An increase in detection rates of the critically endangered Baltic Proper harbor porpoise in Swedish waters in recent years

Kylie Owen1 | Martin Sköld1,2 | Julia Carlström1

1Department of Environmental Research and Monitoring, Swedish Museum of Natural History, Stockholm, Sweden
2Department of Mathematics, Stockholm University, Stockholm, Sweden

Abstract
The Baltic Proper harbor porpoise (*Phocoena phocoena*) is currently listed as critically endangered (CR), with the Static Acoustic Monitoring of the Baltic Sea Harbor Porpoise (SAMBAH) project concluding that only ~500 individuals remain. This population has a distribution that spans the waters of nine countries, making regular abundance estimates and management action challenging. Given the continued decline of other depleted porpoises, namely the vaquita (*Phocoena sinus*), the question is often raised about whether management action would even have a positive impact, or whether it is too late for population recovery. When abundance estimates are sparse over time, monitoring programs at key sites are likely to serve as the best indication of population trends, and may provide an early indication of changes at the population level. We compared passive acoustic monitoring data from 12 stations that were utilized both in the SAMBAH project (2011–2013) and as a part of the Swedish National Monitoring Program (2017–2020) to determine trends in detection rates. There was a 29% increase in mean daily detection rate during May–October (over the breeding season) between the two study periods. At the three stations with the highest number of detections, log linear regression revealed a yearly increase of 2.4% between 2011 and 2019 (4.4–9.6, 95% CI). This may be indicative of the beginnings of population recovery, or simply an indication that the decline has stalled. The rate of increase is still well below what is likely to be possible for porpoise populations, and unlikely to buffer against any potential increase in pressures in the future. We therefore call for urgent management action to remove threats and protect this CR population, the only resident cetacean in the Baltic region, in order to give it the best chance of recovery.

Keywords
 cetacean, conservation, C-POD, passive acoustic monitoring, population dynamics
1 | INTRODUCTION

The harbor porpoise is the only resident species of cetacean in the Baltic region. Historically, porpoises were once numerous and more widely distributed in the Baltic Proper (Koschinski, 2001; Lindroth, 1962; Skóra & Kuklik, 2003), but a wide range of threats have led to a dramatic reduction in abundance over the past century (Koschinski, 2001). Genetic and morphometric studies have both concluded that porpoises in the Baltic Proper are distinct from those in the Kattegat, Skagerrak, and North Sea (Galatius, Kinze, & Teilmann, 2012; Lah et al., 2016; Wiemann et al., 2010).

The first and only assessment of the abundance of the Baltic Proper harbor porpoise population occurred between 2011 and 2013, when the Static Acoustic Monitoring of the Baltic Sea Harbor Porpoise (SAMBAH) project estimated that there were only 497 individuals (80–1,091, 95% CI) remaining (SAMBAH, 2016). The Baltic Proper harbor porpoise is currently classified as critically endangered (CR) by both the International Union for Conservation of Nature (IUCN) and the Helsinki Commission (HELCOM) (Hammond et al., 2008; HELCOM, 2013). The species is also listed in Annex IV of the EU Habitats Directive (Council Directive 92/43/EEC, European Commission (1992)), implying that a strict protection regime must be in place across their entire distributional range. Despite this, for three consecutive assessment periods (2007, 2013, and 2019) under Article 17 reporting for the Habitats Directive, all relevant EU Member State assessments and the EU biogeographical assessment have classified the conservation status of the Baltic Proper Harbor porpoise as “unfavorable-bad.” Due to the small population size, there are limited data available on key biological and ecological factors affecting the population. This includes a lack of regular abundance estimates, and information on the extent to which the population is exposed to threats. Consequently, there is a high level of uncertainty on population trends and the future viability of the population.

There are many threats to the Baltic Proper harbor porpoise, with bycatch, contaminants and loud impulsive underwater noise sources classified as “high” threats based on evidence or strong likelihood of an impact on individual mortality, health and/or reproduction, likely leading to negative population effects (ICES, 2019). Further, threats such as prey depletion, shipping noise, and habitat degradation have been classified as “medium.” For 10 of the 13 species, subspecies and populations ("units") of small cetaceans listed as CR on the IUCN Red List (including the Baltic Proper harbor porpoise), bycatch is the main threat (Brownell et al., 2019). In the Baltic Proper, 97% or more of the harbor porpoise bycatch has been reported to occur in gillnets (Berggren, 1994; EC-DGMARE, 2014; Skóra & Kuklik, 2003). The limit of allowable human-caused mortality for the Baltic Proper population has been estimated to be 0.7 animals per year (North Atlantic Marine Mammal Commission & Norwegian Institute of Marine Research, 2019) based on the potential biological removal (PBR) approach (Wade, 1998). A bycatch rate close to zero can only be reached by closing all gillnet fisheries within the distribution range of the Baltic Proper harbor porpoise, as pingers do not completely remove the threat of bycatch (Dawson, Northridge, Waples, & Read, 2013; Larsen & Eigaard, 2014; Palka, Rossman, VanAtten, & Orphanides, 2008). In May 2020, ICES released Emergency Measures advice, recommending spatial–temporal closures of fisheries throughout many Natura 2000 sites within the distributional range of the population, and obligatory use of pingers on all static nets (ICES, 2020a). This advice is still currently being considered by the EU and member states.

Unlike other severely depleted species (e.g., vaquita) or populations of harbor porpoises (e.g., U.S. Morro Bay stock) that are able to be managed by the legislation set by one country, the Baltic Proper harbor porpoise has a distribution that spans nine countries. This issue makes regular distribution-wide surveys logistically and politically challenging, increasing the importance of local monitoring programs on the population. Such programs enable investigations of changes in detection rates that could be an early indication of changes in abundance. The SAMBAH project revealed that, during May–October, most detections occurred in Swedish waters (Carlén et al., 2018), suggesting that this region is important for the population over the breeding season. Based on the results of SAMBAH, a new Natura 2000 site was designated specifically for porpoises in Sweden that is the largest Natura 2000 site in the Baltic Sea (area of over 1 million hectares). The Baltic Proper harbor porpoise was also placed onto the Swedish National Red list as CR in 2020 (SLU Artdatabanken, 2020).

In 2017, the Swedish National Monitoring Program (SNMP) for porpoises began in the Baltic Sea. This program was designed to utilize 12 of the stations from the SAMBAH project, in order to facilitate a comparison of detection rates over time. The aim of this study was to determine whether there has been a change in the detection rate of Baltic Proper harbor porpoises in Swedish waters over the past decade that could be indicative of higher-level changes occurring within the population.

2 | METHODS

2.1 | Acoustic data collection and processing

The C-POD was used as the passive acoustic data collection instrument. This device contains an omni-directional...
hydrophone that records the timing of zero-crossings (accuracy to 200 ns) and the peak amplitude between zero crossings (Tregenza, Dawson, Rayment, & Verfuss, 2016). These data are then used to identify the narrow-band high-frequency (NBHF) clicks of harbor porpoises (Au, Kastelein, Rippe, & Schooneman, 1999; Macaulay, Malinka, Gillespie, & Madsen, 2020; Villadsgaard, Wahlberg, & Tougaard, 2007). Data were collected from 12 stations (average depth 44 m, range 29.0–60.0 m) that were used both as a part of the SAMBAH project (April 2011–July 2013) and the SNMP (April 2017–March 2020) (Figure 1). C-PODs were anchored with the hydrophone approximately 2 m off the bottom, and the loggers were serviced every 3–6 months for battery and SD card changes, and functionality tests. A different C-POD was deployed at the station each time for logistical reasons, and to facilitate removal of systematic bias that could be caused by different sensitivities of the individual C-PODs.

All files downloaded from the C-PODs (including both the SAMBAH and SNMP data) were cut at midnight after deployment, and midnight prior to retrieval. Custom software (CPOD.exe, v. 2.044, https://www.chelonia.co.uk/) was used to process the data. The average and variance of the instantaneous frequency, click duration, peak amplitude, and two measures of the click envelope were saved for each click. The KERNO classifier was then used to identify click trains and label them as either porpoise (NBHF), other cetacean, boat sonar, or unclassified. A second classifier specifically developed for the Baltic Sea marine region (Hel1, Tregenza, 2014) was also applied to the data to reduce the false positive rate, by removing click trains falsely identified as originating from a porpoise. When the number of detection positive minutes was below 60 a year, the file was visually validated to ensure that there were no false detections.

### 2.2 Potential sources of bias

Diel patterns have been shown in the vocal behavior of harbor porpoises (Carlström, 2005; Osiecka, Jones, & Wahlberg, 2020; Todd, Pearse, Tregenza, Lepper, & Todd, 2009). As there is a theoretical possibility of changes in vocal behavior over time in response to changes in prey availability or quality, we analyzed a range of acoustic metrics to minimize the risk of the results being influenced by behavioral changes over time. The analyzed metrics were: number of encounters, number of clicks, detection positive seconds (DPS) (all presented in Appendix S1), and detection positive hours (DPH) (presented in results) in a day.
Given the extremely low sighting rate, it is not possible to tag Baltic Proper harbor porpoises to collect data on vocal rate over time. However, the use of a range of acoustic metrics (number of encounters, number of clicks, DPS, and DPH, in a day), and ensuring that the results are consistent over these metrics, should minimize the influence of both changes in the acoustic behavior of the animals and diel patterns in the vocal behavior of porpoises over time. Given the low detection rate of Baltic Proper harbor porpoises (max detection of 11 DPH per day), saturation with detections did not influence the results.

There were gaps in data collection over time (due to equipment failure, delayed battery changes due to inclement weather, and unexpected loss of equipment [i.e., being caught in trawl gear]) resulting in varying effort at each of the stations. Based on the results of the SAMBAH study, the Baltic Proper population is thought to congregate into a major cluster during May–October, which is when breeding takes place. During November to April the population has a more dispersed distribution pattern (Carlén et al., 2018). To account for the varying effort and seasonality, missing data were imputed using a seasonal model fitted separately for each station and only detections over the breeding season were used to calculate a yearly population index (see Section 2.2). Regression imputation with a generalized additive model (Wood, 2011) was used, assuming that the number of DPH (or number of encounters, number of clicks, DPS; analysis was repeated for each of the acoustic metrics investigated, see Appendix S1) per day $n_{jy}$ on Julian day $j$ in year $y$ follow a Poisson-distribution with mean $\lambda_{jy} = \exp(s(j) + b_y)$. Here $s(j)$ defines a cyclical spline function, such that $s(0) = s(365)$, which describes the seasonal pattern common to all years, and $b_y$ is a fixed yearly effect. The model was fit in R (R Core Team, 2020) with the mgcv package using default options for automatic selection of basis dimension, providing estimates $\hat{\lambda}_{jy}$ that were used to impute missing counts. Further details of the model fitting can be found in the Supporting Information. The proportion of missing days for each station and year is presented in Table S1.

Temperature affects sound propagation in seawater, so the temperature recorded by the C-PODs was examined over the years. Since temperature varies greatly seasonally, and the porpoise data were examined during May–October, the temperature data were examined over the same time period. An equation that calculates how the absorption of sound (dB/km) is influenced by various acoustic (frequency) and environmental (temperature, salinity, depth, acidity) factors from a previous study (Ainslie & McColm, 1998) was used to investigate the potential effect of temperature changes over the years on the detection rate. To do this, we assumed a frequency of 130 kHz (based on the likely frequency of harbor porpoise signals (Macaulay et al., 2020; Villadsgaard et al., 2007)), salinity of 8 ppt (given the brackish waters of the Baltic Sea), depth of 44 m (average depth of the C-PODs), and acidity of 8 pH.

The Baltic Sea does not have any significant tides (a few centimeters) due the small opening to the North Sea, therefore this factor was not considered a potential source of bias. Additionally, characteristics of the station, such as depth and bottom type may influence detection. However, as the same 12 stations were used over time, and trends were examined at each station, it is unlikely that these factors influenced the detection rates recorded over time.

### 2.3 Temporal trend analysis

In order to investigate how the detection rate of harbor porpoises changed over the years (2011–2019), data from three stations (1032; 1036; and 1041) with 90% of the DPH in this study (across both SAMBAH and SNPMP) were selected, as they are also located in an area of high density for this population during May–October when breeding takes place (Northern Midsea Bank, Figure 1) (Carlén et al., 2018). The selection of these stations also ensured that the detections were likely to be for animals from the Baltic Proper population, as stations closer to the proposed May–October management border further to the west (Carlén et al., 2018) are more likely to contain detections that could be from the neighboring Belt Sea population. Using only the data from May to October, a yearly population index was defined as $\mu_y$, the arithmetic mean of (possibly partially imputed- see Section 2.2) counts, a measure of the average number of DPH per day. In order to investigate trends over time, log-linear regressions were fitted to yearly indices for each of the three stations. Only five complete years of data were collected over the course of the two studies (SAMBAH 2011, 2012; SNPMP 2017, 2018, 2019). For the purposes of this study, data were assumed to meet model assumptions (e.g., normality), even though it was not possible to test with five data points.

### 2.4 Indicators of population trends in abundance

Under EU legislation (European Commission 1992, 2008), all countries with harbor porpoises in their waters are required to set regional or sub-regional indicator thresholds that provide information on whether the species has achieved good environmental status for abundance. For the North Sea population of harbor porpoises and other cetacean populations within the OSPAR
region, OSPAR has proposed a threshold for trends in abundance, set as a 5% change over 10 years (significance level $\alpha < .05$) (CEMP, 2019). An abundance indicator is still currently in development for the Baltic Proper population of harbor porpoises within HELCOM. However, we calculated the power to detect a 5% change over 10 years in the Baltic Proper data (using detection rates, not abundance data) at these Swedish stations. These stations represent the area with the highest detection rates in the May–October distribution range of the Baltic Proper population (Carlén et al., 2018), and are therefore, most likely to be able to detect a change. We also calculated the number of years required to have 80% power to detect a 5% change in this region, as this information may be useful for further indicator development. Although our calculations are based on detection rates (not abundance estimates) it is likely that detection rates will need to be utilized as an index of abundance to be used as an indicator for this population within HELCOM over the next two to three EU reporting cycles, and repeatedly also after that. This is due to the fact that obtaining enough updated estimates of absolute abundance for this population to estimate a trend is still likely to be decades away (assuming one abundance estimate every 10–12 years), and even longer before such surveys can be carried out once per six-year reporting cycle.

3 | RESULTS

3.1 | Detection of harbor porpoises

A total of 444 detection positive days (DPD) were recorded as a part of the SAMBAH study over 6,422 days of recording (6.9% of days, mean of 0.157 DPH per day) (Table 1). In comparison, 737 DPD were recorded over 8,117 days during the SNMP (9.1% of days, mean of 0.188 DPH per day) (Table 1). While there were large differences between the detection rates of each station (Table 1, Figure 2), the distribution pattern of detections did not vary greatly between stations across both studies (Figure 2). During both studies, the highest detection rates were recorded in May–October (Figure 3), validating the decision to only use these months, when examining yearly trends (below). Additionally, the May–October peak appeared to be bimodal in distribution at the stations with the most detections (Figure 3).

3.2 | Potential sources of bias

The mean water temperature at the stations increased slightly over the years, ranging from $0.9 \pm 1.2^\circ\text{C}$ in 2011 to $3.7 \pm 1.9^\circ\text{C}$ in 2019, a total change of $2.8^\circ\text{C}$. This change likely resulted in an increase in absorption of $0.2 \text{ dB/km}$ ($12.8 \text{ dB/km}$ at $0.9^\circ\text{C}$ vs. $13.0 \text{ dB/km}$ at $3.7^\circ\text{C}$; equation from Ainslie & McColm, 1998). With a maximum detection range of 400 m (https://www.chelonias.co.uk), and an effective detection radius well below 100 m, this change in temperature is likely to have had a negligible effect on absorption, and the detection rate of porpoises over time. Even if there was an effect, an increase in absorption over time is likely to have resulted in a decrease in detections of porpoises over time.

3.3 | Temporal trend analysis

The mean DPH per day sampled (DPH/day) across the full year was 20% higher during the SNMP compared to SAMBAH, and nine of the 12 stations had higher detection rates (75% of stations, one station had no change, the remaining two showed a decline—these stations also had exceptionally low detection rates) (Table 1). When only considering May–October, mean DPH per day was 29% higher, and 10 of the 12 stations (83%) had higher detection rate (one no change, one showed a decline) (Table 1).

For three stations (1032; 1036; and 1041), there were enough detections over the course of both studies to estimate a yearly index for all 5 years of May–October data collection. At these stations, the combined trend was a yearly increase in detection rate of 2.4% (95% CI: $-4.4, 9.6$) (Figure 4, Table 2). The station with the most detections (1036) appeared the most stable, with only a 0.6% (95% CI: $-7.3, 9.2$) increase. In comparison, the other two stations (1041 and 1032) showed a much higher yearly increase of 12.6% (95% CI: $-4.2, 32$) and 15.9% (95% CI: $0.3, 34$), respectively (Figure 4, Table 2). Note that the common signs of trends at separate stations may be an effect of spatial correlation in data; hence, they may not be interpreted as fully independent evidence of increase. It is further worth noting, that in the overall trend, and for some of the stations, the 95% CI also includes a negative growth, indicating that a continued decline is still possible. However, given the 29% increase in detection rates between SAMBAH and the SNMP, we feel that the results are more indicative of either a stall in the decline or a possible increase in detection rates. Additionally, the pattern in % of detections attributed to each station was similar across the two study periods (Figure 5). Regardless of which acoustic metric was selected (the number of encounters, the number of clicks, DPS, and DPH), the trend of increasing detections over time was observed (see Appendix S1).
| Station | Full data | May–October |
|---------|-----------|-------------|
|         | Days recorded | DPD | Daily mean DPH | Change DPH (%) | Days recorded | DPD | Daily mean DPH | Change DPH (%) |
|         | SAMBAH | SNMP | SAMBAH | SNMP | SAMBAH | SNMP | SAMBAH | SNMP | SAMBAH | SNMP | SAMBAH | SNMP | SAMBAH | SNMP |
| 1014    | 732    | 943   | 11     | 28    | 0.015 | 0.036 | 140   | 415   | 466   | 4     | 21    | 0.010 | 0.056 | 479   |
| 1019    | 486    | 708   | 10     | 33    | 0.023 | 0.066 | 193   | 336   | 366   | 0     | 24    | 0.000 | 0.085 | NA    |
| 1020    | 497    | 942   | 9      | 17    | 0.020 | 0.020 | 0     | 284   | 504   | 2     | 6     | 0.007 | 0.012 | 69    |
| 1021    | 232    | 172   | 5      | 1     | 0.030 | 0.006 | 81    | 147   | 154   | 4     | 1     | 0.041 | 0.006 | 479   |
| 1024    | 567    | 296   | 2      | 1     | 0.004 | 0.003 | 4     | 266   | 254   | 0     | 0     | 0.000 | 0.000 | NA    |
| 1025    | 634    | 686   | 7      | 8     | 0.013 | 0.015 | 16    | 356   | 435   | 2     | 5     | 0.008 | 0.014 | 64    |
| 1026    | 293    | 666   | 3      | 18    | 0.010 | 0.039 | 281   | 234   | 465   | 3     | 14    | 0.013 | 0.045 | 252   |
| 1029    | 272    | 345   | 7      | 14    | 0.033 | 0.061 | 84    | 272   | 183   | 7     | 10    | 0.033 | 0.087 | 164   |
| 1031    | 682    | 1,015 | 4      | 19    | 0.006 | 0.020 | 226   | 377   | 527   | 0     | 7     | 0.000 | 0.013 | NA    |
| 1032    | 733    | 858   | 21     | 50    | 0.030 | 0.070 | 133   | 420   | 493   | 14    | 39    | 0.036 | 0.097 | 173   |
| 1036    | 629    | 768   | 304    | 404   | 1.332 | 1.402 | 5     | 359   | 464   | 236   | 337   | 1.855 | 1.950 | 5     |
| 1041    | 665    | 718   | 61     | 144   | 0.123 | 0.294 | 138   | 353   | 438   | 56    | 132   | 0.212 | 0.438 | 106   |
| All stations | 6,422 | 8,117 | 444    | 737   | 0.157 | 0.188 | 20    | 3,819 | 4,749 | 328   | 596   | 0.205 | 0.265 | 29    |

Abbreviations: DPD, detection positive days; DPH, detection positive hours; SAMBAH, Static Acoustic Monitoring of the Baltic Sea Harbor Porpoise; SNMP, Swedish National Monitoring Program.
3.4 | Indicators of population trends

The power to detect a 5% change in detection rates was highest at the station with the most detections (1036, 73%), yet for the other two stations, the power to detect a change was much lower (Table 2). It is estimated that in order to have 80% power to detect a 5% change at each of these stations, between 11 and 17 years of data are required (Table 2). When combing data from all stations the number of years to detect a change reduces to 10 (Table 2).

4 | DISCUSSION

We show that the detection rate of harbor porpoises in the Baltic Proper appears to have increased over the last decade in Swedish waters, though evidence of a persisting trend is still weak. Changes in factors such as prey quality or schooling behavior could have influenced the acoustic behavior of porpoises over time. However, the consistent results across all acoustic metrics suggest that the increase is likely the result of more individuals in the area, rather than changes in acoustic behavior.
Additionally, the slight increase in absorption due to temperature changes over time is likely to have resulted in a decrease in detections of porpoises over time, not an increase, so this is also unlikely to have caused the observed increase in detection rates. It is also possible that a change in the vertical distribution of sound speed may have influenced the detection rates; however, we feel that this is unlikely to have resulted in the magnitude of increase observed. Therefore, it is likely that the increase in detection rate may indicate a stall in population decline, or the beginnings of population recovery for the Baltic Proper harbor porpoise.

The area monitored in this study represents the area with the highest detection rates during the SAMBAH project (Carlén et al., 2018). The increase in detection rates could indicate a shift in distribution over time, yet the pattern of detections across the stations was relatively stable in both studies (Figure 2, Figure 5). While the proportion of detections at station 1036 has decreased slightly, the number of detections at this station still increased, indicating that there is likely more animals in the area rather than just the same number of animals spreading out. Movement of individuals from the neighboring Belt Sea population into new areas in the Baltic Sea could also explain the increase in detection rates. However, this is unlikely given that we examined the detection rates during May–October when the distributional range of these two populations is thought to be separated (Carlén et al., 2018). Additionally, a potential increase in detection rates has also been observed in recent years in other parts of the Baltic, including Poland (Swistun et al., 2019) and Denmark (Sveegaard, 2020), suggesting that this increase may also be occurring throughout the distributional range of the population. This provides strong support for the need for a new population-wide abundance estimate, in order to confirm

**TABLE 2** The estimated yearly trends (%) with 95% confidence intervals of harbor porpoise (*Phocoena phocoena*) detections at three stations during May–October between 2011 and 2019 in the Baltic Sea. The estimated power to detect a 5% yearly change over 10 years at a significance level of 0.05 with a lower 95% confidence bound, and the number of years required to achieve 80% power to detect a change in detection rate are also shown for each station. The yearly trend and power estimations are also calculated as a summary across all three stations

| Station | Yearly trend % | Power to detect trend based on 10 years data | Years required for 80% power |
|---------|----------------|---------------------------------------------|-----------------------------|
|         |                | −5%  | 5%                          | −5%  | 5%                          |
| 1032    | 15.9 (0.29, 34) | 0.36 (0.11) | 0.34 (0.11) | 16   | 16                          |
| 1036    | 0.6 (−7.3, 9.2) | 0.73 (0.19) | 0.69 (0.18) | 11   | 11                          |
| 1041    | 12.6 (−4.2, 32) | 0.31 (0.11) | 0.29 (0.1)  | 17   | 17                          |
| 1032 + 1041 + 1036 | 2.4 (−4.4, 9.6) | 0.86 (0.24) | 0.82 (0.22) | 10   | 10                          |

![Figure 4](image-url) Yearly indices with log-linear fitted regression lines (solid line) of harbor porpoise (*Phocoena phocoena*) detections for three passive acoustic monitoring stations in the Baltic Sea, and an overall yearly index combining these three stations. Note the differing scale of the y-axes between panels, as the detection rate varied greatly among stations. Grey bars indicate 95% confidence intervals.
whether we are beginning to see the start of a recovery of this population. The low power to detect changes over time supports the need for continuous monitoring programs, so that any potential changes in abundance is detected.

Although detection rates increased over time, the rate of increase (2.4%) is still very low relative to what is likely possible for porpoise populations in the absence of threats. The annual rate of increase for the Morro Bay stock of harbor porpoises has been estimated to 9.6% (95% credible interval [CI] 6.2–13.0%) for the years 1991–2012, after bycatch was mostly eliminated (Forney, Moore, Barlow, Carretta, & Benson, 2020). Additionally, management using the PBR method assumes a possible annual increase rate of 4% across all cetacean species (Punt et al., 2020; Wade, 1998). In the absence of any additional anthropogenic stressors above the current baseline, the Baltic Proper population of harbor porpoises has been estimated to be capable of an annual growth rate of 2.3% (SD 6.4%) (Cervin, Harkonen, & Harding, 2020); similar to the rate observed in this study. Therefore, to enable recovery rates more in line with what porpoise populations are capable of, further removal of anthropogenic threats is required to ensure population recovery, and that the population achieves good environmental status in the future.

It is unknown what may have driven an increase in detection rates over time. Of the threats classified as “high” for the Baltic Proper harbor porpoise (ICES, 2019), a reduction in bycatch risk is most likely to be the most significant factor as it would directly influence mortality rate of the population. Between 2009 and 2018, gillnet fishing reduced by 45% over the entire Baltic Sea (ICES subdivision 24–32; ICES, 2020b), which may have simultaneously lowered the bycatch risk. However, it should be noted that most of the fishing activity takes place outside the seasonal management range of the Baltic Proper population (ICES, 2020b), implying that the extent of reduction within the seasonal distribution range may be different. The true rates of bycatch over the last decade are unknown and poorly reported. Since 2005, pinger use in the Baltic Sea has been regulated by Council regulation (EC) 812/2004 (until 2019), followed by regulation (EU) 2019/1241. Both regulations specify the same two areas in which pingers are mandatory for gillnetters larger than 12 m. In practice, these specifications have no impact on the harbor porpoise bycatch rate as all or almost all gillnetters in the areas are smaller than 12 m. More thorough and dedicated monitoring, and mandatory reporting of bycatch in this region is required.

The increase in detection rates is less likely to be explained by changes in the other high threats, that is, pollution and loud impulsive noise sources (ICES, 2019). Pollution with contaminants has caused reduced reproductive success in Baltic Sea animals (Sonne et al., 2020), and in harbor porpoise populations (Murphy et al., 2015). However, while contaminant levels of harbor porpoises in the Baltic Proper region were historically high (Berggren et al., 1999; Kannan, Falandysz, Tanabe, & Tatsukawa, 1993), current contaminant levels are unknown. The trends of polychlorinated biphenyl (PCB) concentrations in Baltic biota vary, but are overall decreasing since early 2000 (Nyberg et al., 2015). However, they still remain higher than in for example the North Sea, and PCB concentrations in Baltic Sea sediments appear to be at or near steady-state (Sobek, Sundqvist, Assefa, & Wiberg, 2015).
This low level of reduction is likely to have limited influence on a top predator within one generation length (estimated to 11.9 years for the species under predisturbed conditions for a stable population, Taylor, Chivers, Larese, & Perrin, 2007). The data on loud impulsive noise sources during the last decade in the Baltic Sea is incomplete (ICES, 2021), but the pressure is likely rapidly increasing due to a raising interest in offshore wind power (4 C Offshore, 2021).

The impact of changes in prey availability is difficult to assess, as there is lack of information on the current diet of the Baltic Proper population. Most knowledge is based on historic stomach content analyses, that indicate that the diet is likely to be highly variable (Koschinski, 2001) and different to that of other populations (Benke & Siebert, 1996; Lindroth, 1962). The collection of any specimens of potential Baltic Proper harbor porpoise is essential to assess contaminant loads, diet, and cause of mortality in order to fully understand which factors may be influencing population dynamics.

The Baltic Proper population is thought to congregate on the Northern Midsea Bank (NMB) (Figure 1) during the summer to breed (Carlén et al., 2018). For the Belt and North Sea populations in Danish and Swedish waters, calving peaks in June and mating occurs in late July or August (Börjesson & Read, 2003; Sørensen & Kinze, 1994). The bimodal peaks observed on the NMB in this study (May followed by September/October) may provide some preliminary insight into the breeding behavior of this population, with calving occurring at the first peak (females with calves are thought to communicate the most (Sørensen et al., 2018)) and the second peak indicating the arrival of males for mating. However, the timing is inconsistent with neighboring populations, so further research is required to understand what caused the bimodal peaks in detection.

Similar to the Baltic Proper harbor porpoise population, the vaquita (Phocoena sinus) is a porpoise species that is CR (Rojas-Bracho & Taylor, 2017) and is threatened by gillnetting (mostly illegal gillnetting in the case of the vaquita) (Jaramillo-Legorreta et al., 2017; Taylor et al., 2017). In 1997, the population size was similar to the Baltic Proper population (567 individuals [95% CI 177–1,073], Jaramillo-Legorreta, Rojas-Bracho, & Gerrodette, 1999) but this was followed by a steady annual decline (Gerrodette et al., 2011; Jaramillo-Legorreta et al., 2017; Taylor et al., 2017) resulting in fewer than 19 vaquitas remaining by 2018 (Jaramillo-Legorreta et al., 2019). This decline was despite several conservation efforts aimed at removing the threat of bycatch (Rojas-Bracho & Reeves, 2013), including an emergency gillnet ban that cost $74 million USD to compensate fishers (Jaramillo-Legorreta et al., 2019), and an emergency rescue effort to attempt to place two vaquitas in captivity, involving 90 experts from nine countries at a cost of $5 million USD (Rojas-Bracho et al., 2019). The continuing decline was likely the result ineffective management that was too late to reverse the decline, a lack of monitoring and compliance in the designated protection areas (Rojas-Bracho & Reeves, 2013), and illegal fishing remaining an ongoing problem (Jaramillo-Legorretta et al., 2017, 2019).

In contrast, the Morro Bay stock of harbor porpoises in central California demonstrates a more hopeful example of population recovery. This population had declined in abundance; likely due to bycatch in gillnets (Forney, 1995). In order to reduce this threat, various conservation measures were put in place, including regulatory action on the use of pingers, depths of fishing, and large time-area closures to fishing activities (Barlow & Cameron, 2003; Moore et al., 2009), until set gillnet fishing was permanently prohibited in waters shallower than 110 m off central California (Forney et al., 2020). These enforced regulations allowed the Morro Bay stock of harbor porpoises to increase from 571 individuals in 1990 (95% CI 252–2,666) to a population size of 4,191 (95% CI 1,900–11,971) porpoises by 2012 (Forney et al., 2020). These two examples demonstrate that prompt and enforced conservation measures can have a positive influence on population recovery, and that a lack of enforced regulations and management action in protected areas can lead to extinction.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Kylie Owen and Julia Carlström: Developed the ideas, and collected and processed the data. Martin Sköld: Completed the data analysis with assistance on interpretation from Julia Carlström and Kylie Owen. Kylie Owen: Wrote the manuscript, with strong input on intellectual content from Julia Carlström and Martin Sköld.
DATA AVAILABILITY STATEMENT
The data supporting the study’s findings can be accessed by contacting the corresponding author. All code used for the analyses is available on GitHub https://github.com/mskoldSU/Owen_et_al_2021).

ORCID
Kylie Owen https://orcid.org/0000-0002-8986-482X
Julia Carlström https://orcid.org/0000-0001-7039-6715

REFERENCES
Ainslie, M. A., & McColm, J. G. (1998). A simplified formula for viscous and chemical absorption in sea water. Journal of the Acoustical Society of America, 103(3), 1671–1672.
Au, W. W. L., Kastelein, R. A., Rippe, T., & Schooneman, N. M. (1999). Transmission beam pattern and echolocation signals of a harbor porpoise (Phocoena phocoena). The Journal of the Acoustical Society of America, 106, 3699–3705.
Barlow, J., & Cameron, G. A. (2003). Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift Gill net fishery. Marine Mammal Science, 19, 265–283.
Benke, H., & Siebert, U. (1996). The current status of harbor porpoises (Phocoena phocoena) in German waters. International Whaling Commission, SC/47/SM49, Cambridge, England.
Börjesson, P., & Read, A. J. (2003). Variation in timing of conception between populations of the harbor porpoise. Journal of Mammalogy, 84, 948–955.
Brownell, R. L., Reeves, R. R., Read, A. J., Smith, B. D., Thomas, P. O., Ralls, K., ... Wang, J. W. (2019). Bycatch in gillnet fisheries threatens critically endangered small cetaceans and other aquatic megafauna. Endangered Species Research, 40, 285–296.
Carlström, J. (2005). Die1 variation in echolocation behavior of wild harbor porpoises. Marine Mammal Science, 21, 1–12.
CEMP. (2019). OSPAR’s Coordinated Environmental Monitoring Programme (CEMP) guideline for indicator M4 on cetacean abundance. Retrieved from https://www.ospar.org/documents?v=39019
Cervin, L., Harkonen, T., & Harding, K. C. (2020). Multiple stressors and data deficient populations; a comparative life-history approach sheds new light on the extinction risk of the highly vulnerable Baltic harbor porpoise (Phocoena phocoena). Environmental International, 144, 106076.
Dawson, S., Northridge, S., Waples, D., & Read, A. (2013). To ping or not to ping: The use of active acoustic devices in mitigating interactions between small cetaceans and gillnet fisheries. Endangered Species Research, 19, 201–221.
EC-DGMARE. (2014). Lot 2: Retrospective and prospective evaluation on the common fisheries policy, excluding its international dimension. Ref. No MARE/2011/01. Study in support of the review of the EU regime on the small-scale driftnet fisheries. Appendix 4.6: Poland case study report (Final project report No. Ref. Ares (2014)1501494–12/05/2014).
European Commission. (1992). Habitats directive: Council directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Official Journal of the European Union, 206, 7–50.
European Commission. (2008). Directive 2008/56/EC of the European Parliament and of the Council of June 17, 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). Official Journal of the European Union, 164, 19–40.
Forney, K. A. (1995). A decline in the abundance of harbor porpoise, Phocoena phocoena, in nearshore waters off California, 1986-93. Fisheries Bulletin, 93(4), 741–748.
Forney, K. A., Moore, J. E., Barlow, J., Carretta, J. V., & Benson, S. R. (2020). A multidecadal Bayesian trend analysis of harbor porpoise (Phocoena phocoena) populations off California relative to past fishery bycatch. Marine Mammal Science, 37(2), 546–560.
Galatius, A., Kinze, C. C., & Teilmann, J. (2012). Population structure of harbour porpoises in the Baltic region: Evidence of separation based on geometric morphometric comparisons. Journal of the Marine Biological Association of the United Kingdom, 92, 1669–1676.
Gerrodette, T., Taylor, B. L., Swift, R., Rankin, S., Jaramillo-Legorreta, A. M., & Rojas-Bracho, L. (2011). A combined visual and acoustic estimate of 2008 abundance, and change in abundance since 1997, for the vaquita, Phocoena sinus. Marine Mammal Science, 27(2), E79–E100.
Hammond, P. S., Bearzi, G., Bjørge, A., Forney, K., Karczmarsi, L., Kasuya, T., ... Wilson, B. (2008). Phocoena phocoena (Baltic Sea subpopulation) (The IUCN Red List of Threatened Species 2008: e.T17031A6739565).
HELCOM. (2013). HELCOM Red List of Baltic Sea species in danger of becoming extinct. Baltic Sea Environmental Proceedings No. 140.
ICES. (2019). Working group on marine mammal ecology (WGMME). ICES Scientific Report, 1(22), 131.
ICES. (2020a). EU request on emergency measures to prevent bycatch of common dolphin (Delphinus delphis) and Baltic Proper harbour porpoise (Phocoena phocoena) in the Northeast Atlantic. In Report of the ICES Advisory Committee, 2020. ICES Advice 2020, sr.2020.04. https://doi.org/10.17895/ices.advice.6023
ICES. (2020b). Workshop on fisheries emergency measures to minimize BYCatch of short-beaked common dolphins in the Bay of Biscay and harbour porpoise in the Baltic Sea (WKEMBYC). ICES Scientific Reports, 2(43), 344.
ICES. (2021). Impulsive noise events registry in support of OSPAR and HELCOM. Retrieved from https://underwaternoise.ices.dk/impulsive/map.aspx

Jaramillo-Legorreta, A., Cardenas-Hinojosa, G., Nieto-Garcia, E., Rojas-Bracho, L., Ver Hoeft, J., Moore, J., ... Taylor, B. (2017). Passive acoustic monitoring of the decline of Mexico’s critically endangered vaquita. Conservation Biology, 31, 183–191.

Jaramillo-Legorreta, A. M., Nieto-Garcia, E., Rojas-Bracho, L., Thomas, L., ver Hoeft, J. M., Moore, J., ... Tregenza, N. (2019). Decline towards extinction of Mexico’s vaquita porpoise (Phocoena sinus). Royal Society Open Science, 6, 190598.

Jaramillo-Legorreta, A. M., Rojas-Bracho, L., & Gerdottete, T. (1999). A new abundance estimate for vaquitas: First step for recovery. Marine Mammal Science, 15, 957–973.

Kannan, K., Falandysz, J., Tanabe, S., & Tatsukawa, R. (1993). Persistent organochlorines in harbour porpoises from Puck Bay, Poland. Marine Pollution Bulletin, 26(3), 162–165.

Koschinski, S. (2001). Current knowledge on harbour porpoises (Phocoena phocoena) in the Baltic Sea. Ophelia, 55, 167–197.

Lah, L., Trense, D., Benke, H., Berggren, P., Gunnlaugsson, P., Lockyer, C., ... Tiedemann, R. (2016). Spatially explicit analysis of genome-wide SNPs detects subtle population structure in a mobile marine mammal, the harbor porpoise. PLoS One, 11, e0162792.

Larsen, F., & Eigaard, O. R. (2014). Acoustic alarms reduce bycatch of harbour porpoises in Danish North Sea gillnet fisheries. Fisheries Research, 153, 108–112.

Lindroth, A. (1962). Baltic salmon fluctuations 2: Porpoise and salmon. Reports of the Institute of Freshwater Research, Drottningholm, Sweden. 105–112.

Macaulay, J. D. J., Malinka, C. E., Gillespie, D., & Madsen, P. T. (2020). High resolution three-dimensional beam radiation pattern of harbour porpoise clicks with implications for passive acoustic monitoring. The Journal of the Acoustical Society of America, 147, 4175–4188.

Moore, J. E., Wallace, B. P., Lewison, R. L., Žydelis, R., Cox, T. M., & Crowder, L. B. (2009). A review of marine mammal, sea turtle and seabird bycatch in USA fisheries and the role of policy in shaping management. Marine Policy, 33, 435–451.

Murphy, S., Barber, J. L., Learmonth, J. A., Read, F. L., Deaville, R., Perkins, M. W., ... Jepson, P. D. (2015). Reproductive failure in UK harbour porpoises Phocoena phocoena: Legacy of pollutant exposure? PLoS One, 10(7), e0131085.

North Atlantic Marine Mammal Commission and the Norwegian Institute of Marine Research (NAMMCO and NIMR). (2019). Report of Joint IMR/NAMMCO International Workshop on the Status of Harbor Porpoises in the North Atlantic. Tromsø, Norway.

Nyberg, E., Faxneld, S., Danielsson, S., Eriksson, U., Miller, A., & Biggert, A. (2015). Temporal and spatial trends of PCBs, DDTs, HCHs, and HCB in Swedish marine biota 1969–2012. Ambio, 44, 484–497.

Osiecka, A. N., Jones, O., & Wahlberg, M. (2020). The diel pattern in harbour porpoise clicking behaviour is not a response to prey activity. Scientific Reports, 10, 14876.

Palka, D. L., Rossman, M. C., VanAtten, A., & Orphanides, C. D. (2008). Effect of pingers on harbour porpoise (Phocoena phocoena) bycatch in the US Northeast gillnet fishery. Journal of Cetacean Research and Management, 10, 217–226.

Punt, A. E., Siple, M., Francis, T. B., Hammond, P. S., Heinemann, D., Long, K. J., ... Zerbini, A. N. (2020). Robustness of potential biological removal to monitoring, environmental, and management uncertainties. ICES Journal of Marine Science, 77(7-8), 2491–2507.

R Core Team. (2020). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Rojas-Bracho, L., & Reeves, R. R. (2013). Vaquitas and gillnets: Mexico’s ultimate cetacean conservation challenge. Endangered Species Research, 21, 77–87.

Rojas-Bracho, L., & Taylor, B. L. (2017). Vaquita Phocoena sinus IUCN (The IUCN Red List of Threatened Species 2017: e. T17028A50370296.

Rojas-Bracho, L., Gulland, F. M. D., Smith, C. R., Taylor, B., Wells, R. S., Thomas, P. O., ... Walker, S. (2019). A field effort to capture critically endangered vaquitas Phocoena sinus for protection from entanglement in illegal gillnets. Endangered Species Research, 38, 11–27.

SAMBAH. (2016). Final report for LIFE+ project static acoustic monitoring of the Baltic Sea harbour porpoise LIFE08 NAT-S/0002615. Retrieved from https://www.sambah.org/SAMBAH-Final-Report-FINAL-for-website-April-2017.pdf

Skóra, K. E., & Kuklik, I. (2003). Bycatch as a potential threat to harbour porpoises (Phocoena phocoena) in Polish Baltic waters (Vol. 5, pp. 303–315). Tromsø, Norway: North Atlantic Marine Mammal Commission Scientific Publications.

SLU Artdatabanken. (2020). Rödlistade arter i Sverige 2020. Uppsala: SLU.

Sobek, A., Sundqvist, K. L., Assefa, A. T., & Wilberg, K. (2015). Baltic Sea sediment records: Unlikely near-future declines in PCBs and HCB. Science of the Total Environment, 518–519, 8–15.

Sonne, C., Siebert, U., Gomnson, K., Desorges, J., Eulaers, I., Persson, S., ... Dietz, R. (2020). Health effects from contaminant exposure in Baltic Sea birds and marine mammals: A review. Environmental International, 139, 105725.

Sørensen, P. M., Wisniewska, D. M., Jensen, F. H., Johnson, M., Teilmann, J., & Madsen, P. T. (2018). Click communication in wild harbour porpoises (Phocoena phocoena). Scientific Reports, 8, 9702.

Sørensen, T. B., & Kinze, C. C. (1994). Reproduction and reproductive seasonality in Danish harbour porpoises, Phocoena phocoena. Ophelia, 39, 159–176.

Sveegaard, S. (2020). Notat om resultater fra udlægning af akustiske lystesterstationer for marsvin under Havstrategidirektivet. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, xx s. – Notar nr. 2020/5. Retrieved from https://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Notatet_2020/N20205.pdf

Swistun, K., Yalcyn, G., Aninowska, M., Broczak, O., Sapota, M., & Thomsen, F. (2019). An increase of harbour porpoises in Polish waters? A case study using passive acoustic monitoring. Abstract submitted to the World Marine Mammal Conference, Barcelona.

Taylor, B. L., Chivers, S. J., Laresse, J., & Perrin, W. F. (2007). Generation length and percent mature estimates for IUCN assessments of cetaceans. NOAA NMFS Southwest Fisheries Science Center Administration Report LJ-07-01 21.

Taylor, B. L., Rojas-Bracho, L., Moore, J., Jaramillo-Legorreta, A., Ver Hoeft, J. M., Cardenas-Hinojosa, G., ... Hammond, P. S.
(2017). Extinction is imminent for Mexico’s endemic porpoise unless fishery bycatch is eliminated. *Conservation Letters, 10*, 588–595.

Todd, V. L. G., Pearse, W. D., Tregenza, N. C., Lepper, P. A., & Todd, I. B. (2009). Diel echolocation activity of harbour porpoises (*Phocoena phocoena*) around North Sea offshore gas installations. *International Council for the Exploration of the Sea Journal of Marine Science, 66*, 734–745.

Tregenza, N. (2014). *CPOD.exe: A guide for users*. Mousehole, England: Chelonia Ltd Retrieved from https://www.chelonia.co.uk/cpod_downloads.htm

Tregenza, N., Dawson, S., Rayment, W., & Verfuss, U. (2016). Listening to echolocation clicks with PODs. In *Listening in the ocean, modern acoustics and signal processing* (pp. 163–206). New York, NY: Springer.

Villadsgaard, A., Wahlberg, M., & Tougaard, J. (2007). Echolocation signals of wild harbour porpoises, *Phocoena phocoena*. *Journal of Experimental Biology, 210*, 56–64.

Wade, P. R. (1998). Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science, 14*, 1–37.

Wiemann, A., Andersen, L. W., Berggren, P., Siebert, U., Benke, H., Teilmann, J., ... Tiedemann, R. (2010). Mitochondrial control region and microsatellite analyses on harbour porpoise (*Phocoena phocoena*) unravel population differentiation in the Baltic Sea and adjacent waters. *Conservation Genetics, 11*, 195–211.

Wood, S. N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society, 73*(1), 3–36.

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Additional supporting information may be found online in the Supporting Information section at the end of this article.

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