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Investigation of Spatiotemporal Patterns of Harbour Porpoise (*Phocoena phocoena*) Strandings in Swedish Waters for Improved Monitoring and Management

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Abstract: Harbour porpoises (*Phocoena phocoena)* are the only cetacean residents found year-round in Swedish waters and they are exposed to numerous natural and anthropogenic threats. Since the in situ monitoring of cetaceans can be difficult, invasive and often expensive, investigation of stranding patterns and examination of stranded animals can be used as a cost-effective source of data to study these elusive animals. The aim of this study was to investigate the spatiotemporal patterns of harbour porpoise stranding reports and the possible underlying causes in Swedish waters over a ten-year period (2014–2023). Additionally, the Swedish stranding network plays a key role in the collection of stranded carcasses for health and disease surveillance, and geographic coverage of the network also was analysed. When making spatial comparisons, the ten-year period was divided into two five-year blocks. Data on 854 stranded harbour porpoises were analysed from the coasts of the Skagerrak, Kattegat, and Baltic Seas. Both significant spatial and temporal patterns could be identified. Strandings peaked in July through September and hotspots occurred along most of the Swedish west coast, with the most frequent hotspots located around Öresund and especially the area around the Kullen peninsula. The spatial patterns of strandings found in this study are consistent with data on porpoise abundance, prey abundance, and gillnet fisheries' efforts. The latter is known to be one of the primary causes of porpoise mortality. Furthermore, the coverage of the Swedish stranding network increased between the two periods, likely reflecting an increased awareness of the carcass-based surveillance program, and gaps requiring network expansion efforts were identified. These results also provide baseline data to enable the continued monitoring of stranding trends, as changes may indicate changes in population distribution, size or mortality rates.

Keywords: harbour porpoise; stranding; *Phocoena phocoena*; cetacean; marine mammal; wildlife monitoring; wildlife health surveillance; spatiotemporal patterns; gillnet fisheries

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1. Introduction

Harbour porpoises (*Phocoena phocoena*) are top predators in temperate marine ecosystems and the only permanent cetacean residents in Swedish waters [1]. Globally and in Europe, the harbour porpoise is listed by the International Union for Conservation of Nature (IUCN) as being of Least Concern (LC) [2,3]. There are three genetically and morphometrically separate populations within Swedish waters, including the North Sea population extending into the Skagerrak, the Belt Sea population, and the critically endangered Baltic Sea population [4–6]. Abundance estimates were most recently made by the SCANS-IV surveys and SAMBAH project, where abundances for the North Sea and Belt Sea populations were estimated to include 338,918 (95% CI = 243,063–476,203) and

14,403 (95% CI = 9555–21,769) individuals, respectively [7], while the Baltic Sea population was estimated to include 491 (95% CI = 71–1105) individuals [8]. Estimates for the North Sea population are similar to estimates from previous SCANS surveys. In contrast and of concern, the Belt Sea estimate of 14,403 is considerably lower than earlier estimates of 42,324 (95% CI = 23,368–76,658) in 2016 and 40,475 (95% CI = 25,614–65,041) in 2012 [7,9,10].

Some of the most significant threats to harbour porpoises include environmental contaminants, noise pollution, the loss of habitat, reduced food availability as a result of fishing, and bycatch [11], with bycatch in gillnets continuing to be one of the greatest threats [12–16]. The most significant factors contributing to porpoise bycatch in gillnets are the mesh size, soak time and vessel length [17], with porpoises mainly being bycaught in larger mesh sizes (>120 mm) [18].

Berggren [12] identified gillnets as being responsible for more than 80% of the bycatches of harbour porpoises in Swedish waters. Fisheries with the highest levels of bycatch differed between the three regions assessed by Berggren: Skagerrak, Kattegat and the Baltic Sea. Gillnets set for cod (*Gadus morhua)* accounted for large shares of bycatch in all three areas, with the highest being 72% in the Kattegat Sea. However, the largest share of bycatch observed in the Baltic Sea was from driftnets for salmon (*Salmo salar*). In the Skagerrak Sea, gillnets set for spiny dogfish (*Squalus acanthias*) accounted for most of the bycatch [12]. According to records held by Swedish Museum of Natural History (NRM), harbour porpoises have also been reported as bycatch in Swedish fisheries for lumpfish (*Cyclopterus lumpus*), pollock (*Pollachius pollachius*), Atlantic mackerel (*Scomber scombrus*), turbot (*Scophthalmus maximus*), and langoustine (*Nephrops norvegicus*). However, since Berggren's assessment, there have been noteworthy changes in fisheries activities. Namely, there have been zero quotas on spiny dogfish since 2011 in accordance with council regulation (EU) No 57/2011 [19], but spiny dogfish fisheries have resumed operations in 2023 [20], and targeted fishing on cod has been heavily reduced or prohibited [21]. Yet bycatch still poses a threat to porpoise populations [1,11].

Recent necropsy data on stranded animals examined from Swedish waters show that bycatch, when considered together with probable bycatch, is the most frequent cause of death, supporting previous studies [1]. The carcasses of stranded animals are often in poor states of preservation due to decomposition, handling, scavenging, the delay between stranded animals being reported and collected for necropsy, and the possibility of carcasses drifting for extended periods before stranding. This masks the characteristic signs of bycatch and makes it more difficult to assign a cause of death. Consequently, both the numbers of bycaught individuals and probable bycaught individuals are likely underestimated in the necropsies of stranded porpoises [1,22]. Therefore, an efficient and extensive stranding network is vital to obtaining fresh individuals for necropsies to facilitate the determination of the cause of death and the identification of bycatch and other threats.

Because porpoise populations face numerous threats, harbour porpoises are protected and listed as a species in need of conservation efforts and monitoring in several conventions and directives both in Sweden and internationally [11]. Some examples include the Habitats Directive (92/43/EEC) [23], the Oslo-Paris (OSPAR) Convention [24], the Helsinki Commission (HELCOM) [25], and the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Sea (ASCOBANS) [26], for which, the harbour porpoise is named as the flagship species. Despite efforts and conventions, knowledge of the health status of harbour porpoises in Swedish waters is described as inadequate by the Swedish Agency for Marine and Water Management (SwAM) [11]. Efficient and systematic monitoring schemes are essential in augmenting our knowledge of this species.

Monitoring porpoise populations not only helps with assessing the health of the species itself but also provides management with vital information to assess the overall health and stability of marine ecosystems because top predators reflect the health and stability of the environments in which they reside [1,27]. Marine mammals often have long life spans, which, combined with feeding at high trophic levels, leads to the accumulation of environmental contaminants in their tissues [28]. Since harbour porpoises share the coastal environment and food sources with people, they may also function as effective sentinels for human health [1,28]. Furthermore, with the increasing noise pollution and disturbance from commercial shipping and the construction of offshore wind farms, the need to monitor marine mammals is even greater to detect impacts which may even have cascading, negative effects on the rest of the ecosystem [29].

However, monitoring cetaceans in situ, i.e., at sea, can be costly and challenging due to their elusive nature, high mobility, and ability to spend extended periods underwater [1,30,31]. As an alternative to in situ methods, strandings can be used as a cost- and time-effective way of monitoring cetacean populations and they provide excellent opportunities for biological sampling [1,30]. The documentation of stranding reports and the collection of stranded individuals for necropsies over time enables the identification of spatial and temporal changes in stranding patterns, as well as changes in overall population health [1,22]. Several studies in Northern Europe have investigated spatiotemporal trends in cetacean strandings and factors that affect the distribution and cause of strandings, such as life history parameters, population density, fisheries activity, and weather phenomena [22,32,33]. However, to our knowledge, similar studies have not been conducted in Sweden.

The primary aim of this study was to investigate whether or not spatiotemporal patterns in harbour porpoise strandings occur in Sweden, and if they occur, to describe their nature and investigate possible underlying factors. Additionally, this study aimed to investigate the coverage of Sweden's stranding network to identify areas of inadequate coverage where there is a high clustering of stranding reports. Finally, with no similar studies yet conducted in Sweden, this research serves to establish baselines for future monitoring and provides further evidence for the value of using strandings to inform management.

2. Materials and Methods

2.1. Data Collection and Study Area

For this study, stranded harbour porpoises were defined as porpoises that were found onshore, or in rare cases, found dead, drifting at sea with an unknown history or cause of death. Porpoises that were submitted directly from known fishery interactions, i.e., were retrieved from nets set at sea, were excluded, as they did not represent strandings. Reports of stranded harbour porpoises are made by the general public to the Swedish Museum of Natural History (NRM). Since 2021, reports have been submitted to NRM via a web-based formulary (https://marinadaggdjur.nrm.se accessed on 31 October 2023) [34]. Before the website's launch, reports were submitted to NRM via telephone and email and those have retrospectively been added to the reporting database. Reports generally contain the geographic coordinates (latitude and longitude), number of individuals, and observation date. Reports also often include a short comment, and the submission of photographs is encouraged. When they are deemed an animal of interest and resources are available, stranded harbour porpoises are retrieved by the Swedish Veterinary Agency's (SVA) stranding network and submitted for necropsy examination. Examination includes a determination of the cause of death, investigation of other pathologies, surveillance for pathogens and collection and archiving of an extensive suite of samples and data as described in Neimanis et al. [1]. The stranding network includes private citizens, academic institutions, non-governmental organizations, municipalities, counties, the police, the Coast Guard, fishermen, and hunters [35]. The study area encompasses all of Sweden's coastline which runs from 59.0° N, 11.0° E on the west coast to 65.7° N, 24.2° E on the northeast coast.

2.2. Stranding Data, Necropsy Data, and Processing

Data on stranded harbour porpoises from 1 January 2014 to 31 December 2023 were retrieved from NRM and consisted of 1007 reports. Suspected or confirmed double reports (N = 161) and findings from outside of the Swedish territory (N = 4) were excluded from the dataset. Reports containing pictures were quality-controlled to remove other marine fauna that were misidentified as porpoises (N = 1). Furthermore, a few observations were missing coordinates (N = 14). For these, an approximate position was added in cases where the location was clearly described in the comments (N = 13). In some cases, the number of individuals was reported as more than one, while the comment indicated only one finding. In these cases, the numbering of individuals was corrected to one for a conservative estimation (N = 13). Observations where the comment clearly stated that the individual was submitted as bycatch rather than stranded (N = 11) were also omitted from the data set. All analyses were conducted using the individual count rather than the number of reports since some reports include more than one individual.

Necropsy data for the years 2020–2022, provided by the SVA, was acquired from Sweden's dataportal (www.dataportalen.se accessed on 27 November 2023) [36]. Furthermore, necropsy data from 2014–2019 was provided in Neimanis et al. [1] and data from 2023 was directly accessed from the SVA's database, SVALA.

2.3. Seasonality and Cluster Identification

Temporal variations and seasonality in stranding reports were assessed using chi-squared tests to ascertain whether the distribution of yearly and monthly occurrences deviated from a uniform pattern. Linear trends in annual recorded strandings were examined using Pearson correlation statistics to determine whether there was an upward, downward, or stable trend in the recorded strandings. Stranding reports of skeletal remains (N = 16 individuals) were excluded from the temporal analysis since the finding date does not necessarily reflect the stranding date. However, skeletal remains were included in the spatial analyses. Results were visualised using bar plots containing the month and year on the x-axis and the number of stranded individuals on the y-axis.

Spatial analyses utilised administrative-level data for Swedish municipalities. Topographical data for administrative areas were obtained from Lantmäteriet on 17 November 2023 [37]. Only topographical information of administrative regions where stranded porpoises were located was included in the analysis. A grid with 5 × 5 km cells was created to refine the spatial analysis, employing administrative areas as the spatial framework. Clusters were discerned using the Local Moran's I statistic [38], implemented with the spdep package version 1.2-8 [39]. The Local Moran's statistics were computed with the "greater" alternative and queen contiguity as spatial weights. The alternative "greater" was applied to evaluate only positive autocorrelation, meaning identifying only clusters with low values surrounded by low values, "coldspots", and clusters with high values surrounded by high values, "hotspots". A significance level was calculated for each grid cell where $p < 0.05$ indicates significance. The Local Moran's I statistic was calculated individually each year to assess cluster persistence over time. Additionally, the ratio of animals retrieved for necropsy from each clustered grid cell to the total number of stranded individuals in the corresponding cell was calculated to quantify coverage by the stranding network and pinpoint areas lacking coverage. The difference in coverage over time was calculated using a Wilcoxon rank sum test [40,41].

Maps were created using the packages ggplot2 version 3.4.4 [42], rworldmap version 1.3-8 [43], and ggspatial version 1.1.9 [44]. The 10-year period was split in two. Maps were produced for both 5-year periods (2014–2018 and 2019–2023) to facilitate comparison and because 5-year periods were deemed to be suitable time frames to follow trends for management purposes. Coverage maps were visualised with grids from clusters, but also grids not identified as clusters where individuals had been collected for necropsies. All statistical and spatial analyses were conducted using R version 4.2.2 [45].

3. Results

3.1. Seasonality and Temporal Trends in Stranding Reports

After data processing, the dataset for the temporal analysis contained 814 stranding reports with 838 individuals. Chi-squared tests showed yearly distributions significantly deviating from a uniform pattern ($\chi^2 = 169.35$, d.f. = 9, $p < 0.001$), with the lowest number of stranding reports occurring in 2014 (N = 18) and the highest number of stranding reports occurring in 2022 (N = 147) (Table 1 & Figure 1). Pearson correlation tests showed a significant upward trend in stranded individuals across years (r = 0.853, d.f. = 8, $p = 0.002$). Monthly strandings also differed from a uniform pattern ($\chi^2 = 368.64$, d.f. = 11, $p < 0.001$), with reported strandings peaking in late summer (July and August) and early autumn (September and October) and with minimal reported strandings in the winter months (December, January, and February) (Table 1 & Figure 2).

Table 1. Counts of reported stranded harbour porpoise individuals (*Phocoena phocoena*) across the months and years of 2014–2023. Skeletal remains are included in counts and specified in brackets.

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Total Reported Stranded Individuals
Total	18 (1)	37 (1)	63 (1)	111 (1)	64 (2)	81 (2)	104 (2)	120 (2)	147 (2)	109 (2)	854 (16)
January	0	5	1	4 (1)	2	3	2	3	9	2	31 (1)
February	0	1	5	1	1	2	3	0	11	4	28
March	3	1	1	3	1	11	2	14	9	3	48
April	3	1	1	10	2	2 (1)	5 (1)	5	5	5	39 (2)
May	0	5 (1)	3 (1)	5	1	2	3	14	24	5	62 (2)
June	0	3	1	13	6 (1)	2	4	10 (1)	10 (1)	5	54 (3)
July	3	2	13	11	11	12	22 (1)	16	31	26 (1)	147 (2)
August	5	3	11	25	11	11	31	22	22	21	162
September	2 (1)	3	16	11	16	16	15	18 (1)	10 (1)	20	127 (3)
October	0	4	2	16	8 (1)	16 (1)	7	9	10	13	85 (2)
November	2	7	8	9	2	4	6	8	5	3	54
December	0	2	1	3	3	0	4	1	1	2 (1)	17 (1)

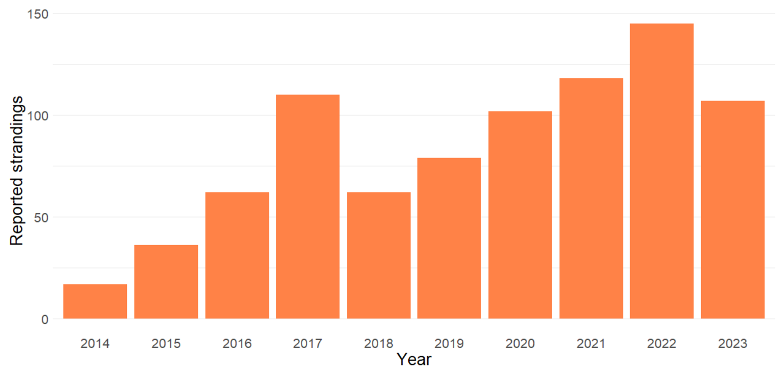

Figure 1. Annual counts of stranded individual harbour porpoises (*Phocoena phocoena*) reported in Sweden for the period of 2014–2023.

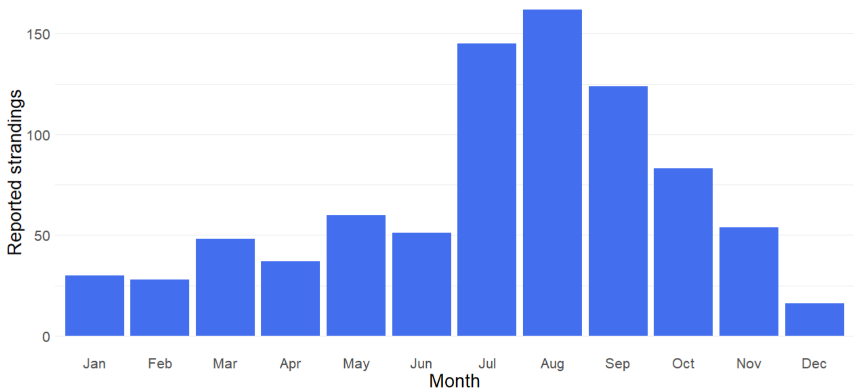

Figure 2. Monthly counts of stranded individual harbour porpoises (*Phocoena phocoena*) reported in Sweden across the period of 2014–2023.

3.2. Distribution of Total Strandings

Data sets for spatial analyses included reports of skeletal remains and contained 829 stranding reports with 854 individuals. Strandings were observed in 187 grids in total (N = 125 in 2014–2018 and N = 156 in 2019–2023), covering essentially the whole Swedish west and south coast. However, almost no strandings were reported on the East Coast, with the exception of a few strandings in the Simrishamn municipality between 2014 and 2018 and single findings in the Ronneby municipality and the western coast of Öland in the Mörbylånga municipality between 2019 and 2023 (Figure 3). Although generally increasing, strandings appear to be reasonably consistent spatially, with the highest stranding numbers occuring in southern Halland along the coastlines of Halmstad and Laholm, and in Scania along Öresund.

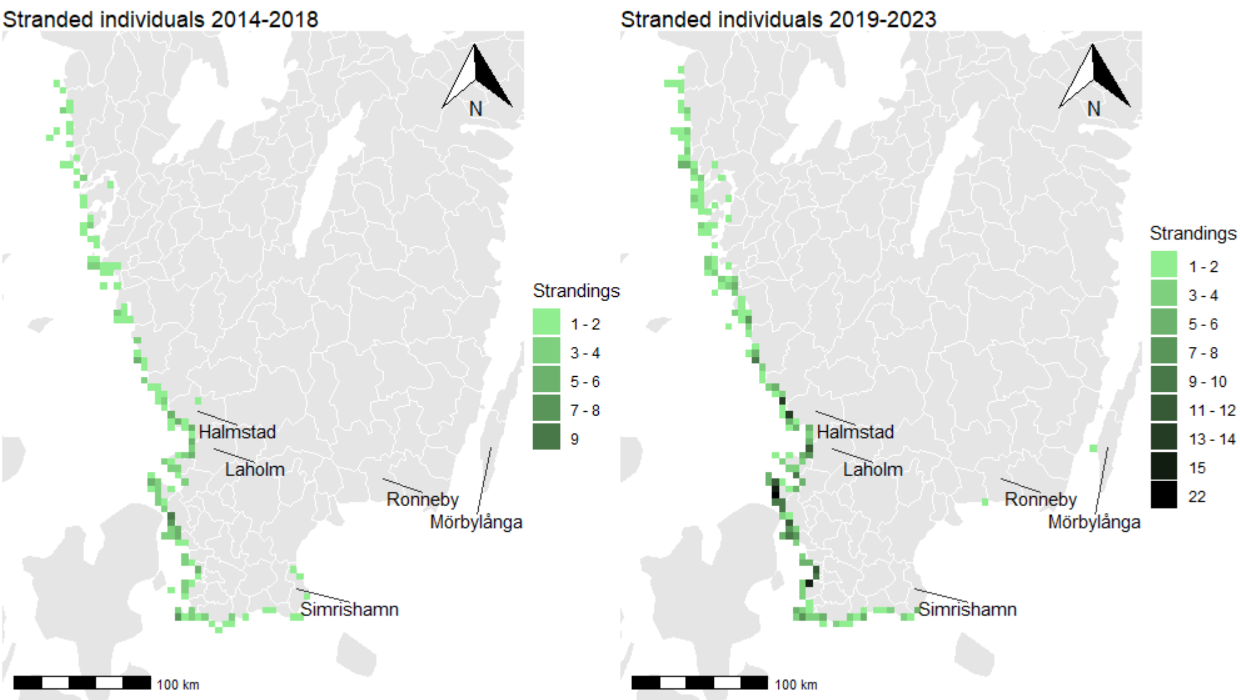

Figure 3. Grid map showing all reports of stranded harbour porpoises (*Phocoena phocoena*) in each grid cell over the two periods of 2014–2018 and 2019–2023. Darker grid cells indicate a higher abundance of stranded individuals.

3.3. Spatial Clusters and Cluster Persistence

Significant clustering was identified for 103 grids for the total period (N = 65 in 2014–2018 and N = 80 in 2019–2023). All identified clusters were grids containing high values surrounded by high values and, therefore, "hotspots". Stranded individuals in clusters (Figure 4) and cluster persistence, i.e., how many years a cluster appears during the period (Figure 5), appear to be very similar, with areas with high strandings being persistent as clusters over time.

Generally, the cluster distribution is similar for both 2014–2018 and 2019–2023, with the cluster appearance being denser in Öresund and southern Halland and gradually becoming more scarce further north, south, and east of these areas. In 2014–2018, no clusters appeared in more than three out of the five years. More persistent clusters (i.e., clusters appearing two to three times) appear around Öresund, especially the northern part along the coastline of the Höganäs municipality known as the Kullen peninsula, but also along the coastlines of the municipalities of Helsingborg, Landskrona, and the coastlines of the municipalities of Halmstad and Laholm in Halland. Clusters occurred more frequently in 2019–2023, with some clusters occurring all five years. Similar to the previous five years, the most persistent clusters are situated along the coasts of Höganäs, the Kullen peninsula, Helsingborg, and Landskrona, but even more distinctly than previously. Distinct clusters in Halmstad and Laholm also persist. Notably, the largest difference between the two periods is the appearance of persistent clusters along all of Lommabukten, north of Malmö.

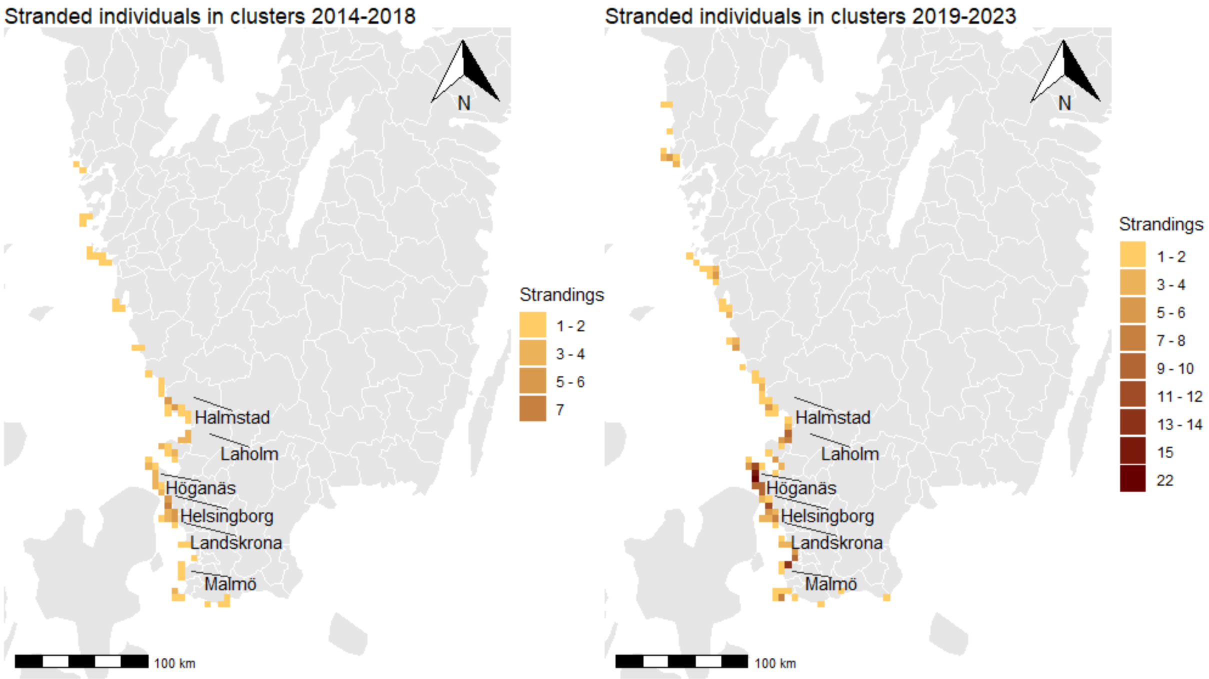

Figure 4. Grid cells with a significant clustering of harbour porpoise (*Phocoena phocoena*) stranding reports (hotspots) and the number of stranded harbour porpoises in each grid for each respective period. Only reports from years where the grid cell was identified as a cluster are included. Darker grid cells indicate higher numbers of strandings.

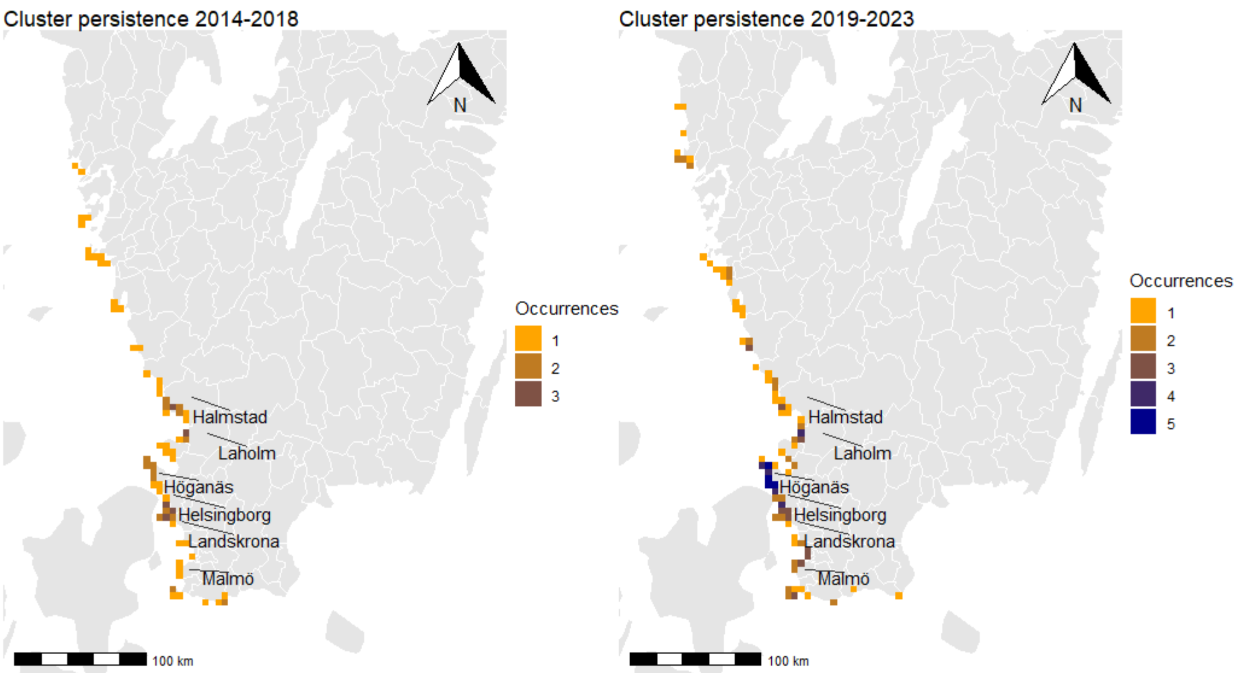

Figure 5. Grid cells with a significant clustering of harbour porpoise (*Phocoena phocoena*) stranding reports (hotspots) and the occurrence of each significant cluster across each respective period. Occurrences refer to the number of years each grid cell has been identified as a significant cluster for each period. Darker grid cells indicate more persistent clusters that occur more often.

3.4. Stranding Network Coverage

Median coverage increased between the two periods of 2014–2018 (Mdn = 0, $\overline{x}$ = 0.0679) and 2019–2023 (Mdn = 0.0839, $\overline{x}$ = 0.175) ($p < 0.001$). During both periods, several individuals located outside of grids identified as clusters were retrieved for necropsy. This includes areas, for both periods, far north on the West Coast and, for the later period, on the South Coast, as well as individuals east of Scania. Most areas in 2014–2018 had nearly zero coverage. Coverage increased in general during 2019–2023 and there were fewer areas with zero coverage. However, some distinct regions with nearly zero coverage remain. These are highlighted with red circles in Figure 6. These regions include the coast of Falkenberg, northern Halmstad, southern Gothenburg, and areas around Lommabukten. While efforts are made to enter all reports of known strandings into the database, two of the grid cells for 2019–2023 had more individuals retrieved for necropsies than there were stranded individuals recorded for that grid (2 in a grid cell of 1 and 3 in a grid cell of 2). These were set to have a coverage of 1.00.

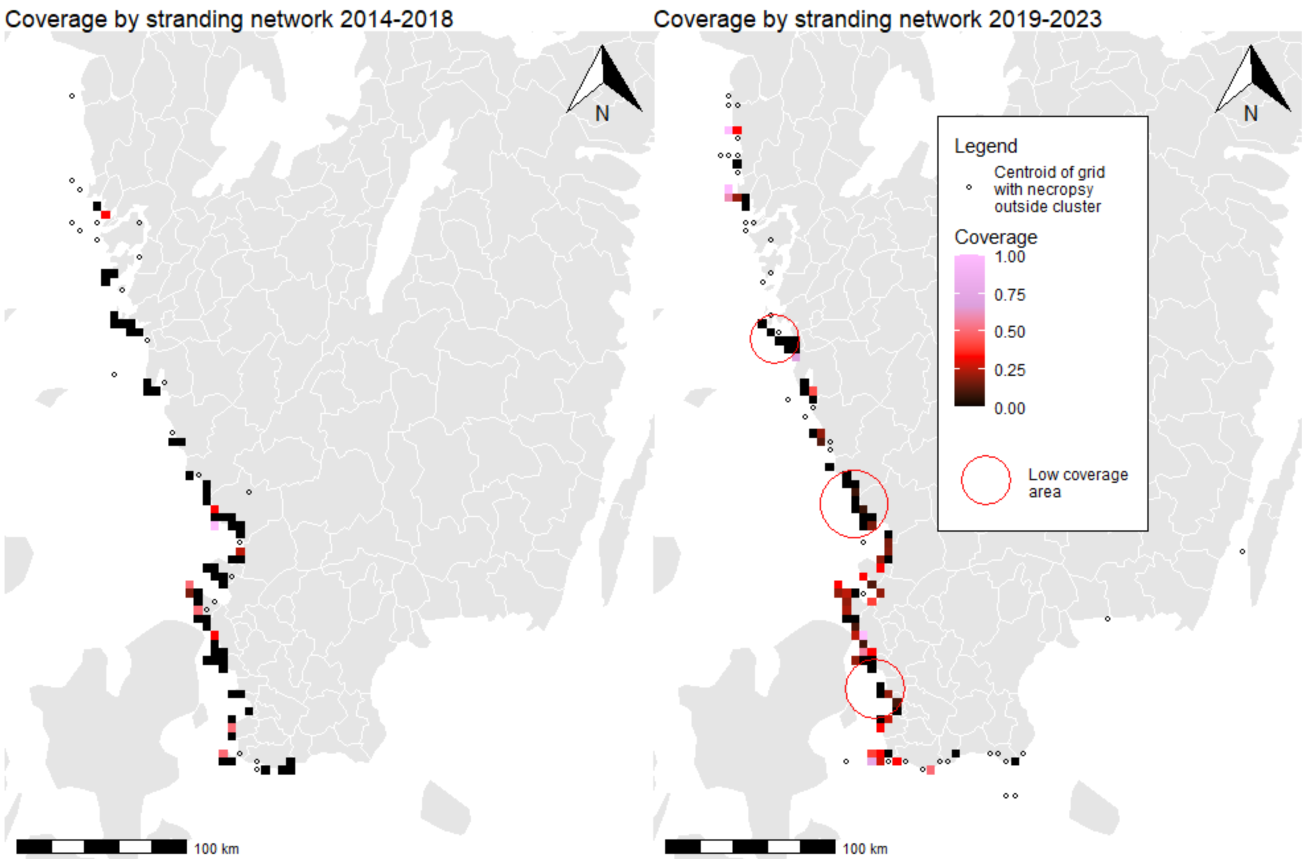

Figure 6. Grid cells with a significant clustering of harbour porpoise (*Phocoena phocoena*) stranding reports (hotspots) and the coverage by the stranding network is represented by the share of stranded individuals in that area retrieved for necropsy. Darker grid cells indicate lower coverage. Small black circles represent the centroids of grid cells not identified as hotspots where porpoises have been recovered for necropsy. Large red circles highlight larger areas with nearly zero coverage for the period of 2019 to 2023.

4. Discussion

Similar to other studies [22,32,46], stranding reports in Sweden have significantly increased over time (r = 0.853, d.f. = 8, $p = 0.002$) (Figure 1). The increasing trend in Sweden is very clear, with the exception of the uptick in stranding reports in 2017. Increased strandings, as suggested by McGovern [32], can be attributed to various factors; these include (1) an actual increase in strandings where population abundance has remained relatively static, (2) an increased porpoise abundance in the area, (3) an increased reporting effort, and (4) currents and weather conditions shifting. Increased strandings as a consequence of a higher porpoise abundance in the area is unlikely, considering that no increase in porpoise abundance has been identified by the SCANS-IV survey (2022) [7] when compared to the SCANS-III survey (2016) [10] in the North Sea or the Kattegat and Belt seas. In fact, the inverse is happening in the Belt Sea, where the estimates from the SCANS-IV survey of 14,403 and the estimates from miniSCANS-II of 17,301 [46] are alarmingly lower than the previous estimates of 42,324 from SCANS-III. Instead, these estimates support the possibility of (1) being true because a population decrease may be caused by a higher mortality and consequently lead to more porpoises stranding, provided the stranding probability of dead animals and the reporting effort remains relatively static. However, a population decrease can also be the result of a population shift away from the survey area or a decreased reproductive rate.

Interestingly, stranding rates spiked in 2017 and stand out when compared to earlier years and the year after, having almost twice as many strandings as 2016, and 2018. According to Gilles et al. [7], a decline in the porpoise abundance in the Belt Sea cannot be excluded, and a further analysis using a Bayesian approach is planned to investigate the status of the Belt Sea population. If these analyses suggest a significant population decline since 2016, it would be interesting to investigate whether or not stranding data regarding the Belt Sea population from Denmark and Germany also indicate stranding peaks in 2017. If so, we hypothesize that this year may have marked a year of unusually high mortality and warrants further investigation of the causes.

Although an actual increase in strandings may have contributed to an increase in reports over time, stranding reports are furthermore influenced by the reporting effort [47] and may have increased as a consequence of raised awareness. In 2021, a new health and disease surveillance program was officially launched, resulting in increased outreach efforts to raise awareness of the need for reporting strandings. This also coincided with the COVID-19 pandemic when people generally spent more time outdoors. Double reports of the same stranded animal have occurred more frequently since the start of 2021, supporting an increased awareness and effort from this time point, and this reinforces the reliability of the data from 2021 onwards. However, double reports were difficult to identify prior to 2020 because digital tools to easily identify double reports were not yet available. This makes it difficult to assess whether double reports actually have increased or whether new tools have facilitated distinguishing double reports. Despite this, the distinct jump in double reports since 2021 and the new digital infrastructure suggest that the effort should be comparable from 2021 and onwards. Under that assumption, strandings appear to be fairly consistent between 2021 and 2023. Whether or not shifting currents or weather conditions have affected strandings over time was beyond the scope of this study and requires further investigation.

Annually, strandings clearly peak in the months of July, August, and September, then gradually decrease to a minimum in December (Figure 2). Summer stranding peaks align with previous studies, both from neighbouring countries, and studies outside of Northern Europe. In German waters, peak strandings were recorded from June to August in the North Sea while they were delayed until July to September in the Baltic Sea [22]. Along the north-eastern coast of the North Sea and in Danish waters, multiple studies consistently also confirm the strong seasonality of strandings in summer [48–50]. Looking outside of Europe, strandings have also been found to peak within July to August in the Sea of Azov [51].

Seasonality in strandings is caused by the variation in the abundance, distribution, or mortality of animals and the non-biological components, oceanographic and effort factors, of the strandings process [33]. Calving season has been discovered to strongly correlate with stranding peaks, with high rates of calves, neonates, and yearlings stranding [22,51]. This is a particularly vulnerable time for neonates and calves that are inexperienced and still depend on their mothers. Mating occurs shortly after calving. Mean conception dates, estimated to be 25 July ± 20.3 days for the Kattegat and Skagerrak seas, and considerably later in the Baltic Sea at 18 August ± 11.8 days [52], strongly align with stranding peaks in those same areas from Siebert et al. [22] and also from this study. Additionally, summer is an energetically demanding period for adult females that are near parturition and/or lactating and a time of independent foraging for yearlings, possibly leading to risky foraging behaviour near gillnets for both groups [51]. Precarious foraging behaviour may not only lead to higher mortality among adult females, but also to their dependent, nursing calves, yielding more strandings in summer [51,53].

Strandings to some extent reflect the relative abundance of harbour porpoises in the surrounding waters and fluctuations in abundance contribute to seasonality in strandings [32,49]. Sveegard et al. [54,55] mapped the abundance of harbour porpoises in Danish waters and along the Swedish west coast using satellite tracking between 1997 and 2007 and acoustic surveys in 2007. They concluded that high-density areas are relatively stable over time and that both satellite tracking and acoustic surveys are powerful tools to monitor porpoise density. Satellite tracking showed porpoise densities to be highest near the Swedish west coast from March to April, while acoustic surveys showed higher abundances from July to August, partially supporting strandings' representativeness of the relative abundance of at-sea populations when compared to the stranding seasonality found in this study.

Lockyer and Kinze [48] suggest the possibility of the reporting effort in summer affecting the pattern of stranding reports, with more people moving around the coastline. While it is true that sightings of live porpoises, just like strandings, often peak in summer [22,48,56], there are also examples of sightings peaking earlier, in February, while the stranding peak remains in summer [50]. Furthermore, studies with a constant effort across years and months in German waters have shown evidence of stranding peaks occurring in summer [22], supporting the probability of these patterns being true increases in strandings, although the contribution of an increased reporting effort in the summer cannot be excluded. Additionally, stranded animals have a higher probability of being observed than sightings of live animals at sea because stranded animals are less mobile, suggesting strandings are a more accurate data source of species occurrence than sightings [32]. However, even though they are less mobile than living specimens, stranded individuals can move due to waves, winds, and currents, occasionally getting completely swept away from the original stranding location.

In accordance with abundance data, all discerned hotspots were located on the west and southern coasts (Figure 5), inhabited by the Belt Sea and North Sea populations [7]. Hotspots increased in both number and frequency in the second period when compared to the first one, aligning with there being more stranding reports in general and an increased reporting effort since 2021. Furthermore, the spatial distribution of hotspots is, in general, similar between the periods, indicating no significant population shifts during the study period. Additionally, when comparing Figures 4 and 5, stranding reports seem to reflect the hotspot occurrence for each respective period, indicating no or very few extreme stranding events have occurred.

Persistent hotspots appear in Öresund, especially in the areas around Kullen. Previous studies, using satellite and acoustic surveys, have pointed out Kullen as a key habitat for harbour porpoises and as the area most important to adult female porpoises in the waters around Scania. Porpoises aggregate around Kullen and central Öresund in the spring, summer, and fall, which overlaps with calving and mating periods [48,57]. Porpoises have also been found to follow specific prey species such as cod, herring, and gobies, with a high occurrence of cod in porpoise stomachs year-round. Cod appears to be an especially important food source in summer when larger cod (20–45 cm), which are known to constitute the majority of consumed cod, accumulate in Öresund [58,59]. Notably, fishing efforts by the Swedish and Danish commercial gillnet fleets are high in Öresund and around Kullen, with studies mapping gillnet fishing efforts in 2018 [18] and for the period of 2010–2020 [17]. The areas with the highest gillnet fishing efforts from these studies are very similar to the most frequently occurring stranding hotspots found in this study, especially when considering larger mesh sizes (≥120 mm), in which porpoises are known to more frequently getcaught. We demonstrate a clear association between harbour porpoise abundance, gillnet fisheries' effort, prey abundance, and stranded porpoises. However, to what extent each factor influences strandings is unclear.

Hotspot occurrence relies on stranded porpoises being reported. Naturally, the geography of the areas in which strandings occur can influence the extent of detection and, consequently, the reporting of stranded animals [47]. For example, the coastal landscape of Halland and Scania is, in general, flat, with numerous sandy beaches which are easily accessible. On the contrary, the coastal landscape around Gothenburg and further north consists of a rocky, sometimes inaccessible archipelago, often with steep cliffs. Therefore, the geography on the Swedish west coast might additionally influence the detection rate and reporting rate and would hypothetically influence rates on the northern half of the Swedish west coast negatively. Furthermore, the extent of oceanographic conditions' and weather conditions' effect on stranding frequency and location requires further research.

The increase in stranding network coverage is likely influenced by the establishment of an official health and disease surveillance program for harbour porpoises in Sweden in 2021. Starting in 2016, a limited number (10–15) of post-mortem examinations of stranded and bycaught porpoises were funded under the directive of the SwAM as part of Sweden's environmental monitoring [1]. Since the new health and disease surveillance program was launched in 2021, over 40 porpoises have been examined via necropsy per year [36]. Targeted outreach efforts have been made since 2021 to increase awareness of the need for reporting strandings. Furthermore, the stranding network has expanded since the establishment of the surveillance program to facilitate the recovery of stranded porpoises and is thereby contributing to more extensive coverage.

Many necropsied individuals were recovered from areas outside of clusters. This can be explained by the nature of the health and disease surveillance program. The recovery of carcasses is largely influenced by the geographical location of the contacts in the stranding network and the accessibility of the locations of stranded porpoises. Additionally, some porpoises are prioritized for retrieval for necropsy. Examples may include individuals from threatened populations, stranding anomalies in time and space, and recently deceased individuals, which yield post-mortem investigations of higher quality [60]. Targeted efforts to recover porpoises from the Baltic Sea Proper can be ascribed to the conservation status of the critically endangered Baltic subpopulation, giving it high surveillance priority. The Baltic subpopulation at times overlaps with the Belt Sea population around southeastern Scania, which helps explain the high recovery efforts in those areas despite a lack of clustering.

5. Conclusions

There has been an increasing trend in the stranding reports of harbour porpoises over the last 10 years in Sweden. The underlying causes cannot be determined with certainty, but the increasing trend can likely, in part, be attributed to the increased reporting efforts from the increased awareness due to outreach efforts and the launch of a new health and disease surveillance program in 2021. Porpoise abundance remains seemingly static for the North Sea population, while the Belt Sea population experienced a possible decrease which could help explain the increase in reported strandings. However, whether the increase in stranding reports marks an actual increase in morality requires further investigation.

Stranding patterns showed a significant seasonality, similar to other studies on harbour porpoise strandings in the same or surrounding areas [22,33,48,49], with most stranding reports occurring from July to September. Notably, the stranding reports' peak coincides with calving season for porpoises in the waters surrounding Sweden. Clustering exclusively occurs on the west and southern coast of Sweden, reflecting the relative porpoise abundance in the surrounding waters and remains relatively similar over the study period. Furthermore, Öresund, and especially the area around the Kullen peninsula, a suspected calving ground, displays a frequent clustering of porpoise strandings. The same area shows high abundances of porpoises, high prey abundance, and high fishing efforts with gillnets, providing support for the connection between porpoise abundance, prey abundance, gillnet fisheries' effort, and strandings. Further research is required to investigate the relative contributions of each factor to help inform appropriate management actions including limiting access to vulnerable areas at certain times. Public awareness campaigns are already in place to minimize the disturbance of porpoises in high-density areas such as around the Kullen peninsula and to encourage the reporting of stranded animals. Such initiatives could be expanded to other hotspots. The influence of weather and oceanographic variables such as currents on strandings also needs further investigation.

We also conclude that coverage has increased from the first period of 2014–2018 to the second period of 2019–2023. However, some larger areas with significant clustering still lack coverage, including the coast of Falkenberg, southern Gothenburg, northern Halmstad, and certain areas around Lommabukten. Extending the stranding network through targeted outreach efforts to cover these gaps will facilitate the retrieval of stranded animals and will result in post-mortem examinations of higher quality to maximize insights into the health status of the population, possible threats, and causes of mortality to inform management. Furthermore, outreach efforts appear to have a positive effect on reporting rates and the quality of data has increased in recent years. Further improvements on the reporting forms, such as accurate carcass measurement tools and detailed pictures, would facilitate determining the age class, degree of decomposition, and identifying bycatch marks, yielding important information for the management of Swedish harbour porpoise populations and potentially identify areas of ecological importance, such as calving grounds, and areas of conflict between wildlife and human activity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/oceans5020010/s1, Datafile S1: Dataset of harbour porpoise (*Phocoena phocoena*) strandings in Sweden 2014–2023.

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