Four criteria and seven sub-criteria were developed to provide the science-based framework needed to objectively identify critical sites: Criterion C "Life-history," Sub-criterion C1 "Reproductive Areas" refers specifically to sites critical to species' reproductive success such as mating, birth, egg-laying, or providing refuge or other advantages to the young (Hyde et al., 2022). Such information may be used by relevant management bodies when considering spatial management, and multiple data sources and methods can support this. For example, fisheries catch data can be used to predict habitat suitability and diversity hotspots to support marine spatial planning (e.g., for deep-sea elasmobranchs off the Azores) (Das et al., 2022).

1.4 | Stock status of *R. clavata* in the North Sea

R. clavata is classified as near-threatened on the IUCN Red List of Threatened Species (Ellis, 2016) and is also of conservation concern to the Regional Seas Convention OSPAR, listed as a threatened and/or declining species (OSPAR, 2010). Updated status assessments of *R. clavata* showed improving indicators in parts of the Greater North Sea Region (includes Shetland, OSPAR Region II; OSPAR, 2021), but experts maintained that much uncertainty in stock estimates remains, thus population trends in each OSPAR region are fairly inconclusive.

The International Council for the Exploration of the Seas (ICES) provides fisheries advice for skates and rays, informing annual changes to the total allowable catches (TACs) that aim to regulate exploitation.

ICES recently indicated stable/increasing *R. clavata* stocks for the Greater North Sea Subarea 4 (includes Shetland), which underpinned advice to increase landings by 9% for 2022 and 2023 (ICES, 2021a).

However, both OSPAR and ICES identified important knowledge gaps, including locations of nurseries and other habitats where juvenile *R. clavata* are regularly found, and population demographic data more generally (ICES, 2020, 2021b; OSPAR, 2021).

Existing population knowledge for *R. clavata* is based on data from surveys such as ICES' standardized International Bottom Trawl Survey (IBTS). However, the large size of the vessels and areas involved in the IBTS mean that the coverage in inshore areas is restricted and data for *R. clavata* are limited. For example, results from the 2022 North Sea IBTS Quarter 3 showed zero catches of *R. clavata* in the entirety of Area 1, which covers a large part of the northern North Sea, including Shetland (DATRAS; https://www.ices.dk/data/data-portals/Pages/DATRAS.aspx). This highlights the difficulty in analysing data from large-scale surveys in cases where the species' habitat preference is not fully covered by the surveys targeting depths, especially when these data are used to inform management decisions. This applies to *R. clavata* where they are thought to be most abundant in coastal areas at 10–60 m depth, commonly up to 100 m (OSPAR, 2010). In this instance, smaller-scale surveys that provide more intensive coverage, including in shallow waters, are preferential.

1.5 | Shetland Islands context

Data collected from local fisheries-independent surveys can provide complementary information to other trawl surveys, such as the IBTS. Finer-scale locally run surveys, such as the Shetland Inshore Fish Surveys (SIFS), could allow for more regionalized and local monitoring as well as detailed analysis of spatial trends (Fraser et al., 2022).

The high-resolution and intensive coverage available from the SIFS data can be examined to provide new information on *R. clavata* juvenile habitat use and overall demographics in Shetland's coastal zone. This information may contribute to addressing previously mentioned ICES and OSPAR knowledge gaps and may simultaneously benefit the OSPAR status assessments for OSPAR Region II, ICES stock assessments for the Greater North Sea ecoregion, and the IUCN's recently launched ISRA process.

1.6 | Study aims

This study aimed to identify sites around Shetland that may be of conservation significance to *R. clavata*, and specifically to determine whether Shetland's shallower coastal water habitats (20–50 m water depth; henceforth "shallow") are relatively more important to juveniles than deeper water habitats (50–150 m water depth; henceforth "inshore"), thus to test whether *R. clavata* in Shetland waters utilize shallower areas as nursery grounds, similar to other elasmobranch species. To achieve this, survey data unique to Shetland were used to examine population demographics over space and time in terms of length and life class composition of *R. clavata* in inshore habitats and those much shallower. This allowed us to better understand annual population trends and determine whether any changes are more distinctive in shallower *v.* inshore habitats.

2 | METHODS

2.1 | Study location and habitats

The Shetland Islands (Shetland) are a subarctic Scottish archipelago in the North Atlantic located between the United Kingdom, Faroe Islands, and Norway. Shetland is located in an oceanographically dynamic area between the North Sea and Atlantic Ocean, dominated by the influence of the North Atlantic Current. The bathymetry around Shetland is highly diverse, and the substratum is of mixed character with both areas of soft sediment and rocky ridges found close to shore. Shetland has an extensive and complex coastline exceeding 2700 km and comprising more than 100 islands.

Marine industries such as fishing, aquaculture, oil and gas, and commercial shipping are fundamental to the local economy. Shetland, a Scottish port district (Marine Scotland, 2022), lands the second-largest total tonnage and value (economic) of fish and shellfish in the United Kingdom (Napier, 2021; Marine Scotland, 2022; Reade et al., 2023). Additionally, more finfish were landed in Shetland than all of England and Wales combined in 2021 (Napier, 2021). Therefore, the sustainability of fish stocks in Shetland waters is vital for the continued success of local fisheries and is significant in the context of UK fisheries, particularly through economic value.

2.1.1 | Shallow water *v.* inshore habitats around Shetland

Notably around Shetland there are numerous fjordic inlets, which are locally referred to as "voes," similar to sheltered sea lochs found elsewhere in Scotland. Shetland's voes tend to be less exposed to wave action than other coastal areas and thus may serve as elasmobranch nurseries. Due to the prevalence of finfish aquaculture and static fishing gear (especially creels, also known as pots) in Shetland's shallower water habitats, combined with their inaccessibility, unsuitable topography, and locally regulated closure areas, these habitats are less vulnerable to the pressures of commercial fishing with towed gear. In contrast, some of the deeper inshore habitats are impacted by mobile fishing gear, and many are not regulated through any closures.

2.2 | SIFS data

Long-term trawl survey data collected by UHI Shetland, formerly NAFC Marine Centre, was used to investigate the *R. clavata* population around Shetland. The SIFS has been conducted annually since 2011 around the coastal waters of Shetland, comprising nearshore and very shallow trawl sets (20–50 m water depth; henceforth "shallow") and those in deeper waters but still within 12 nautical miles of the shore (50–150 m deep; henceforth "inshore"). The data enable the construction of valuable time series data for investigating fish population dynamics and provide extensive and unique coverage of Shetland's coastal environment (Fraser et al., 2022).

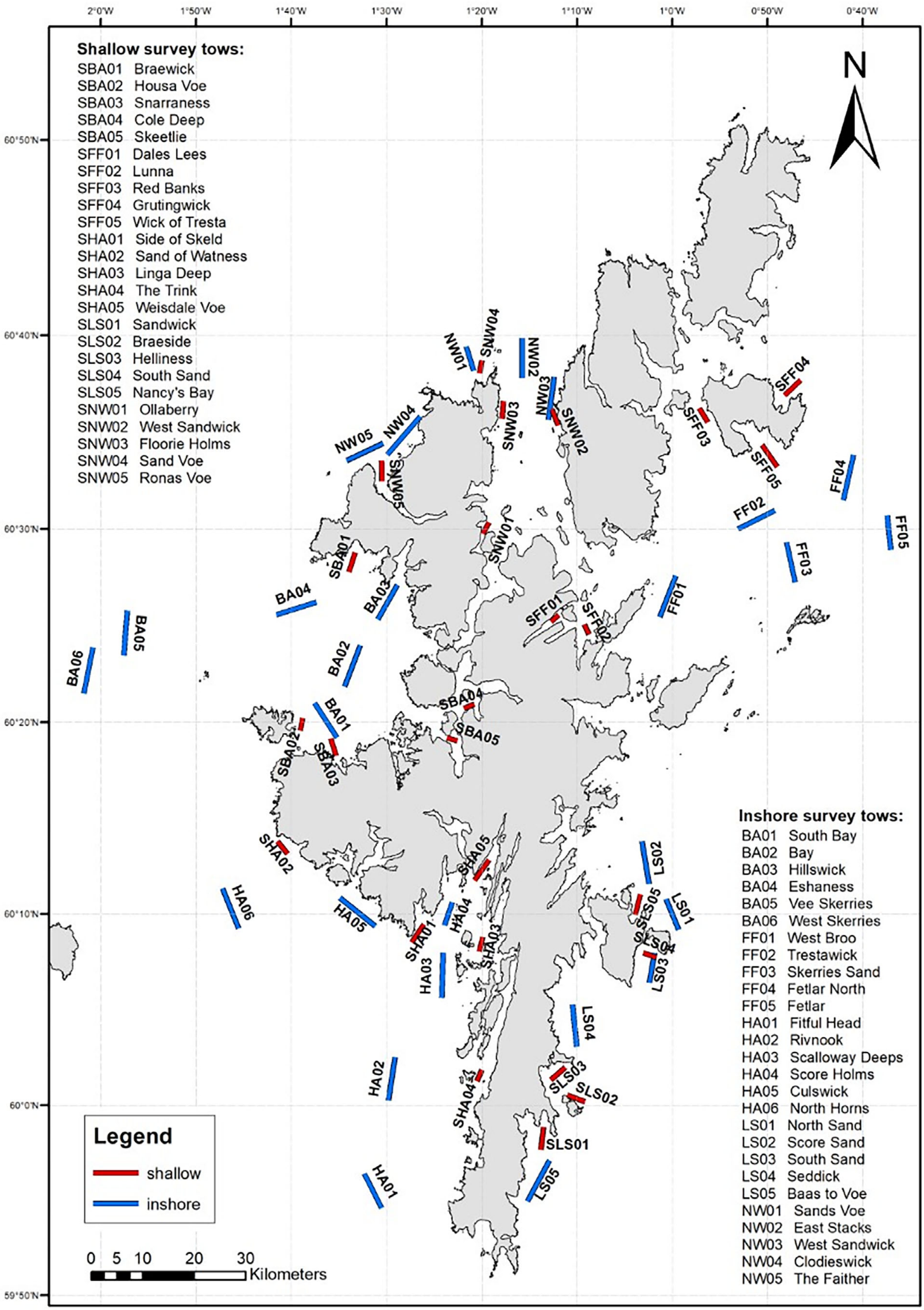

FIGURE 1 Inshore (blue) and shallow (red) survey tow habitats during Shetland Inshore Fish Survey. Tows identified by their station code and corresponding fishing grounds, for example, HA01, Fitful Head.

TABLE 1 Summary of survey and sample sizes used for length composition analyses of *Raja clavata* from 2017 to 2022.

Habitat	Depth range (m)	Year surveys began	Years analysed in this study	Mean number of tows per year	Total number of *R. clavata* individuals sampled	Total number of individuals <60 cm sampled	Total number of individuals ≥60 cm sampled	Total number of survey tows containing *R. clavata*
Inshore	50–150	2011	2017–2022	26.8 (*26–27*)	**304**	94	210	**55**
Shallow	20–50	2017	2017–2022	24.3 (*22–25*)	**581**	269	312	**102**

Note: Data represent raw sample sizes before standardization. Numbers in italic show the range of tows over the years.

2.3 | Survey design and trawling methods

The SIFS takes place annually, during August and September, using the 12 m MFV *Atlantia II* (LK 502) survey vessel and standardized survey gear, comprising a four-panel box trawl fitted with a small mesh (20 mm) cod-end liner. The use of a relatively small survey vessel allows effective sampling of shallow and constrained habitats that would otherwise be inaccessible to the larger vessels that undertake larger, regional-scale surveys such as the IBTS. The standard survey (since 2011) involves 27 inshore standard tow sites (50–150 m), and since 2017, 25 shallow standard tow sites (20–50 m; Figure 1; Table 1).

Tow depth is recorded using the vessel's onboard echosounder, and 50 m was used as a convenient threshold to separate habitat types for this study due to the available survey data that historically distinguish shallow and inshore areas by this threshold. The survey gear is towed using a standardized method at approximately 2.5 knots with trawl performance continuously assessed using a wireless monitoring system to ensure that fishing effort is consistently quantified. Further details on the survey design and sampling method can be found in Fraser et al. (2022).

One tow is completed at each inshore or shallow site with tow duration being 1 h where possible, but this varies due to ground suitability, especially in shallow areas (Fraser et al., 2022). The catch from each tow is sorted and weighed by species. Lengths are taken for commercially important species, including *R. clavata*, measured as the total length from nose to end of the tail. Skate species are also sexed by visual identification of the presence/absence of claspers.

2.3.1 | Ethics statement

This study complied with all the ethical requirements of the *Journal of Fish Biology*. *R. clavata* were sampled from commercial fisheries and obtained from research cruises. No organisms were killed expressly for this study.

2.4 | Data analysis

An overview of the data and sample sizes used for subsequent analyses are available in Table 1.

2.4.1 | Differences in overall catch per unit effort between habitat types

To begin exploring differences in catches of *R. clavata* between shallow and inshore habitat types CPUE (catch per unit effort) was calculated to enable visualization of changes in relative abundance over the years 2011–2022 (inshore), and 2017–2022 (shallow). A linear model and ANOVA were then conducted in RStudio, version 4.1.3 (RStudio Team, 2022) to test for significant differences in mean *R. clavata* CPUE_n (Equation 1) between inshore and shallow habitats across the years 2017–2022. When comparing inshore and shallow parameters, all subsequent analyses were restricted to the years 2017–2022 to avoid any temporal disparity in the data.

$$\text{CPUE}_n = \frac{\text{abundance of } R.\ clavata \text{ (adult and juvenile) per tow}}{\text{tow duration (hours)}} \quad (1)$$

2.4.2 | Length-frequency distribution

A stacked histogram length-frequency plot was constructed to visualize the raw length-frequency data, by sex, of *R. clavata* in shallow and inshore locations around Shetland over the years 2017–2022. This presents the raw count data, summed up across the years 2017–2022.

2.4.3 | Length at maturity estimates

Length at maturity is a key parameter for informing size restrictions (minimum landing sizes) of commercially exploited fish species, highlighting its importance in an applied context (McCully et al., 2012) and in the context of identifying potential nursery sites.

Lengths at maturity for male and female *R. clavata* in British waters were obtained through investigation of the most recent literature. McCully et al. (2012) indicated length at 50% maturity as 66.6 cm (males) and 76.6 cm (females). Estimates from Ebert and Stehmann (2013), also used in Shark Trust (2020), indicated maturity between 60 and 77 cm (males) and 60–85 cm (females).

Therefore, the present study split length data into two length classes (<60 cm and ≥ 60 cm) and inferred *R. clavata* individuals below 60 cm as juveniles.

2.4.4 | Differences in length class composition between shallow and inshore habitats

After this initial exploration of overall $CPUE_n$ trends and length-frequency composition, a series of analyses were conducted focusing specifically on 1 cm length classes to investigate potential shallow water nursery grounds in the SIFS dataset.

Length distribution results were standardized by tow effort ($CPUE_L$) for every 1 cm length class for inshore and shallow habitat tows for the years 2017–2022 by dividing the count by the corresponding tow duration (Equation 2). Note, even though inshore tows have taken place since 2011, analysis of this dataset was restricted to tows from 2017 onwards to allow direct comparison to survey years for the shallow habitat tow sites, which did not begin until 2017.

$$CPUE_L = \frac{\text{abundance of each 1 cm length class per tow}}{\text{tow duration (hours)}} \tag{2}$$

$CPUE_L$ for each length class was the focal response variable in the present study and used to identify potential nursery sites sensu Heupel et al. (2007). In this way, the present study could test whether (i) the mean CPUE of juveniles in shallow water tow sites exceeded mean CPUE in the deeper inshore habitat sites and whether (ii) shallow water habitats are repeatedly used by juveniles across years whereas deeper inshore habitats are not.

For the subsequent analyses, any 1 cm length class not recorded in any annual survey was removed.

The following workflow was implemented using the software PRIMER, version 6.0 (Clarke & Gorley, 2006). A triangular Bray–Curtis similarity matrix was constructed from the shallow and inshore CPUE datasets. The matrix was used to generate a non-metric multidimensional scaling (nMDS) plot to help visualize similarity in length compositions between years and habitat types. The matrix was also used to conduct comparison of a one-way analysis of similarities (ANOSIM) to quantify the strength and statistical significance of any difference in length class composition between habitat types (inshore *v.* shallow; 999 permutations). An ANOSIM global *R*-value of 0 would indicate no dissimilarity between habitats, and a value of 1 indicates complete dissimilarity between habitats. To investigate any statistically significant differences in length class data further, a similarity of percentages (SIMPER) analysis was conducted to specifically identify which 1 cm length classes contributed most to the characteristic differences between inshore and shallow habitats. SIMPER performs pair-wise comparisons to tabulate the average percentage contribution of each length class to the dissimilarity between habitat types.

These analyses in PRIMER enable the data to be investigated further and in finer detail, by statistically analysing population composition for each 1 cm length class, than may be possible by conventional population ecology approaches.

2.4.5 | Juvenile spatial distribution and temporal persistence in shallow water *v.* inshore habitats

Next, a base map was used in RStudio, version 4.1.3 (RStudio Team, 2022), to create spatial and temporal distribution CPUE abundance hotspot maps of *R. clavata* juvenile individuals (<60 cm) around Shetland from 2017 to 2022. These maps were then used to test whether shallow water habitats specifically are repeatedly used by juveniles across years, whereas deeper inshore habitats are not.

2.4.6 | Sex ratio differences between inshore and shallow habitats

Sex ratios (proportion of males: females [M:F]) were calculated for all individuals, and those ≥90 cm total length, in inshore and shallow locations, for years 2017–2022. The threshold of ≥90 cm was used to infer large, mature adults, based on the length at which nearly all are mature (McCully et al., 2012). A χ^2 test was performed in RStudio, version 4.1.3 (RStudio Team, 2022) to test for significant differences in sex ratios between shallow and inshore habitats.

3 | RESULTS

3.1 | Differences in overall CPUE between habitats

Total CPUE of *R. clavata* across all length classes was significantly higher in shallow habitats (mean CPUE = 12.18) compared to inshore tow locations (mean CPUE = 1.94, ANOVA, $F = 72.52$, $df = 1, 5$, $p < 0.001$). Inshore CPUE (2011–2022) was relatively stable, whereas CPUE in shallow habitats (2017–2022) indicated a decreasing trend in relative abundance (Figure 2).

3.2 | Length-frequency distribution

The length-frequency histogram showed an overall skewed distribution over the range of 17–109 cm, with two apparent peaks at approximately 60 and 80 cm (Figure 3). Higher frequencies of *R. clavata* individuals were observed in shallow water compared to the inshore locations (Figure 3). The distribution of males and females is similar (Figure 3); sex ratio results are discussed further in Section 3.5.

This length-frequency distribution allows visualization of the raw data, while the following results enable detailed investigation into length class composition, and account for standardization of the data.

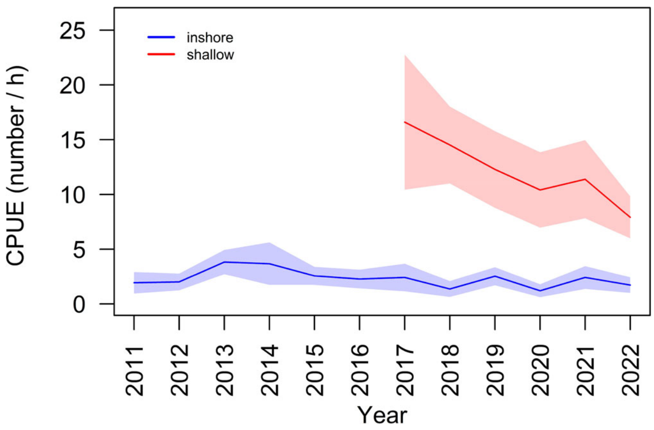

FIGURE 2 Catch per unit effort (CPUE) of *Raja clavata* for the shallow (red) (2017–2022) and inshore (blue) (2011–2022) survey locations. The mean result is shown by solid lines, and the shaded area represents the variability between tows (standard error).

3.3 | Differences in length class composition between habitat types

The nMDS plot showed very clear distinctions between inshore and shallow water habitat survey data (Figure 4). Shallow surveys were highly clustered, whereas inshore habitats showed lower cluster and fluctuations over survey years. The raw data matrix indicated that this may be driven by fluctuating size compositions and abundances in inshore survey results. A 2D-stress value of 0.06 indicates a representative plot ordination.

For *R. clavata*, there was a statistically significant difference in the length compositions between shallow and inshore habitats (ANOSIM, $R = 0.96$, $p = 0.002$), based on the Bray-Curtis similarities between different surveys. The *R*-value was very close to 1, representing near-complete dissimilarity in length composition between shallow and inshore habitats.

SIMPER results showed an average dissimilarity of 77.49 (Table 2), meaning that length composition differed by 77.49% between inshore and shallow habitats. Half of the cumulative contribution to this dissimilarity was made up by length classes ranging from 37 to 80 cm, but mostly by juveniles <60 cm (62.5% of the 50% cumulative contribution), which were more abundant in shallow habitats. Notably, the length composition was remarkably similar across years in the shallow water habitat tow locations (average similarity = 52.68%; Figure 4) in comparison to length class composition that varied inter-annually in inshore tow locations (average similarity between years = 38.08%; Figure 4), reinforcing the close cluster of shallow locations in the nMDS plot *v.* the looser inshore cluster (Figure 4).

3.4 | Juvenile spatial distribution and temporal persistence

Juvenile *R. clavata* individuals (<60 cm length) were consistently found in higher abundances (CPUE) in shallow *v.* inshore tow locations across all years (2017–2022; Figure 5). Areas with peak juvenile CPUE include annual persistent strongholds in the shallow locations of: Lunna (SFF02) and Cole Deep/Skeetlie (SBA04/SBA05); (Figures 1 and 5). For example, 99 juvenile individuals (per hour) were found in Lunna in 2017. In Cole Deep and Lunna, >20 juvenile individuals (per hour) were present in 100% and 50% of the years 2017–2022, respectively.

3.5 | Sex ratio differences between inshore and shallow habitats

There was no significant difference in the sex ratio (proportion of males to females, M:F) between inshore and shallow habitats for all individuals ($\chi^2 = 0.03$, $df = 1{,}1$, $p = 0.9$), and individuals ≥90 cm ($\chi^2 = 0.09$, $df = 1{,}1$, $p = 0.8$).

3.6 | General SIFS observations (2017–2022)

High abundances of *R. clavata* (adults and juveniles) were observed over the study period in tows SFF03, SFF04, SFF05 (Figure 1). In addition, catches in this same area consistently contained large mature females (≥90 cm length). These tows (Figure 1: SFF03, SFF04, SFF05) were absent from the 2021 survey due to delays in receiving the required permissions from relevant regulators.

Cole Deep (SBA04; Figure 1) was a short tow (9 min), but after standardization to account for tow effort, a total abundance of 46 juvenile *R. clavata* (<60 cm) per hour were found in 2021.

4 | DISCUSSION

4.1 | Density hotspots and potential nursery grounds

This study is the first to present population ecology findings and investigate potential areas of importance for the *R. clavata* population around Shetland, Scotland. The results provide strong evidence of differing size compositions between shallow and inshore habitats whereby smaller, juvenile length classes were more abundant in shallow habitats and contributed the greatest dissimilarity between inshore and shallow habitats. This is consistent with Ebert and Stehmann (2013), indicating juveniles as typically found in <30 m depth. These findings suggest that shallow areas around Shetland may be important nursery areas for *R. clavata*.

Results showing high cluster of shallow habitats over time highlight these areas as supporting stable population size compositions. Stability through time is important for population integrity and persistence in the face of disturbance (Kerr et al., 2010), which are, therefore, important areas to identify and target for conservation management. Population stability is used to assess marine reserve

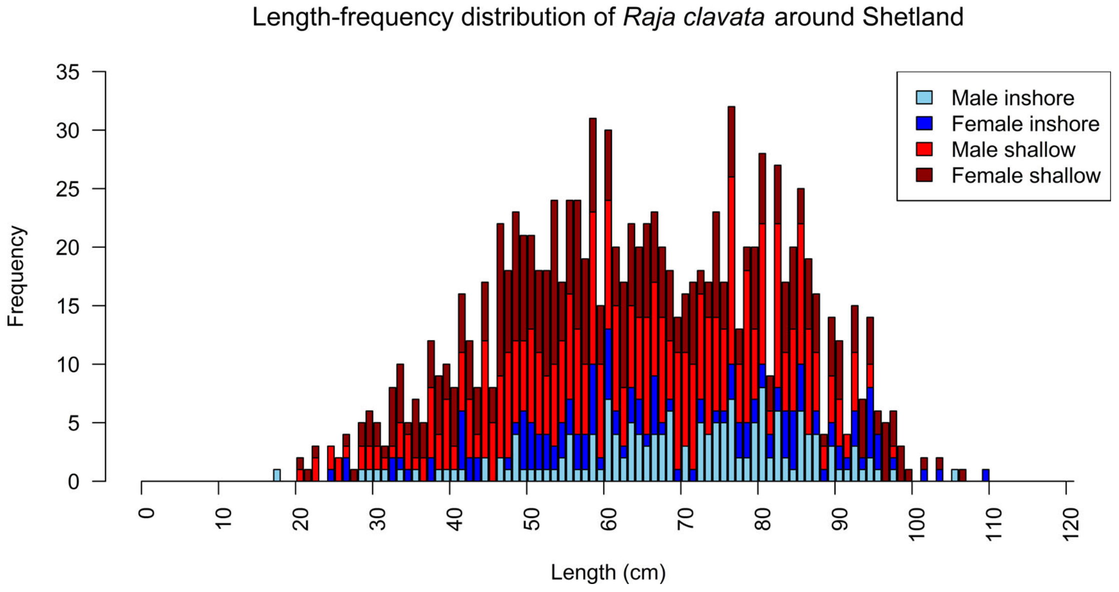

FIGURE 3 Length-frequency distribution, by sex, of *Raja clavata* in shallow and inshore locations from 2017 to 2022. This presents raw count data, before standardization to account for tow effort. Counts are summed up across the years 2017–2022.

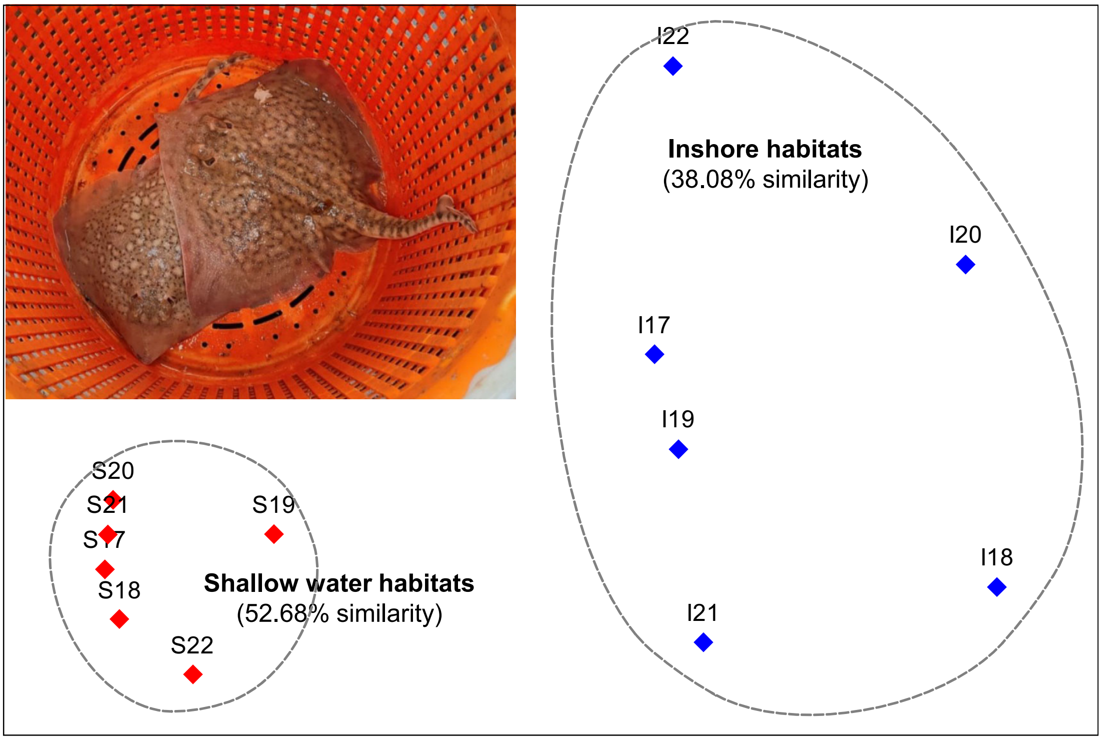

FIGURE 4 Non-metric multidimensional scaling (nMDS) plot showing ordinations generated from a Bray–Curtis similarity matrix on *Raja clavata* catch per unit effort (CPUE) Bray-Curtis similarities between shallow water and inshore habitat tow locations. Surveys are grouped into shallow (red) and inshore (blue) habitats. Labels represent survey habitat and year, for example, I22 = Inshore survey conducted in 2022. nMDS plot 2D stress is 0.06, indicating a clear distinction of the two clusters (dashed lines). Inset picture shows two *Raja clavata* sampled in a tow; basket diameter at base is 35 cm.

effectiveness, such as in the Caribbean reef shark (*Carcharhinus perezi*) population in Glover's Reef Marine Reserve, which displayed stability characteristics through constant CPUE and mean lengths over time (Bond et al., 2017).

Significantly higher relative abundance of *R. clavata* in shallow areas compared to inshore areas highlights the importance of these shallow areas for the overall *R. clavata* population around Shetland. These shallow habitats have already been suggested as important

TABLE 2 SIMPER analyses of Raja clavata length class composition dissimilarity based on catch per unit effort (CPUE) between inshore and shallow water habitat tow surveys (2017–2022).

	Inshore	Shallow		
Length class (cm)	Mean CPUE	Mean CPUE	Contribution to dissimilarity (%)	Cumulative dissimilarity (%)
Average dissimilarity: 77.49				
46	0.01	0.32	2.87	2.87
47	0.01	0.29	2.65	5.52
65	0.02	0.29	2.53	8.04
44	0.01	0.26	2.42	10.47
37	0.01	0.25	2.42	12.89
49	0.04	0.26	2.4	15.28
48	0.03	0.3	2.39	17.67
53	0.02	0.28	2.36	20.03
50	0.03	0.26	2.36	22.39
55	0.04	0.24	2.27	24.66
56	0.03	0.25	2.23	26.89
61	0.04	0.24	2.15	29.04
76	0.06	0.28	2.1	31.15
71	0.01	0.22	2.01	33.16
67	0.03	0.22	1.96	35.12
59	0.01	0.22	1.96	37.08
51	0.02	0.23	1.94	39.02
58	0.06	0.26	1.89	40.91
70	0.02	0.21	1.86	42.76
39	0.01	0.19	1.82	44.59
74	0.04	0.19	1.63	46.21
80	0.06	0.22	1.6	47.82
57	0.03	0.19	1.56	49.37
63	0.06	0.19	1.51	50.88

Abbreviation: Catch per unit effort (CPUE).

nursery areas for other commercially important species such as plaice (*Pleuronectes platessa*), monkfish (*Lophius piscatorius*), and cod (*Gadus morhua*; Fraser et al., 2022). There is some evidence of a decline in relative abundance of *R. clavata* in shallow locations from 2017 to 2022, which further indicates the importance of research into these shallow areas to help protect this population from further declines.

The potential presence of nurseries in Shetland's shallow waters is further supported through spatial distribution maps, highlighting a relatively higher presence of juveniles in shallow than inshore areas, along with consistent abundance hotspot areas used over time, such as Cole Deep/Skeetlie and Lunna. These locations are both similar voe habitats and may be important areas for the species, warranting further investigation.

Additional support for the presence of *R. clavata* nurseries in Shetland's shallow waters is indicated through fulfillment of two of the nursery criteria formulated by Heupel et al. (2007), whereby juvenile individuals are more commonly encountered (and in higher densities) in shallow waters than deeper inshore habitats. Through evidence of stable size compositions and spatial distribution maps, this study also shows that shallow waters were being used repeatedly by juveniles, whereas deeper inshore habitats were not.

The consistent presence of large, mature females in certain areas through time highlights the importance of shallow areas for these females. Large, mature females are hugely important for population recruitment, resilience, and viability; their removal may promote negative rapid life-history changes such as those observed in *G. morhua* (Aramayo, 2015). Although there was no statistically significant difference in the sex ratios of *R. clavata* (all individuals, and those ≥90 cm) between shallow and inshore survey locations, further investigation into sex ratios in specific areas may be valuable.

There were limited early-stage individuals (<20 cm) in this dataset that could be due to SIFS (August/September) not overlapping with peak hatching of *R. clavata* in the UK (November, following peak spawning in June) (Holden, 1975; Serra-Pereira et al., 2011). Consequently, the hatched juveniles from this peak period will have the

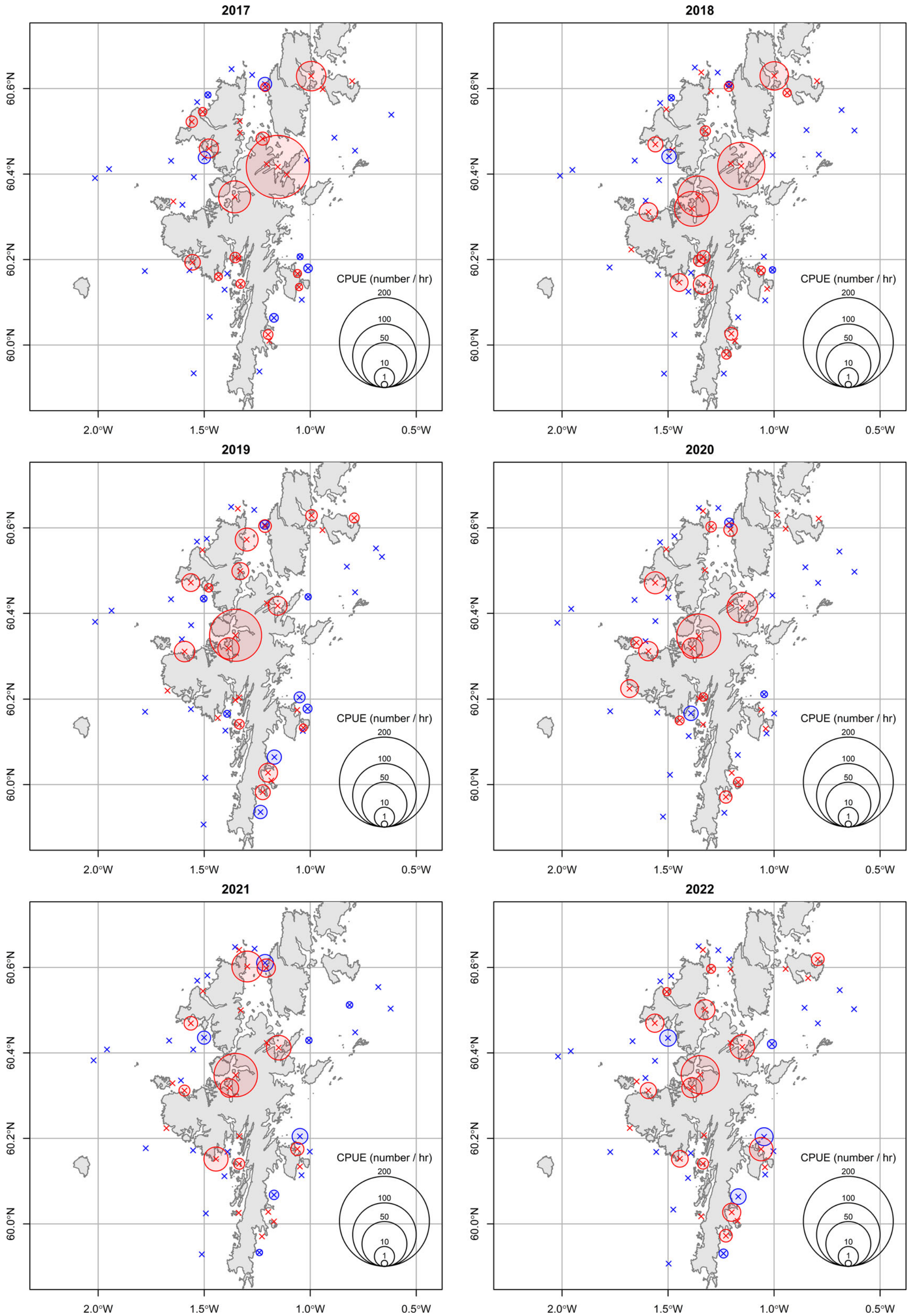

FIGURE 5 Spatial distribution of juvenile *Raja clavata* (<60 cm) catch per unit effort (CPUE) from annual Shetland inshore fish surveys (SIFS) conducted between 2017 and 2022. Blue crosses indicate inshore habitat surveys (20–50 m water depth), and red crosses indicate shallow water habitat surveys (50–150 m water depth). The size of circle indicates CPUE. The location of each *R. clavata* individual was assigned as the midpoint of the associated tow.

proceeding months to grow, potentially >20 cm, before the next SIFS. Alternatively, the early-stage individuals may be in even shallower areas or may prefer rockier habitats inaccessible by trawl gear.

Population ecology, and density hotspot information, is especially important to obtain for *R. clavata* (near threatened [Ellis, 2016]) as they have faced declines in the past due to direct targeting by fisheries, and vulnerability to being caught as by-catch, driven by their large size (Hunter et al., 2006; Walker & Hilsop, 1998; Wiegand et al., 2011). Their vulnerability to fishing pressure may explain the larger abundances observed in shallow areas compared to deeper, inshore areas, as they may be moving shallower to gain some protection. Alternatively, these shallow areas may just be their preferred habitat (Ebert & Stehmann, 2013; OSPAR, 2010), and by default they are more protected due to limited opportunities for fishing with towed gear in these areas. Either way, shallow areas may be providing areas for recruits that could help to rebuild deeper inshore populations.

4.2 | International context

Results from this study show evidence for the importance of shallow areas in general, and their potential as nursery grounds for *R. clavata*.

Studies on elasmobranch population demographics provide important new information that helps organizations such as OSPAR, the IUCN, and ICES produce advice that may influence the governance of biodiversity, conservation, and fisheries governance. Nurseries are important areas for protection due to their role in juvenile recruitment into the population (Hoff, 2016). The shallow locations Cole Deep/Skeetlie and Lunna consistently support juvenile *R. clavata*, highlighting their importance as nursery areas.

This study has reduced existing knowledge gaps outlined by ICES and OSPAR (ICES, 2020; ICES, 2021b; OSPAR, 2021) by identifying shallow areas around Shetland as important *R. clavata* juvenile habitats. Additionally, shallow areas, compared to inshore areas, were found to possess population stability characteristics over time, providing valuable population structure information. Therefore, importantly, results from this study could benefit the OSPAR status assessment for OSPAR Region II and ICES stock assessments for the Greater North Sea ecoregion, to help inform a precautionary approach to management.

Results from this study could also be used to inform ISRAs in the potential nursery areas Cole Deep/Skeetlie and Lunna. The ISRA approach outlines a set of criteria to help scientists and experts identify these important areas (Hyde et al., 2022). In conjunction with Criterion A—Vulnerability, this project has identified important life-history areas (Criterion C), particularly nurseries, for *R. clavata* in Shetland waters.

The limited catches of *R. clatava* in the Shetland area during the IBTS (OSPAR Region II, ICES division 4.a) may be caused by the survey grounds not overlapping with the preferred habitats of *R. clavata*. In contrast, there was a higher relative abundance observed in SIFS, which highlights the importance of shallower habitats for *R. clavata* in this area; Fernández et al. (2021) owed the scarcity of *R. clavata* in similar IBTS to lack of survey coverage in shallow habitats that are preferred by the species. In this sense, SIFS data are extremely valuable for providing more accurate population information that is not available from larger-scale surveys. Because surveys such as IBTS are used to inform management assessments and strategies, SIFS is particularly relevant to aid ICES and OSPAR assessments in the Greater North Sea ecoregion and Region II, respectively.

Further research on *R. clavata* as suggested here would enable the development of suitable conservation and management recommendations. It is important to acknowledge previous management for elasmobranchs in general, and *R. clavata* specifically. Management measures to afford protection to elasmobranchs can be sought through establishment of protected areas (Ellis et al., 2005; Knip et al., 2012), but may be effective only when used in conjunction with other strategies (Ellis et al., 2005). Hunter et al. (2006) and Wiegand et al. (2011) estimated that a three-season spatial closure would provide enough protection to ensure the recovery of *R. clavata* in the Thames Estuary and suggested the use of gear restriction and minimum landing sizes to boost closure effectiveness.

4.3 | Value of the Shetland inshore fish survey

The high spatial resolution and extensive inshore and coastal coverage available from the SIFS has provided new information on *R. clavata* juvenile habitat use around Shetland's coastal zone. Additionally, the SIFS data provide insights into more localized contexts than is possible by those collected for the IBTS. However, it is important to recognize some limitations to the data and the surveys. For example, coverage of shallow areas in 2021 was reduced in the Fetlar areas (Figure 1: SFF03, SFF04, SFF05) due to unforeseen delays in receiving the required derogation, and occasionally there may have been some minor depth overlap between some shallow and inshore areas.

The careful monitoring of gear performance ensures that fishing effort is accurately quantified. Nonetheless, practical factors relating to species catchability are recognized and for some species could cause difficulties in the standardization of catch data for varying tow durations.

Future work could include more accurate determination of other assumptions such as the single threshold for length at maturity. The use of a single threshold for maturity has the potential for some inaccuracy; however, given the lack of available age-length literature on *R. clavata* it was not possible to designate maturity groups. Published accounts of *R. clavata* lengths at maturity vary (McCully et al., 2012; Walker & Hilsop, 1998); however our threshold is based on the most recent evidence, and future work should investigate this in more detail, while addressing regional variations.

Overall, continuation of the SIFS is highly recommended to provide added value to the long-term dataset and its contribution to the understanding of demersal fish communities. The scope of the survey methods and data allows for potential implementation of further studies into demersal elasmobranchs; such examples are now briefly outlined.

4.3.1 | Assessing cumulative impacts on *R. clavata* from other sectors

Further research is encouraged to identify/assess the impacts of static mariculture sites on these *R. clavata* nursery areas (Cole Deep/Skeetlie and Lunna) as there is likely to be negligible exposure to mobile fishing gear in these areas. Mariculture sites have been found to affect the health and productivity of the surrounding ecosystem through habitat destruction (Ottinger et al., 2016), pollution (Islam, 2005), and introduction of disease (Lafferty et al., 2015). However, these sites may also be provisioning food for wild fish populations (Felsing et al., 2005; Gentry et al., 2017) through consumption of food pellets (Carss, 1990; Pearson & Black, 2001), waste materials from cage aquaculture (Felsing et al., 2005), and/or secondary attraction of predators to wild prey that are also attracted to cages (Callier et al., 2018). Identifying impacts of these sites on *R. clavata* juvenile hotspots will provide a more holistic understanding of these nursery grounds.

4.3.2 | Understanding juvenile habitat use

Finer-scale investigation into habitat variability of potential nurseries for *R. clavata* such as diet analysis studies could lead to improved understanding of juvenile habitat use. For example, if seasonal prey influences the presence of nursery grounds, corresponding seasonal fisheries management to promote the persistence of these prey items could be considered, as observed in juvenile bull sharks (*Carcharinhus leucas*; Scharer et al., 2017). In an investigation into diet composition of *R. clavata* around Shetland, the diet of individuals in shallow areas was mainly composed of lesser sandeels (*Ammodytes tobianus*), whereas common hermit crabs (*Pagarus bernhardus*) were the most important prey in inshore areas (McAllister & Fraser, 2023), which may indicate the importance of variations in prey-species dynamics for characterizing shallow nursery grounds for *R. clavata*.

The nursery criterion of whether individuals tend to remain or return for extended periods (weeks or months; Heupel et al., 2007) in a particular habitat type could not be tested using the present dataset, but the results from the present study could follow on to support targeted electronic or mark-recapture tagging studies to address this.

5 | CONCLUSION

Overall, this study has been the first of its kind to present population ecology findings and investigate potential areas of importance for the *R. clavata* population around Shetland, Scotland. Understanding size compositions, life-history characteristics, spatial distributions, and relative abundances is required for identification of areas (such as nurseries for juveniles) of importance to skate species, which is generally lacking around the British Isles (Ellis et al., 2005). The findings of this study provide evidence for the potential use of *R. clavata* nurseries in shallow areas and identified specific sites that are consistently used by juveniles over time. Furthermore, the results from this study may simultaneously benefit the OSPAR status assessments for OSPAR Region II, ICES stock assessments for the Greater North Sea ecoregion and the IUCN's recently launched ISRA process. Although this study may have indicated areas for conservation, further research is suggested for any development of effective conservation and fisheries management strategies for *R. clavata* in Shetland's waters. This study reduced knowledge gaps surrounding *R. clavata* and their population ecology around Shetland, while also providing new information that may be beneficial to understanding the species at wider scales and in other geographical areas.

AUTHOR CONTRIBUTIONS

Mia McAllister conceptualized the study design (including methodology), performed the literature review, was involved in data collection, generated the required datasets, conducted and supervised the data analyses, wrote the original draft of the manuscript, and reviewed and edited the manuscript. Shaun Fraser conceptualized the methodology, collected the survey data, conducted data analyses, and reviewed and edited the manuscript. Lea-Anne Henry conceptualized the methodology, conducted data analyses, supervised the literature review, and reviewed and edited the manuscript.

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