Agenda Item 2.7	Review of New Information on Threats to Small Cetaceans Marine Protected Areas
Information Document 2.7b	**Design of a Monitoring Plan for the Southern North Sea Candidate Special Area of Conservation for Harbour Porpoise**
Action Requested	Take Note
Submitted by	United Kingdom

ASCOBANS

Note:
Delegates are kindly reminded to bring their own document copies to the meeting, if needed.

JNCC Report
No: 629

Design of a monitoring plan for the Southern North Sea candidate Special Area of Conservation and wider area

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Executive summary

Our approach to this study was to conduct desk-based reviews of the published and grey literature, to evaluate potential monitoring approaches, and use simulation studies to aid survey design in the context of detecting trends in population abundance. We have used existing reviews of survey methodologies to inform our assessment, providing a high-level evaluation of the pros and cons, resolution, utility (via power analyses), practicalities and cost of each of the survey methods. We suggested at the IAMMWG meeting (January 2018) that an array of static PAM devices was the best approach for long term monitoring at the site relative to the detection scenarios; a long-term decline in the Southern North Sea cSAC relative to the wider area, persistent seasonal changes in abundance, and short-term changes in usage.

Given overall variation in abundance estimates we found that the power achieveable by different survey methods was broadly comparable (Section 3.4.7). Further; the power was fairly low, *e.g.* for the SCANS III aerial survey CV of 0.17, the power to detect a 25% decline over six years of monitoring was 29%, and 48% following 12 years of monitoring. These results are in line with other studies which show that declining populations of marine mammals may reach critical levels before the decline is detected (e.g. Berggren *et al.* 2006b).

Our exploration of the patterns affecting power (Section 5.3.2-5.3.3) revealed that increasing the length of the monitoring programme increased the power of surveys and to a lesser extent increasing the number of static PAM sensors increased the power of the surveys. Outside of our control, but influential in affecting the power is variation (CV) of porpoise click rate; as variability increases, power decreases. One way we explored to increase the power for detecting change in this study was to increase the number of abundance estimates generated in a year (Table 11 and Table 12). We determined that increasing the number of estimates generated can significantly increase power and we would recommend this approach.

Full details of our suggested monitoring design for the SNS cSAC can be found in Section 6.1.1. We recommend a robust at-sea mooring system like those used in the German North Sea (Figure 8) and recommend that the exact number of devices to be deployed should be given careful consideration with reference to the power analysis we conducted in Section 5. To maximise the function of the largescale deployments of moorings we recommend additional noise monitoring and/or other environmental monitoring devices be incorporated where feasible. Indicative costs for our recommended survey design are provided in Table 8 and point to an expenditure of approximately £3,000,000 for the first three years of monitoring with subsequent year-on-year costs in the region of £600,000.

Providing around the clock monitoring, over extended periods of time is an advantage of static PAM as a medium term, large scale and cost effective monitoring option. This monitoring method should provide options for assessing short term displacement/ shifts in distribution patterns (which is critical for a highly mobile, patch-exploiting species like the harbour porpoise) as well as exploring habitat use over annual, seasonal, diurnal or tidal cycles and providing a robust method for monitoring and assessing the status and range of harbour porpoise around the cSAC.

Contents

1 Introduction

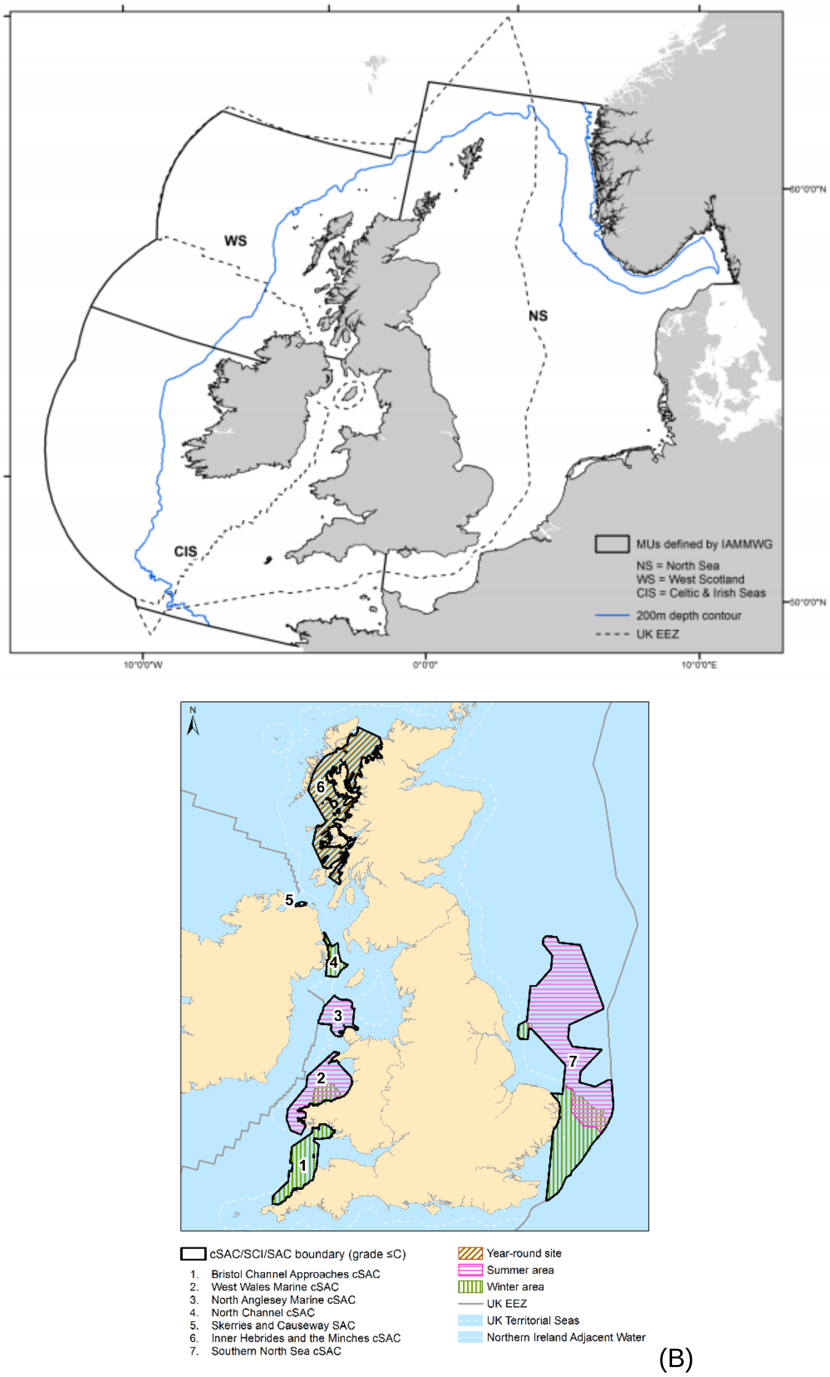
The harbour porpoise (*Phocoena phocoena*) is a highly mobile, abundant Northern Hemisphere species (Bjørge & Tolley 2018). It is the smallest cetacean species found in European waters and predominantly inhabits continental shelf waters (*e.g.* Embling 2010; Booth 2013; Hammond 2013; Heinänen & Skov 2015; Gilles 2016; Hammond 2017). The distribution and abundance of the species is not static with individuals exhibiting deviations in habitat use on the scale of hours (*e.g.* Goodwin 2008; Benjamins 2017), seasons (*e.g.* Verfuss 2007; Gilles 2016) and decades (*e.g.* Hammond 2013, 2017), which presumably mirror changes in the distribution and availability of important prey species.

One continuous population of harbour porpoise is considered to inhabit the eastern North Atlantic from the Bay of Biscay in the south to Norway and Iceland in the north (Tolley 2006; Fontaine 2007, 2014). However, for assessment purposes, five harbour porpoise Assessment Units (AUs) were established in 2014 (ICES 2014) as part of the International Council for the Exploration of the Sea (ICES) advice to the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR). For the purposes of conservation management of harbour porpoise in British waters three management units (MU) have been defined (Figure 1) based on best biological and ecological knowledge, as well as political boundaries and the management of human activities (IAMMWG 2015).

The species is listed in Annexes II, IV of the European Union's Habitats Directive[1] and Appendix II of the Bonn Convention[2]. Article 3 of the Habitats Directive requires the establishment of the Natura 2000 network of Special Areas of Conservation (SACs) that will contribute to the achievement and/or maintenance of favourable conservation status for habitat types and the habitats of species identified in Annexes I and II, respectively, of the Directive. Recently, a further six candidate SACs have been identified in UK waters for harbour porpoise (Figure 1A): Bristol Channel Approaches cSAC; West Wales Marine cSAC; North Anglesey Marine cSAC; North channel cSAC; Inner Hebrides and the Minches cSAC; and the Southern North Sea cSAC.

The Southern North Sea (SNS) cSAC is located to the east of England stretching from the central North Sea (north of Dogger Bank) to the Straits of Dover in the south. The site extends from coastal areas of Norfolk and Suffolk crossing the 12-nautical mile boundary and out to the EEZ (200 nautical miles, see Figure 1B). Both Natural England and Joint Nature Conservation Committee have shared responsibility for this site. With an area of 36,951km^2 the site is the largest cSAC in UK waters and supports an estimated 17.5% of the UK North Sea MU harbour porpoise population (JNCC 2017). The northern part of the site is important for porpoises during the summer season, whilst the southern part supports persistently higher densities during the winter (JNCC 2017). Much of the site is shallower than 40m (range; mean low water to a depth of 75m) and contains a mix of habitats such as sandbanks and gravel beds.

[1] Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.
[2] The Convention on the Conservation of Migratory Species of Wild Animals.



(A)

(B)

Figure 1. A) Management Units for the harbour porpoise in European Atlantic waters (reproduced from ICES 2014). B) Location of the six candidate and single designated marine Special Area of Conservation sites in the UK territorial seas and Northern Ireland adjacent waters (provided by JNCC).

The site overlaps with Haisborough, Hammond and Winterton SAC and North Norfolk Sandbanks and Saturn Reef SAC which feature Annex I Habitats; sandbanks which are slightly covered by sea water all the time and reefs, and Dogger Bank SAC which features sandbanks which are slightly covered by sea water all the time. There is considerable overlap of the SNS cSAC with the offshore wind industry (Figure 2). As listed in the Crown Estate Offshore wind files updated 18 December 2017 there are 17 offshore wind farms in the cSAC, 3 in operation, 5 consented, 6 in pre-planning application and 3 under construction. The site is also heavily utilised by the fishing industry including catches of cod, haddock, monk or angler, plaice, sole, herring, mackerel, crab, lobster and *Nephrops* throughout the cSAC and wider area (MMO 2016).

Under Article 17 of the EU Habitats Directive, Member States (MS) of the European Union are required to report on implementation of the Directive every six years. MS are obligated to achieve or maintain listed species such as the harbour porpoise at a favourable conservation status. Assessments consider conservation status, with particular emphasis on trends in population size, range and habitat quality. Conservation status is assessed through surveillance programs established by MS (Article 11). Monitoring requirements for SACs are implicit in the need to report on the impact of any conservation measures established

The scope of this project was to design a robust monitoring approach to allow the collection of data on the distribution of harbour porpoise through time within the cSAC and the wider area so that continued contribution of the cSAC to the species Conservation Status can be gauged.

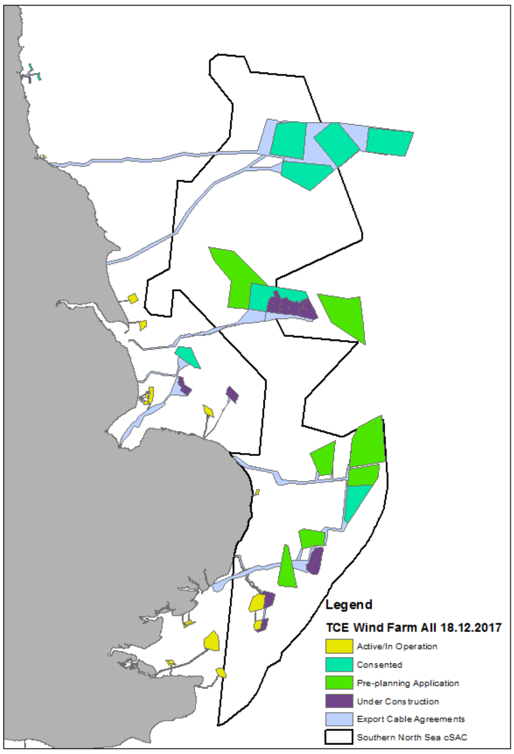


Figure 2. Map of the Southern North Sea candidate Special Area of Conservation for harbour porpoise and offshore wind developments. Data obtained from TCE_Wind_Farm_All_20171218.shp (last updated online December 2017) © Crown Copyright (2017).

2 Project Objectives

The overall goal of the project was to ascertain the best approach to monitoring harbour porpoise in the Southern North Sea (SNS) cSAC. The specified aims of the monitoring were to collect data on the spatial and temporal use of the site and wider southern North Sea by harbour porpoise to inform assessments of site condition and development of site management. Focusing on the spatial scale of the site, anthropogenic activities and estimated £1,000,000 budget for implementing a monitoring approach we intended to explore long-term monitoring methods and their suitability for implementation. In addition our aim was to provide a prospective power analysis to determine the sampling effort required for detecting changes in harbour porpoise relative abundance.

The broad project objectives were further explored at a meeting between the project team and the project steering group and subsequently with the Inter Agency Marine Mammal Working Group (IAMMWG):

- The cSAC monitoring approach will focus on relative abundance/density estimates. This will allow trends in the population in space and time to be assessed with benchmark absolute abundance estimates being obtained on an approximately decadal timescale by the Small Cetaceans in European Atlantic waters and the North Sea (SCANS) surveys.

- We investigated the power to detect three different trends:
    - A long-term decline in the SNS cSAC relative to the wider area; we defined the wider area as a 50km ‘buffer’ aroud the whole cSAC, clipped to land and the UK exclusive economic zone (EEZ).
    - Persistent seasonal changes in distribution with increased use of the north of the cSAC in the summer and the south of the cSAC in the winter.
    - Short-term changes in usage as a consequence of disturbance from offshore construction activities.

- Concurrent monitoring would take place inside the cSAC and in the 50km ‘buffer’ (see Figure 3).

- The target power for surveys was set at 80% with alpha 0.05 (*i.e.* a false positive error rate of 5%) in monitoring scenarios over 6 years and 12 years (to match the Article 17 Habitats Directive assessments reporting structure).

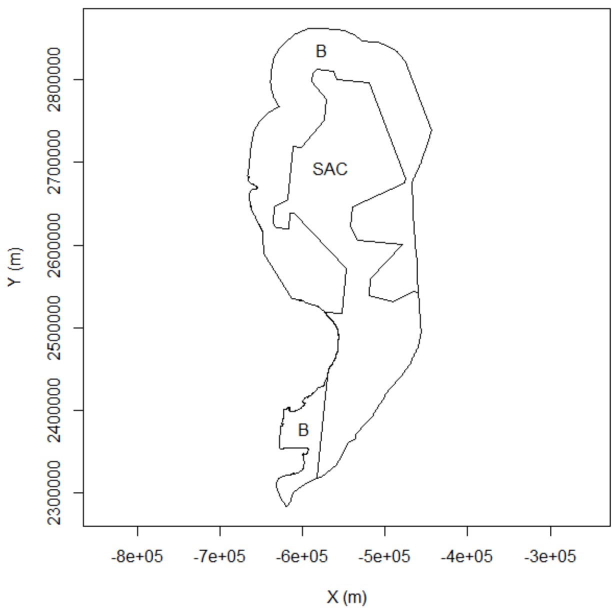


Figure 3. Regions of interest: special area of conservation (cSAC) and buffer (B).

Given the desired power and a tentative estimate of budget available for monitoring[3], the IAMMWG agreed that a detectable change of 25% over 6 years should be the minimum, with an aspiration to detect 10% change over 6 years as a precautionary option.

2.1 Report Intention and Structure

After establishing the project objectives in conjunction with JNCC and Natural England a desk-based review of monitoring methods was conducted (section 4). We presented a synopsis of section 4 to the IAMMWG in January 2018 alongside our recommendation of the most appropriate approach; static passive acoustic monitoring (PAM). The presentation and IAMMWG discussion acknowledged that each approach has associated costs and benefits, but that static PAM provides the best cost option given the objectives and draft budget and has excellent temporal coverage. Static PAM acoustic hardware and deployment options were subsequently reviewed (section 4) and monitoring scenarios were modelled to determine the power for detecting change (section 5). A summary of all recommendations is provided in section 6.

[3] Based on estimates prepared for cetacean monitoring options developed as part of UKMMAS http://jncc.defra.gov.uk/page-3356.

3 Description of monitoring approaches

In this section, we provide a high-level summary of the utility of suitable approaches for monitoring harbour porpoise in the SNS cSAC. The final recommendation is detailed in section 6, following our exploration of the relevant factors affecting robust and feasible survey design.

Monitoring marine mammal populations can be undertaken using several approaches. Suitable monitoring approaches include line transect, fixed point and mark-recapture sampling. The different approaches rely on different survey platforms which may be stationary or moving and the detection methods may also vary including; direct visual or video/photo-based recordings of animals at the surface or acoustic detection of sound producing animals underwater. Depending on the approach, the outputs achieved may be indices of relative abundance or estimates of absolute abundance (*e.g.* Hammond 2002)

Survey methods:

- Line transect surveys
  - Vessel-based visual surveys
  - Vessel-based PAM
  - Aerial visual surveys (with human observers or digital methods)
  - Unmanned Autonomous Vehicles (*e.g.* underwater drones)

- Point transect surveys
  - Static PAM

3.1 Harbour Porpoise Detection Methods

Harbour porpoises can be detected visually when they are at the sea surface (or just below it) or acoustically through the use of passive listening devices when they vocalise. Visual detection using either the naked eye or binoculars is the most traditional method for detecting harbour porpoises and the method has been widely used on abundance surveys (Hammond 2002, 2006, 2013; Gilles 2016; Hammond 2017) conducted both from vessels and from light aircraft.

As an alternative to human observers recording cetacean sightings, technology now allows for high definition video and still images to be captured along aerial line transects (Heide-Jørgensen 2004; Koski 2013; Williamson 2016). Developments in ultra-high-resolution devices has allowed aircraft mounted systems to photograph large areas quickly. The method is being utilised to survey a number of off-shore windfarms around Europe as surveys can be conducted from a higher altitude, reducing the risk of collision with turbine blades (Buckland 2012). Currently, analysis of raw data is conducted in-house by the existing service providers with quality assurance provided by external consultants. The analysis time for digital imagery is important to factor in to the duration and cost of this approach as many thousands of images can require processing.

As with all visual methods, fair weather is a pre-condition for conducting the survey. Harbour porpoise are difficult to detect during visual surveys due to their small size and inconspicuous surfacing behaviours and critically, detection probabilities for harbour porpoise are known to decrease with increasing sea state (*e.g.* Palka 1996; Teilmann 2003) leading to most harbour porpoise visual studies to be restricted to sea conditions up to a maximum of Beaufort sea state two (small wavelets that do not break). It is standard practice for the analysis of ship based visual surveys to only use porpoise effort and sightings data obtained in Beaufort sea state two or less, while data for other species can be used if collected in Beaufort sea state four or less (*e.g.* Hammond 2017). Furthermore, visual surveys can only be conducted during daylight hours (which limits the area that can be surveyed in a day and has implications for the cost of surveys).

Harbour porpoises emit series of echolocation clicks called click trains. The clicks have a very distinct characteristic and are of high frequency with main energy around 130kHz (*e.g.* Villadsgaard 2007). Harbour porpoise use echolocation for foraging (Verfuß 2009; Wisniewska 2012) and orientation (Verfuß 2005) and echolocation like click trains for communication (Clausen 2010). They use their sonar nearly constantly (Akamatsu 2005; Verfuß 2005), allowing for detections as well as the potential to interpret foraging behaviour using buzzes or other acoustic criteria (Carlström 2005; Verfuss 2008; Schaffeld 2016). Detection ranges to porpoises are dependent on the type of equipment used, local noise conditions and the orientation of the animal relative to the hydrophone (as their echolocation signals are highly directional). Typical ranges during towed hydrophone surveys have been up to a maximum of around 200 – 250m (Gillespie 2005), but ranges are likely to be lower from noisier vessels (though this is a poorly studied topic). For static PAM, detection ranges may be larger (because of the use of quieter, moored devices).

Due to their very high frequency, porpoise clicks cannot be heard by humans, but can be detected with specialist PAM equipment. This equipment can be towed behind moving survey vessels or moored on the sea floor. More recently, researchers have investigated the use of miniature recording devices deployed on small autonomous underwater vehicles (AUV's, *e.g.* Klinck 2012; Suberg 2014). The high frequency nature of porpoise clicks means that monitoring equipment must be capable of acquiring data at sample rates well in excess of 300kHz. If raw data are recorded, and a typical sample rate of 500kHz is used, then 86GBytes of raw data are received each day from each monitoring hydrophone. While storing such volumes of data on a vessel carrying a crate of hard drives is relatively straight forward, smaller low power systems incorporate real time detection whereby only a small amount of summary information is recorded for each detected click. In some instances, click detections can be stored alongside a millisecond long waveform snippet.

3.2 Summary of Line transect surveys

Both visual and passive acoustic line transect survey approaches are considered standard methods for generating cetacean density and abundance estimates (Buckland 2001). For example, the SCANS surveys are large-scale aerial and ship-board visual line transect surveys that use a survey design of pre-determined line transects, in a pre-defined survey area, and human observers to record cetacean sightings to estimate the distribution and abundance of cetaceans in European Atlantic waters (Hammond 2002, 2009, 2013, 2017).

Systematic, random survey designs generated using computer programs such as Distance software (Thomas 2010) mean that designing surveys, even in irregular shaped areas is relatively straightforward. However, survey design still requires consideration. Buckland *et al.* (2001) recommend that survey lines should, as far as possible, run perpendicular to any density gradient to maximise precision, and Thomas *et al.* (2004) recommend that for a monitoring approach to estimate trends alone, the same survey lines should be repeated each survey.

Most often deployed concurrently with visual line transect surveys, but not dependent on fair weather or daylight, a towed hydrophone array can be deployed to detect the acoustic signals of marine mammals. The PAM method provides information on the presence of species and relative abundance has been successfully demonstrated across a number of species and studies (Barlow & Taylor 2005; Gillespie 2005). Hydrophones are routinely towed behind a survey vessel and consideration must be given to noise generated by the vessel, water depth, the length of towing cable and the speed of the boat to avoid the risk of the hydrophone making contact with the sea bed. The hydrophone presence behind the boat may also pose a navigational risk and influence the responsive movement of the vessel. The sound signals are digitised and can be detected by automated click and whistle detection software. A widely used and freely available software package is PAMGuard[4] (Gillespie 2008). Real time monitoring can be carried out by trained observers however, detailed post-survey analysis is also required.

The use of Autonomous Underwater Vehicles (AUVs) for surveying marine mammals is a developing research area, involving robotic, programmable vehicles that are untethered to surface ships. Most devices are torpedo shaped and, depending on their propulsion mechanisms, they may drift, drive or glide through the water. Their operation does not require real-time control by human operators (Yoerger 1998; Verfuss 2015) as the vehicles follow pre-programmed courses but there are generally planned communications depending upon the level of control/ oversight required.

The technology typically aboard the AUVs allows the marine environment to be mapped and monitored; however, the vehicles typically move at slow speeds *e.g.* 0.5-2.0m/s^{-1} in marine geoscience surveys and can be influenced by tidal and other currents (Wynn 2014). Powered AUVs are inherently noisy and are only suitable for short duration deployments due to power constraints. Gliding AUVs are capable of long (several month) deployments and are quiet except when adjusting their balance or direction. These vehicles can be fitted with PAM sensors capable of detecting harbour porpoise (Suberg 2014).

3.3 Summary of Point Sampling Surveys

Static PAM utilises fixed point monitoring instruments which incorporate a hydrophone and a hardware data logger to detect echolocation sounds produced by cetaceans. Estimating animal abundance using static hydrophone arrays can provide medium-term monitoring in a cost-effective way (SAMBAH 2016).

It is important to consider that in a PAM program, the selection of appropriate PAM equipment is critical to its success. Each of the different PAM devices available have different specifications regarding depth of deployment and different estimated detection ranges and all are required to be anchored to either the sea bed or to an existing buoy with the hydrophone floating upright in the water column. We explore this further in section 4.

As highlighted above, PAM approaches for porpoises have some limits of their utility. Firstly, they provide data on porpoise activity (absence/presence) in a given area (*i.e.* within a certain range of the hydrophone – thought to be out to an absolute maximum of 400 m for porpoises[5], however it is likely to be lower than this in most situations, though few empirical data are published on this topic. PAM will only record porpoises that are actively echolocating and orientated towards the hydrophone. Without additional auxiliary information, they cannot provide a count of the number of porpoises recorded. For example, a period of 10 detection positive minutes (DPM) may indicate multiple porpoises passing and echolocating on a hydrophone, or it may be a single animal echolocating in proximity to the hydrophone for 10 minutes. It may be that animals vary their vocal behaviour spatially or temporally. One approach to try to address this is in the analysis phase when the user can bin the data. When this is done, the detection data are summarised into DPM (or sometimes 10 minute periods or an hour – DP10M and DPH respectively) and treated binomially. Nonetheless, static PAM can be used to compare the relative frequency of detections/echolocation activity between sites or through time and provide high-resolution,

[4] www.pamguard.org.
[5] http://www.chelonia.co.uk/cpod_specification.htm.

long term temporal monitoring cost-effectively (*i.e.* providing 24/7 monitoring using any other method is likely to cost more than PAM approaches).

3.4 Considerations for delivering a large-scale monitoring project

In this review the focus was on evaluating the survey methods when applied to harbour porpoise monitoring in the largest cSAC in UK waters given the overall aims:

- to provide a measure of relative abundance;
- determine year-round ‘use’;
- collect data on seasonal distribution; and
- to detect changes in harbour porpoise use over time and space.

Each of the survey methods described is able to detect and provide a measure of relative abundance of harbour porpoise, the principal differences lie in the scale of the ability to meet the projects spatial and temporal goals within the expected £1,000,000 budget.

3.4.1 Spatial and temporal resolution

As noted above, the SNS cSAC is very large, spanning 36,951km^2. However, the area of interest for our sampling design is 77,975km^2 as the objective in this study is to deisgn a monitoring approach with the power to detect declines within the cSAC area, that are not reflected in the ‘buffer’ (41,024km^2 buffer zone). With this in mind, we must consider the ability of the different approaches to effectively sample such a large study area.

Both line and static transect approaches will provide data on the presence, distribution and relative abundance of harbour porpoise within the cSAC and ‘buffer’. For line transect survey methods the spatial and temporal coverage, *i.e.* the time to survey the area, will be dependent on the size and speed of the survey craft as well as the proportion of fair weather days for survey. For example, the spatial coverage of aerial surveys can be at a finer scale than ship-board surveys due to the faster craft speed and responsiveness to weather windows (Evans & Thomas 2013; Hammond 2017). Buoyancy driven AUVs are capable of mission durations of several months (Suberg 2014). The devices would need to spend extended periods at sea to be able to complete surveys of the cSAC and buffer and the influence of currents on the devices means that dedicated transect lines would not be followed precisely. However, as with shipboard surveys, unless multiple craft are utilised, assessment of the whole site cannot be done concurrently but will have a time lag across the area. Each survey window will represent a snapshot estimate and repeat surveys (*e.g.* monthly, quarterly) will allow long term monitoring. Budget will most often dictate survey frequency.

For static PAM the spatial resolution of any survey is limited by the detection range for the animals and the deployment arrangement of devices. Survey designs can cover extremely large areas with long-term monitoring arrangements increasing the ability to detect trends (Buckland 2016). Depending on the device parameters, sound recordings can take place continuously over periods of up to 3-4 months (depending on device set-up) when field visits are required for data download and general maintenance. Overall, static PAM is considered a cost-effective long-term monitoring approach as seen in its utilisation in the UK and NW Europe (Teilmann & Carstensen 2012; Brandt 2016; Williamson 2016, 2017).

3.4.2 Project Readiness

Though the majority of the monitoring approaches discussed are standard methods, time will still be needed to prepare, schedule and implement any monitoring regime. Lead-in times may be longer where specialised equipment needs to be ordered or designed. Where ships or aircraft are employed in the survey methodology the availability of suitable crafts and harbours/airstrips may limit where the surveys can be conducted from and the cruise time until the survey effort starts.

Depending on the availability of suitable vessels and trained observers a single platform survey could be conducted; we recommend 4 observers be employed as visual observers, 2 x actively surveying, 1 x note taker and 1 x resting. Similarly, shipboard PAM surveys will depend on availability of PAM equipment and survey methodology will dictate how many trained PAM operators are required. Where real-time monitoring is not required only 1 trained PAM observer would be necessary for system set-up, with detailed analysis of acoustic data being conducted post-survey. Hydrophone sensitivity must be aligned with the echolocation frequencies of the study species.

Aerial monitoring will depend on the availability of suitable aircraft, preferably a high-winged, twin engine craft with bubble windows enabling observers a good view of the transect line. Trained observer availability is also necessary. Evans and Thomas (2013) recommend 3 observers be employed; 2 x actively surveying and 1 x note taker. High-resolution aerial digital surveys do not require trained observers for the surveys, but they do for the post-processing animal identification. This is currently conducted by the companies that collect the data (*e.g.* HiDef Aerial Surveying Ltd, APEM Ltd) and is a substantial proportion of the time/cost estimates as many thousands of images will be taken in a single survey. We recommend that some independent image verification or quality assurance also takes place.

Suitable weather windows are likely to be the most common constraint for line transect surveys, in general surveys should be carried out in sea state 2 or less and good visibility. The main advantage of aerial surveys is the ability to cover large areas, at speed and to be responsive to changes in weather (Evans & Thomas 2013; Hammond 2017).

There are a number of science AUV sector devices now available through providers in the commercial sector *e.g.* Kongsberg REMUS and research sectors *e.g.* the UK National Oceanography Centre (NOC) Autosub. AUVs have the capacity to carry a variety of sensors the nature and weight of the which determines the vehicle altitude, speed and endurance (Wynn 2014). Sensors typically deployed include geophysical, geochemical and oceanographic instruments, development time and costs will likely be incurred to refit acoustic or other monitoring sensors suitable for detecting harbour porpoise to an AUV. The risk of acoustic interference, collision, entanglement device and data loss are valid concerns for AUV providers and researchers as such they are not generally considered suitable for deployment in areas of high military, shipping or fishing activity (Wynn 2014).

There are a number of manufacturers of static PAM devices suitable or adaptable to meet the requirements for long term monitoring of harbour porpoise. The equipment themselves will require some lead-in time to meet the requirements of such a large monitoring project. We explore deployment options further in section 4.

3.4.3 Health and Safety Considerations

Health and safety considerations should be paramount to any programme of monitoring animals at sea. Working from boats in the North Sea will always have risks associated with the weather and sea state. Hypothermia, heat stroke, eye damage due to glare and motion sickness are all relevant, if predictable, conditions to be aware of. Manual handling injuries, personal injury due to boarding vessels and equipment use and in worst case scenarios man overboard risks are all serious but less predictable events to manage.

Alongside the more predictable weather-related health and safety concerns, aerial survey methods include some very low occurrence though catastrophic risks such as air accidents and forced landing at sea. There is reduced risk associated with digital aerial surveys due to there being fewer personnel on board and the option to fly at higher altitude thereby reducing collision risk with offshore windfarm developments. Due to the speed of aircraft the time conducting surveys and therefore the period of risk will be substantially shorter than for any shipboard surveys.

Deployment and servicing or retrieval of AUVs or static PAM devices are the time periods of risk for these survey methods. The risk for static PAM devices will be proportional to the number of devices required to monitor the cSAC and buffer, deployment and retrieval will be the most-risky times with methods ranging from human diver to Remotely Operated Vehicle (ROV) to hydraulic or manual lifting from a vessel. The window of activity is expected be smaller for AUVs due to the limit of the number of devices available for conducting monitoring of this scale, however, this would depend on the level of at-sea oversight required for any device.

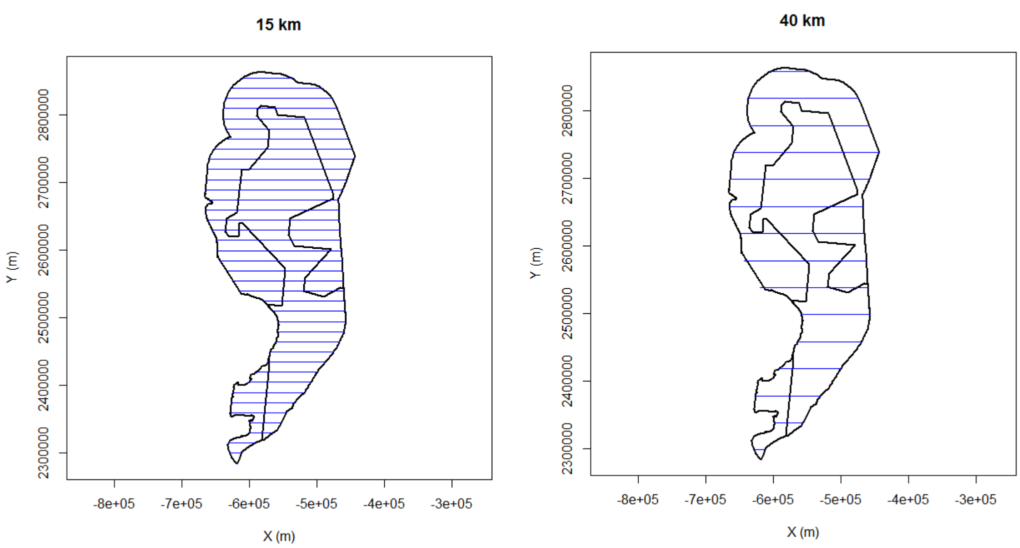
Each method described has different risks and magnitude of risk associated with the work however, one of the biggest factors to consider are the number of personnel involved and importantly the amount of time engaged in the activities.

3.4.4 Survey Effort

Whilst the power, scale and general ‘readiness’ of the different monitoring approaches are key elements in the selection of a monitoring approach for harbour porpoises in the SNS cSAC, it is important to consider the amount of effort to be conducted.

We prepared illustrative examples of systematic, random parallel line transect and point sampling monitoring designs below (Figure 4) using Distance v7.1 software. For line transect surveys, the considerations are of the number of survey lines required, their length (summing to the survey distance to be surveyed) and the speed of the craft (*i.e.* plane or vessel). For static PAM survey, the consideration is the number of sensors to deploy (Figure 4) and the effort to retrieve and redeploy sensors (*i.e.* for data retrieval).

For line transect surveys we explored the amount of effort that might be required to complete these surveys once (which can be extrapolated if quarterly or monthly surveys are desired). The resulting effort are presented in Table 1 and Table 2.



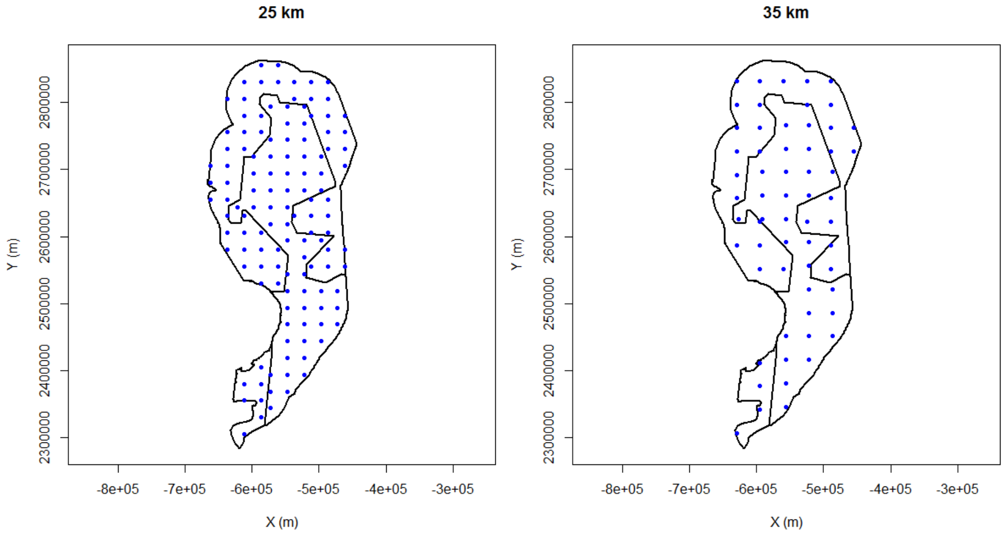


Figure 4. Indicative survey effort maps for line transect surveys (15km and 40km spacing) and static PAM sampling (25km and 35km spacing).

Table 1. Summary of the indicative PAM survey design including spacing between units and number of sensors and the estimate of the number of days for deployment and quarterly service trips depending upong the number of PAM sensors.

	Region	Device Spacing	Number of devices	Deployment (days)	Quarterly Service trip (days)
Static PAM	cSAC	25	59	33	25
	Buffer	25	66		
	cSAC	35	30	17	12
	Buffer	35	33		
	cSAC	40	23	14	10
	Buffer	40	26		

Table 2. Summary of the indicative survey designs including the survey distance to be travelled and the estimate of the number of days of survey required to complete the survey depending on the survey design if conducted by a boat (estimated speed 10 knots, 18.5km/h, Macleod 2010) or a plane (estimated speed 100 knots, 185km/h, Macleod 2010; Gilles 2016).

	Region	Line Spacing (km)	Distance (km)	Speed of craft (km/h)	Survey hours (h)	Winter survey (days)	Summer survey (days)
Shipboard	cSAC	15	2491	10	135	19	9
	Buffer	15	2766	18.5	150	21	10
	cSAC	40	940	18.5	51	7	3
	Buffer	40	1012	18.5	55	8	4
Aerial	cSAC	15	2491	185	13	2	1
	Buffer	15	2766	185	15	2	1
	cSAC	40	940	185	5	1	1
	Buffer	40	1012	185	5	1	1

Based on these pseudo-survey designs the number of days at-sea in winter to complete a full survey of the cSAC and 'buffer' would range between 15 and 40 days depending which survey spacing design was (Table 1). Aerial survey methods would be faster ranging between 1 and 2 days for winter surveys (Table 1) and would allow for faster response times to take advantage of weather windows. Survey spacing for the static PAM devices has a direct influence on the spatial resolution of the survey, though the temporal resolution will remain unchanged with the devices monitoring constantly. With between 49 and 124 sensors across the cSAC and 'buffer', we have estimated deployment time would range between 14 and 33 days and service trips between 10 and 25 (Table 2).

3.4.5 Power to detect declines

The ability of a study to detect change is quantified by a statistic called power. The power with which a change can be detected by the different approaches is a critical factor in assessing the suitability of different monitoring methods for harbour porpoise. Before the project scenarios are considered, we review the concept of the power of a study in the context of detecting a trend. While the approach used in this introduction is simple, it nevertheless highlights that length of study and the variability in the population being measured are important components to the power.

3.4.6 Detecting a trend

If abundance (which is obtained from density multiplied by area) has been estimated over time (for example once a year for six years – but see below regarding multiple estimates per year) a linear trend can be identified when a regression model fitted to density estimates has a slope that is different from zero (Figure 5). This can be denoted by:

$$D = \beta_0 + \beta_1 Y + \epsilon \qquad (1)$$

where D is density estimated for year Y, β_0 is the intercept, β_1 is the slope and ϵ is the random error term (which has a specified distribution). Both linear and non-linear trends can be modelled in this formulation. An estimated slope coefficient (*i.e.* β_1) that is zero, or very close to zero, indicates that there is no change in abundance over time (apart from natural variability). A statistical hypothesis test can be used to decide objectively whether the slope coefficient is significantly different from zero or not; in particular, we want the test to reject a hypothesis that there is no trend when in fact there is one of a magnitude that we believe to be biologically important. The probability that the test does this is called the power of the test and is illustrated for a simple scenario (*i.e.* abundance estimates obtained over some period of time) below. The same approach can be applied to indices of population size – one is then estimating trend in the index, rather than trend in the population.

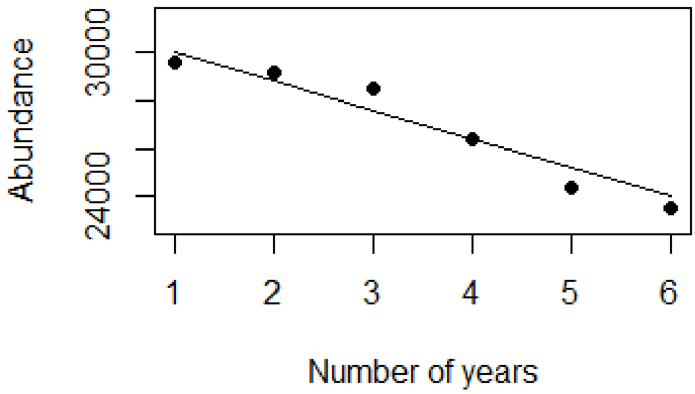


Figure 5. Example of a 25% decrease in estimated abundance (dots) over six years with a starting abundance of 30,000 with an estimated trend line.

Using simple approaches (*e.g.* Gerrodette 1987; Barry 2017), the power to detect a trend can be calculated by specifying four parameters:

- the number of time steps (*e.g.* number of annual surveys);
- the rate of change of the quantity being estimated (*e.g.* percentage change in abundance);
- the variation in the estimates; and
- the probability of incorrectly concluding that a trend has occurred when there is none (Type I error) denoted by α.

As an illustration, using the software package *Emon* (Barry & Maxwell 2017), a linear trend is generated and a *t*-test on the slope parameter of a linear regression model is applied. The process is repeated a large number of times (1,000) and the proportion of times the slope parameter was significantly different from zero (determined by α) provides the power. Given a starting population of 30,000 (based on the density obtained from SCANS-III (Hammond 2017) and the size of the cSAC) other parameters values were specified as follows:

- number of annual surveys: 6 and 12 (year monitoring programme);
- rates of change are specified as the percentage decrease between the first and last year: 10 and 25% decrease;
- variability: a linear trend is assumed and the variability is specified by generating random values from a Normal distribution with mean based on the linear trend and standard deviation (SD) calculated from SD = population size x CV where coefficient of variation (CV) takes values between 0.05 and 0.6;
- $\alpha = 0.05$;
- The number of estimates calculated per year.

Results are shown in Figure 6. Albeit a simple approach, this illustrates that the power to detect a change declines substantially as the variability in the estimates (CV) increases and the rate of change decreases but the longer the study the higher the power to detect a change.

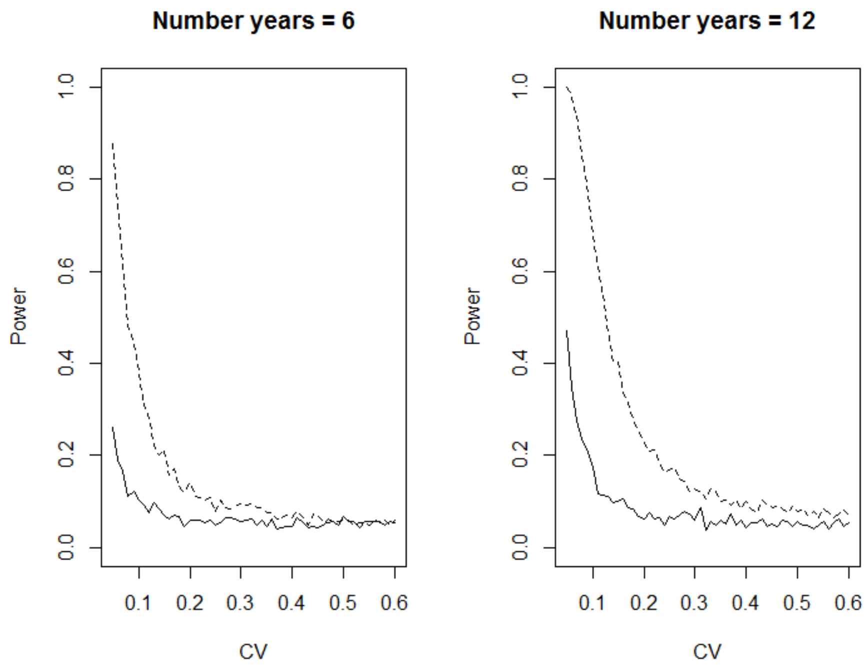


Figure 6. Power against CV for different percentage decreases in abundance: 10% (solid line) and 25% (dashed).

In the example given above, interest was in the power to detect a trend (decline or increase) over time, however, for the purposes of this project, the power to detect changes between regions taking into account other variables, such as seasonal changes, are of interest. The statistical model, shown in equation 1, can be adapted as required to account for non-linear trends and other factors specific to the study population and region of interest. However, to incorporate additional factors into data generated in order to fit the model, and hence estimate the regression coefficients, a more sophisticated simulation tool needs to be used.

Before leaving this simple illustration, we introduce one more component particularly relevant to acoustic surveys: the effect of deriving multiple estimates per year. Static acoustic surveys can effectively operate year-round, so it is possible to generate multiple estimates per year, for example (if the sensors are serviced on a four-monthly schedule) three times per year. All other things being equal, this can substantially increase the power to detect a trend and was explored by Booth *et al*. (2017) as part of a larger sensitivity analysis (Figure 7). Note, the increase in power does rely on the assumption of independent errors between survey periods. Whilst it is unlikely that this assumption will hold (*i.e.* there will not be total independence), the level of correlation that exists in real datasets will dictate the true increase in power as a result of generating multiple estimates. The current assumption likely overestimates the increase in power, but we cannot say by how much. With a real dataset, models would be developed with a suitable correlation structure for the errors to account for observable correlations.

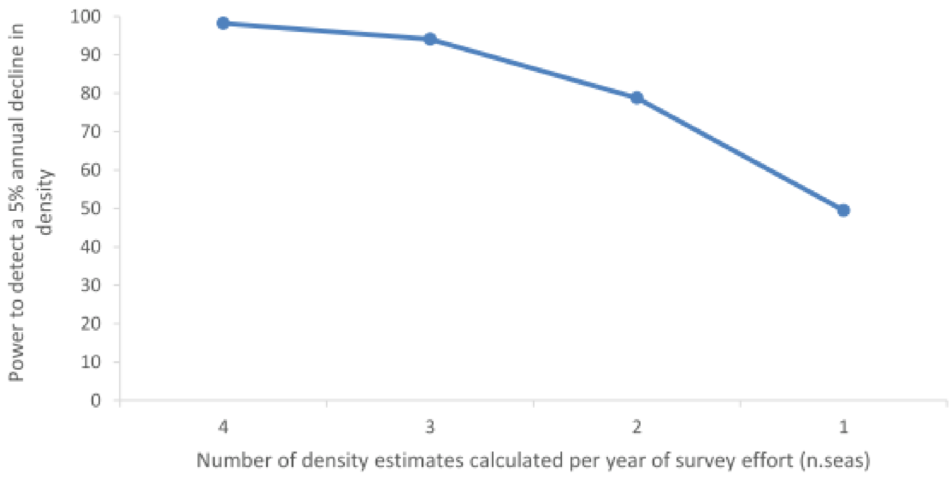


Figure 7. from Booth *et al.* (2017): "Shows how survey power varies with the number of estimates calculated for each year of the study."

3.4.7 Comparison of the power of different methods to detect change in harbour porpoise abundance

We assessed the power of line transect survey approaches using the TRENDS program (Gerrodette 1987, 1993) which is an openly available piece of software designed for the assessment of power via linear regression. Simple power analyses were carried out based on annual estimates for 6 and 12 years and overall changes in population size of 10% and 25% over the duration of the monitoring. An alpha of 0.05 was used and a range of CVs from 0.05 – 1. The power was assessed via a negative linear trend and one-tailed test to detect a negative trend. In order to derive a realistic estimate of power for such surveys, we utilised observed CV values for the SCANS III aerial and shipboard surveys (Hammond 2017).

The outputs from the power analyses for line transect surveys are shown in Table 3 (and the CVs achieved from SCANS III in *italics*) and show that for any achievable CV, the power to detect declines are low. For example, (Berggren 2006b) the power to detect a 10% decline over the monitoring period was estimated to be between 11% with six years of monitoring and 15% over 12 years (*i.e.* 85 – 89% of true 10% declines would not be detected). The power to detect a 25% decline over six years of monitoring was 29%, and 48% following 12 years of monitoring. Using the CVs observed for the shipboard surveys resulted in lower power still; with power to detect a 10% change estimated to be 8% and 10% (*i.e.* 90-92% of true 10% declines would not be detected) following six and 12 years of monitoring respectively and power to detect a 25% change estimated to be 17% and 25% respectively. In the SCANS blocks which overlap with the cSAC and buffer region, the CVs were; block O CV = 0.21, block L CV = 0.38, indicating that similar or lower power as described above is possible in this indicative example.

Table 3. The predicted power of line-transect surveys to detect different harbour porpoise population declines using a range of CV values (assuming an annual estimate), including those achieved from SCANS III aerial[1] and ship-based[2] surveys. The power to detect a decline of 10% and 25% following 6 and 12 years of surveying is shown. [1] - from overall estimate of HP from SCANS-III aerial surveys (0.17) with min and max of CVs from individual survey blocks (where they saw HP): 0.21 – 1.02. [2] - from overall estimate of HP from SCANS-III ship surveys (0.28) with min and max of CVs from individual survey blocks 0.3 – 0.47.

	10% change		**25% change**	
CV	***6 years***	***12 years***	***6 years***	***12 years***
0.05	41%	67%	97%	100%
0.08	23%	37%	74%	96%
0.1	18%	27%	58%	85%
0.17[1]	*11%*	*15%*	*29%*	*48%*
0.2	10%	13%	24%	39%
0.28[2]	*8%*	*10%*	*17%*	*25%*
0.5	7%	8%	10%	14%
1.0	6%	6%	8%	8%

A review of monitoring methods and associated power analysis in the Final Report of SCANS-II (Appendix D2.1 and D2.4, Berggren 2006a, 2006b) made clear that for populations of marine mammals that are decreasing they may reach critically low levels before the downward trend could be statistically detected . This is because of the high variability and low power in the data and methods used in marine mammal monitoring schemes.

As part of this study, a series of power analyses have been carried out, the bulk of which have focused on static PAM. These are described and presented fully in section 5 (where we also consider generating multiple robust estimates per year using static PAM time series data). However, to allow comparison with Table 3, we present a summary of power analysis for static systems below (Table 4). This suggests that static PAM can have equivalent power to the theoretical aerial surveys (using a SCANS III CV value), though the true power will be affected by the number of sensors deployed, CV and a range of other factors (as with vessel based or aerial surveys). The number of sensors is indicative of the number that would be required for a specified grid spacing – the actual number may vary due to selecting random start location.

Table 4. Summary of power for static PAM deployments for porpoises using the AVADECAF (Assessing the ViAbility of Density Estimation for Cetaceans from Passive Acoustic Fixed Sensors) tool. The power presented is the power to detect a 25% decline in the cSAC over the monitoring period (using annual estimates). The number of sensors is the number of sensors in the cSAC only given the grid spacing. Alpha = 0.05. Animal cue rate CV = 0.05 in all scenarios. See section 6 for full results and details, and for more information on the effect of multiple estimates per year.

PAM set-up		**25% change**	
Spacing	**# sensors in cSAC**	**6 years**	**12 years**
25 km	59	24%	55%
35 km	30	21%	48%
40 km	23	20%	46%

In general, any estimates from surveys which have large associated variability will have low power to detect a difference. A means to reduce CVs and reduce the high risk of a type 2 error (failing to detect a change when one has occurred) would be to collect more data.

However, increasing survey effort across larger scales will not necessarily result in sufficient power, more important is the need for dedicated cetacean surveys to be conducted as robustly as possible to minimise the variability associated with abundance estimates (Jewell 2012). Taylor *et al*. (1997) explored the potential of monitoring approaches to detect ‘precipitous declines’ of 50% over a 15 year period for different marine mammal species groups. They found that in the majority of cases (*e.g.* 78% for dolphins/porpoise species) surveys lacked the power to detect a true decline of this nature (this was true even in limited case studies presented where annual studies were conducted). Critically, they focus on increasing the total and frequency of survey effort to improve power.

3.4.8 Strengths and weaknesses of survey methods

Producing relative abundance estimates from each survey method is realtively straightforward. However, designing a study to detect harbour porpoise population trends in space and time with sufficient power and within an estimated £1,000,000 budget is not simple. Our evaluation of survey methods has shown that there are strengths and weaknesses for each method and we have summarised these in
Table 5.

Table 5. Summary of survey method strengths and weaknesses.

Vessel-based – Visual

Strengths	Weaknesses
Established and robust methods for survey and analysis of relative abundance	Expensive: high operational costs
Observation strip width large (typically higher encounter rates than aerial surveys)	Expensive: long transit times
Slow platform speed: allows for the collection of additional information such as; animal stage/age structure, morphometrics, associations and health assessment metrics also sea surface temperature, salinity *etc*.	Expensive: Slow platform speed on survey
High spatial monitoring resolution	Possibility of responsive movement (animal movement in relation to the vessel)
Repeat surveys allow for long-term study	Navigational constraints in areas of high anthropogenic utility (shipping, fishing, off-shore wind developments)
Can provide information on distribution	Cannot be validated after the event to assess reliability of counts and species identity
	Visibility restriction due to weather/daylight
	Weather constraints for smaller vessels
	Variability often high, can be difficult to detect trends
	Provides ‘snapshots’ of abundance
	Concurrent monitoring of different areas of the site not possible unless multiple vessels used

Aerial – Visual

Strengths	Weaknesses
Established and robust methods for survey and analysis of relative abundance	Expensive: high operational costs
Short transit times, can cover large areas quickly	Height limitations around off-shore developments
Can take advantage of good weather windows more rapidly than a boat	Cannot be validated after the event to assess reliability of counts and species identity
Less possibility of responsive movement compared to ship-board (animal movement in relation to the vessel)	Re-fuelling logistics will dictate transit times for offshore surveys
High spatial monitoring resolution	Possibility of responsive movement with some aircraft/species
	Provides ‘snapshots’ of abundance but at a finer temporal scale than ship-board due to faster vessel
	Concurrent monitoring of different areas of the site not possible unless multiple craft used

Aerial – Digital video/photo

Strengths	Weaknesses
Short transit times	Expensive: high operational costs and
Images are available for independent verification	Expensive: time-consuming post-processing costs
Aircraft can operate at a height to avoid disturbance to animals	Provides ‘snapshots’ of abundance but at a finer temporal scale than ship-board due to faster vessel speed
Aircraft can operate at a height greater than turbine blades reducing collision risk/ navigational constrains	Depending on strip width greater lengths of transects required for comparable precision with aerial visual surveys (can be reduced with multiple cameras or cameras with larger footprints
Observation strip width small (aircraft fly at much higher altitude than for visual surveys, and the strip covered is currently relatively narrow)	Appropriate width of survey strip may vary by species (so for multi-species surveys, the choice must be a compromise)
High spatial monitoring resolution	Re-fuelling logistics will dictate transit times for offshore surveys
	Concurrent monitoring of different areas of the site not possible unless multiple craft used

Unmanned Autonomous Vehicles

Strengths	Weaknesses
Long missions possible for some devices (*e.g.* solar powered)	Long transit times
	Slow survey speeds
	Performance dependent on vessel/ ambient noise

	Subject to deviation from transect lines, due to weather/ navigational constraints
	Risk of device loss unknown and replacement expensive
	Reliability to complete missions is unknown for some newer technologies

Vessel-based PAM

Strengths	Weaknesses
Method independent of daylight and most weather conditions	Expensive: high operational costs
High spatial resolution data	Expensive: time-consuming post-processing costs
Relative abundance estimate and species identification for harbour porpoise well established	Performance dependent on vessel noise/ ambient noise
Recordings are available for independent verification	Limited detection range of high frequency vocalisation ~200m
	Limited detection ability for highly directional sounds
	Possibility of responsive movement (animal movement in relation to the vessel)
	Navigational constraints in areas of high anthropogenic utility (shipping, fishing, off-shore wind developments)
	Provides ‘snapshots’ of abundance but at a finer temporal scale than ship-board due to faster vessel speed
	Concurrent monitoring of different areas of the site not possible unless multiple craft used

Static PAM

Strengths	Weaknesses
High temporal resolution through continuous monitoring	High frequency detection range is limited to approximately 200m
Relatively inexpensive	Limited detection ability for highly directional sounds
Long-term data collection	Retrieval of most devices is required to obtain the data
Can be used to monitor relative abundance depending on assumptions	Background noise compensation only possible with some devices or if other noise monitoring devices deployed
Recordings are available for independent verification	Limited ability to define detection range
Allows concurrent monitoring of different areas of the site	

4 Comparison of static acoustic hardware and deployment options

Though we present details of our final recommendations in section 6, following our exploration of the relevant factors affecting robust and feasible survey design, in this section, we explore the best combination of static PAM hardware and deployment options that would maximise the success of such a monitoring effort.

The most common PAM hardware successfully used for monitoring harbour porpoises is the porpoise click detector (POD), C-POD and its predecessor, the T-POD and companion software developed by Chelonia Ltd, UK. The POD was, for a long time, the most suitable and cost-effective device for long-term monitoring of porpoises and other toothed whales. Nowadays, a wider range of devices are available and are worthy of consideration when setting up a monitoring regime.

4.1 PAM systems suitable for harbour porpoise monitoring

The clicks of harbour porpoises have a very distinct characteristic and are of high frequency with main energy around 130kHz (*e.g.* Villadsgaard 2007). To be able to record these clicks, a sound recorder must store samples at least every 0.003 millisecond (3µs), which fills up memory space quickly, and thereby limits the time monitoring is possible. To overcome this problem, some developers incorporate a processing routine into their monitoring devices allowing the storage of sound information only at times where possible harbour porpoise clicks occur (*e.g.* the Chelonia Ltd., C-POD, OceanInstruments NZ SoundTrap, Table 6). Other companies have overcome this problem by developing systems which transmit the data in real time or at scheduled intervals to reduce memory requirements and risks of device/data loss (*e.g.* SA Instrumentation Ltd, Table 7). For devices which save only processed data, storage requirements are reduced by orders of magnitude which prolongs the recording time considerably.

Once retrieved, data need to be searched for harbour porpoise detections. This is a substantial amount of work which will require committed personnel and resources for the duration of the monitoring regime. Processing routines, such as those mentioned above which reduce the amount of data, can also be used post-hoc to find potential detections of harbour porpoise. These will, however, reveal a certain amount of “true detections”, *i.e.* clicks truly stemming from porpoises, and “false alarms”, *i.e.* short pulsed sounds in the same frequency ranges as porpoise clicks but not emitted by porpoises. Such false alarms can come from, sonars, ship propellers, and high sea states (Tregenza 2016) depending on the quality of the processing routine visual inspection of potential detections may be needed to a greater or lesser extent.

Chelonia Ltd., have developed a detection algorithm that searches for click trains and classifies them into different categories of likelihood for being a true positive (Tregenza 2016). CPOD system validation studies report good performance of the Kerno classifier algorithm (Herrmann 2011; Krügel 2012). The decision on whether a C-POD porpoise detection is true or false however are solely based on the set of click parameters stored by the C-POD and characteristics of the time interval in-between successive clicks of a click train (the ‘click pattern’). The full frequency spectrum of the sound accompanying a detection is not available.

Greater confidence in determining a true detection based on the structure and frequency content of a click is possible where broadband snippets are recorded. Providing information over the whole frequency range of the sound recordings at the time of click detection, the broadband snippets provide additional information for confirmation/rejection of detections. Automatic detections of potential harbour porpoise clicks with the storage of broadband sound at the time of click detection is a feature of the software PAMGuard (Gillespie 2008). A derivation of PAMGuard click detection algorithm is implemented in the transmitting system Decimus (Table 7). A slightly different, but equally effective algorithm is implemented in the SoundTrap (Table 6) and SoundTrap data can be easily imported into PAMGuard for data analysis. The detection of porpoises, for the monitoring application as described here, is solely based on amplitude and frequency characteristics of single clicks and is therefore prone to false detections. To obtain suitable results, automatic detections should either be visually inspected, or time would need to be invested to determine a set of parameters for the porpoise click classifier, that is applicable to the monitoring data retrieved, and reduces the false-alarm rate to a reasonable minimum. For reducing the false-alarm rate of a classifier, a conservative approach has to be chosen, which will not only reject a higher amount of false alarms but also a higher number of true porpoise clicks, leading to a higher rate of missing porpoise encounters.

Additional to monitoring harbour porpoise echolocation clicks, some monitoring devices can simultaneously record background noise. This feature provides valuable covariate information for the porpoise monitoring data as a) background noise will affect the detection performance of a device and b) porpoise presence may be influenced by other activities in the area such as vessel noise. Monitoring for noise will also support the requirement of the Marine Strategy Framework Directive (MSFD) descriptor 11.

A fundamental consideration for long-term monitoring is the recording time, data storage capability and service cycle for the devices. To ensure the cost benefits of this form of monitoring approach the service cycles must be long, however long service intervals must be balanced with the risk of device loss. The anchoring and marker systems for static PAM devices are critical components for safeguarding equipment and data from natural and anthropogenic influences which may lead to device loss (see section 4.3).

4.2 Pros and cons of archival systems versus transmitting systems

There are two fundamentally different data storage/retrieval methods for static PAM devices; archival and transmitting systems. They each contain their own risks and benefits which we summarise below.

4.2.1 Archival systems

Archival systems (Table 6) are more commonly used and are more widely available for recording acoustic signals from marine animals. These devices have been developed to record and store raw or processed data at the site of recording. To retrieve the data the deployment site must be visited, data downloaded and the device serviced for the next recording window. These self-contained units can be attached to regular underwater moorings (section 4.3). While archival systems, compared to transmitting systems, tend to be at the cheaper end of the product range, overall costs are raised by the need of regular services and potential loss of devices and mooring systems. A limitation of archival devices is that data may be lost for part or the whole deployment period and this will not be known until the next service cycle. Due to the requirements for regular servicing and data download these systems also incur a greater health and safety risk than transmitting systems.

Five developers currently offer systems which allow the recording of harbour porpoise echolocation clicks. The Ocean Instruments NZ Soundtrap 500 and the JASCO Applied Sciences JASCO AMAR systems allow the longest monitoring periods (6-12 months). The

Ocean Instruments NZ SoundTrap 500 further offers the recording of background noise in parallel to porpoise monitoring. The Chelonia Ltd., C-POD system is expected to generate data which will require the least amount of post-processing due to the low false alarm rate of the detection. As with all monitoring, there is a necessary trade-off between assessing every click and summaries from algorithms. Whilst the C-POD detection algorithm is proprietary and is currently independently unverified it represents a useful middle ground in PAM technology. Given the comparably low costs of C-PODs and SoundTraps both systems, may be good candidates for a larger scale long-term monitoring.

Table 6. Archival recording systems suitable for harbour porpoise monitoring. Specifications and approximate costs are taken from online technical materials and past quotes/tenders/ invoices.

Archival systems	Noise monitor-ing	Broad band snippets	Processed data	Max depth (m)	Record-ing time (contin-uous)	Estimated Unit Cost	Developer	Notes
C-POD	-	-	X	100	2-3 months	£1,800 - £3,500	Chelonia Ltd	
C-POD-F	-	-	X		2-3 months	£3,565 - £7,130	Chelonia Ltd	**
DeepC-POD	-	-	X	2000	2-3 months	£3,500	Chelonia Ltd	
EA-SDA1000 recorder	X	-	-	700	35 days*	Price unavailable	RTSys	Import duty, taxes, shipping and insurance to be added to non- UK providers
SM3M Deep	X	-	-	800	52 days*	£9,626	Wildlife acoustics	
SM3M Sub	X	-	-	150	52 days*	£6,952	Wildlife acoustics	
SM4M Deep with click detector	X	-	-	800	4-5 months	Price unavailable	Wildlife acoustics	
SM4M Sub with click detector	X	-	-	150	4-5 months	Price unavailable	Wildlife acoustics	
SoundTrap HF with click detector	X	X	X	500+	2-3 months	£1,907	Ocean Instruments NZ	
SoundTrap 500	X	X	X	500	6 months	£2,844	Ocean Instruments NZ	
JASCO AMAR	-	-	X	500	6-12 months	Price unavailable	JASCO Applied Sciences	

* can be duty cycled to enhance recording time.
** Under development.

4.2.2 Transmitting systems

There is a smaller range of transmitting systems (Table 7) due to their more recent market development. The devices offer remote acoustic detection as do the archival systems, however the products transmit data in regular intervals (*e.g.* daily) with system status updates provided more frequently. The advantages of such systems are: users can have confidence that the system is in place and functioning; early detection of any malfunctions; regular data retrieval without the requirement to work off-shore; and reduced health and safety concerns as fewer service trips are required if solar panel charging options are utilised to extend battery life. To our knowledge at least for Decimus, no ‘off the shelf’ deployment platforms are available, and this adds unknown cost and complexity to any deployment predictions. As with archival recording systems, equipment and mooring charges are to be expected. Costs for transmitting and receiving data will also need to be considered though the reduced need for service trips (especially if a self-powering option is implemented) would reduce vessel costs compared to the archival option as well as the accompanied health and safety risks. However, the viability of such devices for a project of this scale and up to 200 km offshore as far as we are aware remains untested.

Table 7. Transmitting systems suitable for harbour porpoise monitoring. Specifications and approximate costs are taken from online technical materials and past quotes/tenders/ invoices.

Transmitting systems	Noise monitoring	Broadband snippets	Processed data	Estimated Unit Cost	Developer
Decimus	x	x	x	\$2,000 - \$5,000[1] £60,000 – 70,000[2]	SA Instrumentation Ltd
Seiche real time transmission system	x	-	-	Price unavailable	Seiche Ltd
SDA14	x	-	x	Price unavailable	RTSys

[1] Processing board only.
[2] System and mooring.

4.3 Mooring systems

There is an inherent risk to any device deployed at sea for long periods. Static PAM systems and their moorings are sensitive to damage and loss in a number of ways including but not limited to collision and deliberate or unintentional relocation and removal of devices by shipping/fishing/military traffic or natural events such as storms. The devices must therefore be robust to both natural (bad weather) and anthropogenic interaction as there are a number of other users of the SNS cSAC and 'buffer'. One important point to consider for passive acoustic monitoring is that moorings need to be quiet. Anchor chains and other components of a mooring system can be a source of background noise that can hamper the detection of porpoises. This noise will also interfere with noise recordings that may be done alongside the porpoise monitoring.

4.3.1 Moorings with surface markers

Moorings with surface markers have the advantage that they can easily be seen and found during service trips. They can, however, also be seen by any person at sea and are therefore not theft-proofed. Surface markers need to be prominent enough to be visible for vessel traffic and robust enough to survive storms and collision in case vessels overlook them or they are dragged away by fishing nets. The positions and make of the surface markers need to be agreed with the responsible shipping authorities. Accessories such as radar reflectors, lighting and/or maritime markers may need to be added to the buoy, and positions may need to be registered (including registration fee). Shipping authorities may offer the opportunity to rent such moorings.

In the North Sea those moorings should be sufficiently large not only because of the vessel traffic but also to resist the prevailing harsh offshore conditions. The large size required makes this kind of mooring relatively expensive compared to moorings that can be deployed in more sheltered conditions. The first deployment as well as the final recovery will require a large vessel with a sufficiently powerful crane and storage space on board. For the deployment of transmitting systems, moorings with surface markers are the only option. Due to the specifications of the current devices robust mooring options with capacity to hold powering units (*e.g.* batteries, solar panels) are required to support the devices. For the deployment of archival systems, the mooring can be designed so that service visits can be done with smaller vessels. This can be achieved by a mooring consisting of two buoys, one large and heavy main buoy for stabilising and securing the whole system, and one smaller buoy that allows access to the archival monitoring device, which can be lifted by a small crane (*e.g.* Figure 8 and Figure 9). Another option is to employ a diver for exchanging the monitoring system, as may be needed for systems such as shown in Figure 10. To reduce costs while still using the safety of a heavy main buoy, a smaller mooring system can be placed in the vicinity of a fairway buoy (in correspondence with the shipping authorities).

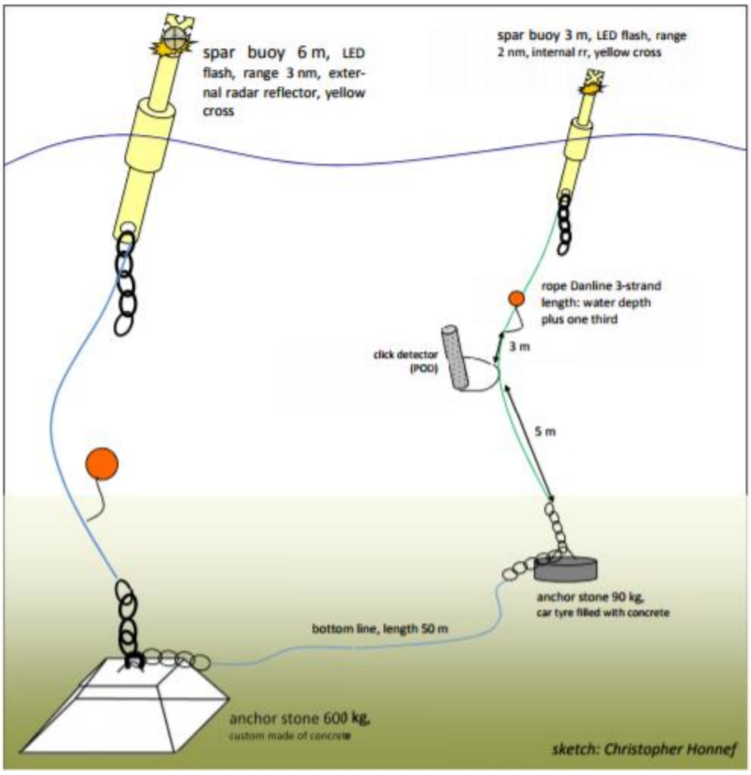


Figure 8. Mooring system used in the German North Sea at the offshore wind farm test site alpha ventus (Rose 2014).

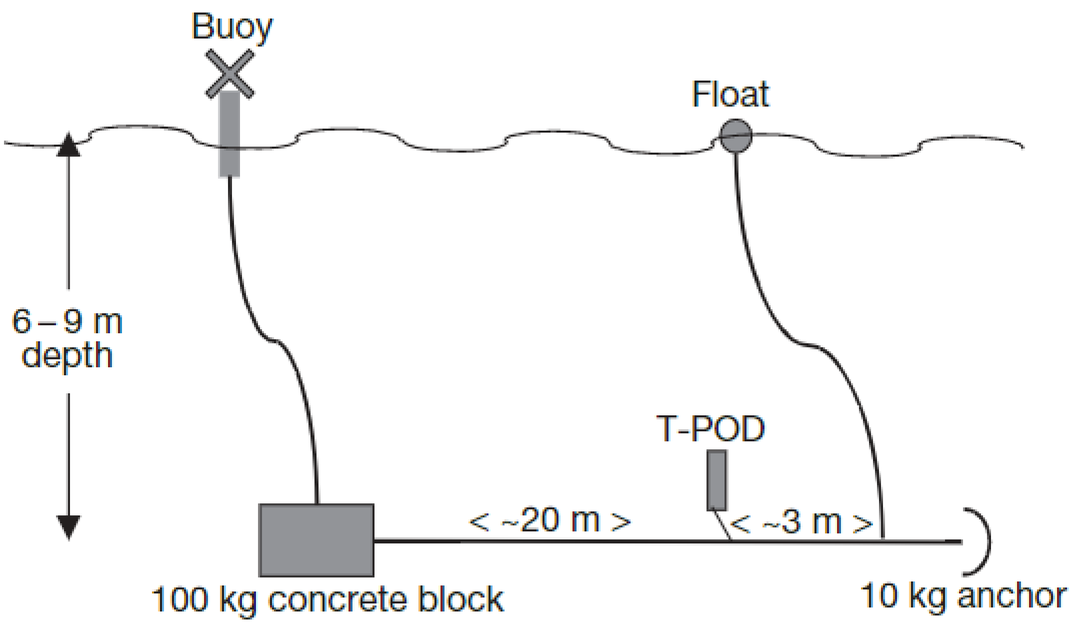


Figure 9. Mooring system used in the Danish Belt Sea at the offshore wind farm site Nysted (Carstensen 2006).

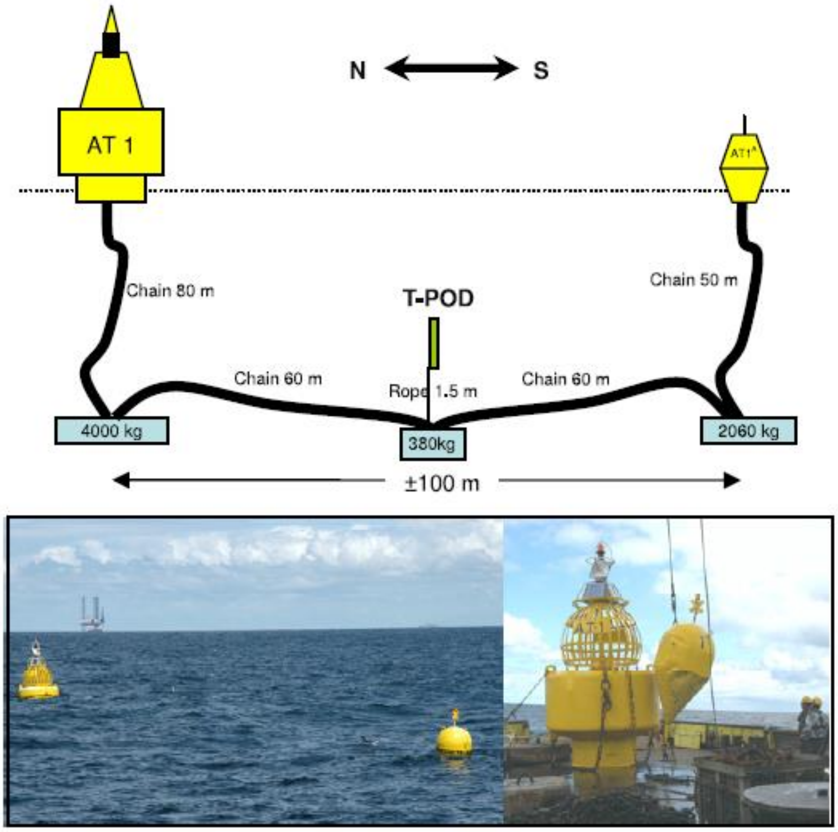


Figure 10. Mooring system used in the Dutch North Sea at the offshore wind farm site Egmond aan Zee (Scheidat 2011).

4.3.2 Moorings with releasing systems

An option often used for archival systems is a mooring with an acoustic releasing system. These moorings consist of an anchoring weight and a releasing mechanism that holds the recording device and floats to keep the whole system upright in the water column. The whole mooring is submerged under water and no surface marker is used. This has the advantage that the mooring is positioned below the vessel traffic (given a sufficient water depth) and can therefore not be overrun by vessels and is theft-proof. It is easy to deploy and only requires a small vessel for deployment, maintenance and recovery. Verfuss (2014) provide a detailed description of such systems for noise loggers (Figure 11) and explain how to assemble such a mooring system and what to consider. While these systems are generally safe from vessel traffic as such, they can be trawled away by fishing vessels. It may also be challenging to find the position of a system during service trips, especially if the system drifted / was dragged away in-between services. Furthermore, releasing systems are prone to malfunction: they may exhibit an early release due to low batteries or being triggered by sounds other than the release-trigger sound they are programmed to. They may also not release at all, or the release system is covered by fowling and the monitoring device cannot float to the water surface. The employment of a vessel with a side-scan sonar to search for the mooring system and a diver or ROV to retrieve it may then be an option for recovery.

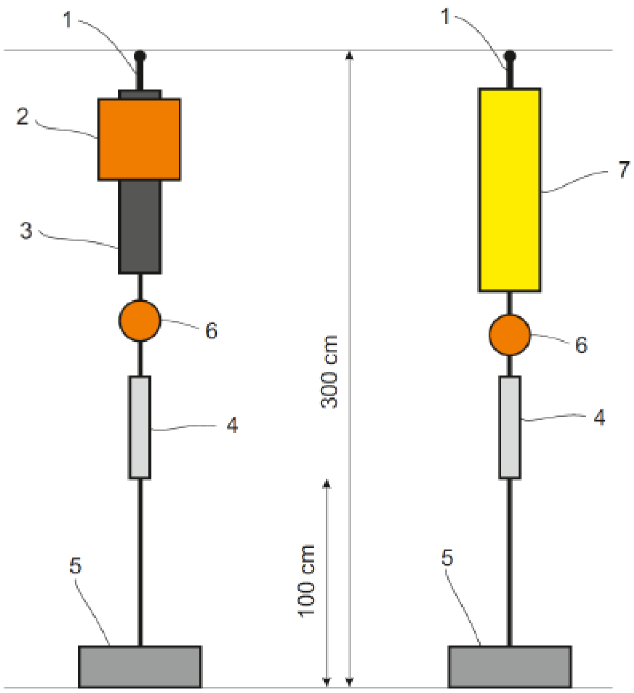


Figure 11: Acoustic release system as proposed by Verfuss (2014) for loggers monitoring continuous noise with 1 – hydrophone, 2 - extra buoyancy, 3 – DSG ocean logger, 4 – acoustic releaser, 5 - ballast weight, 6 – buoy and 7 – SM2M logger.

4.3.3 Trawler safe moorings

Another option that is described in Verfuss (2014) for mooring noise loggers (which is also used for PODs) is a trawler safe mooring. This kind of mooring was invented by the team of the Hel Marine Station, University of Gdansk, specifically for Polish waters of the Baltic Sea, where trawling is one of the major issues when deploying monitoring devices. This mooring is made out of a steel pyramid-shaped frame and a plastic tube that is connected to the frame by means of four strings (Figure 12) allowing the monitoring device to tilt in such cases when a trawler net passes over it. It needs a vessel with a winch and two people for deployment and recovery. If this system would be an option for the application in the cSAC we would recommend detailed discussions with the developers and existing users.

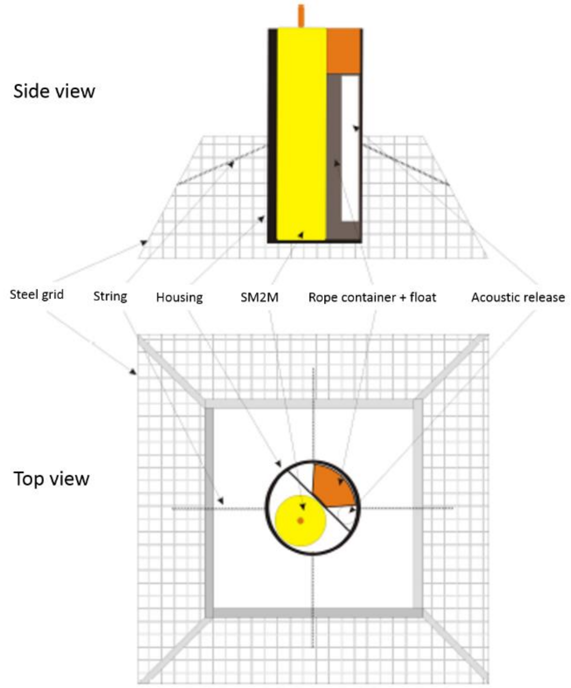


Figure 12. Trawl-protected rig as proposed by Verfuss (2014) for noise loggers.

4.3.4 Estimated costing for static PAM monitoring

We have generated estimates of cost for a static PAM arrays using a Spar buoy mooring system (based on Figure 8) in collaboration with marine mooring equipment specialists (Table 8 A and B). We used the results of the power analysis in section 5 to inform the costing for accuracy in the number of moorings which would be required (63 recording devices) and the distances between deployments (35km). For supply, deployment and 4 x servicing of this mooring system (caveats listed beneath tables) and incorporating the cost of archival recording devices, project management and analytical costs, the total for the first year was estimated to be between £1,175,500 - £1,625,950 depending on the use of acoustic releases on each of the moorings and £609,300 - £537,800 or subsequent years. For a limited set of scenarios we also explored a 40km x 40km grid (49 recording devices). First year monitoring costs for 49 devices ranged between £1,347,350 and £997,000 (depending on use of acoustic releases) see Appendix 1: Estimated costing for 40km x 40km static PAM array for more detail.

Table 8. Indicative schedule of A) first year rates for North Sea supply, deployment and service of 63 static PAM moorings spaced 35km apart and B) subsequent year servicing and maintenance of the monitoring system (developed in collaboration with mooring specialists March 2018). Due to the size and location of the site, with moorings required potentially >120NM from the nearest safe haven a large vessel with 24 hour operations is recommended.

A)

Option	Description	Ind. Quantity	Rate	Total amount	Comments
Year 1 63 sites, 35km apart	Mooring Purchase (Each)	63	£3,500	£220,500	Includes Spar buoy and dahn flag but not Acoustic Release
	Acoustic Release Purchase	63	£7,150	£450,450	Pop-up release with rope canister to recover CPOD
	Deployment (Lump sum)	1	£156,000	£156,000	Assumes 17 ops days and £5k/day vessel costs
	Service Visit (Each)	4	£91,000	£364,000	Assumes 12 ops days to service 63 No. moorings
	Complete Mooring Replacement	0	£3,500	£0	Includes IALA compliant special mark
	Specialist labour to procure and assemble replacement mooring	0	£750	£0	Procure & assemble 1 No. replacement mooring only. To be used in the event of mooring loss.
			Sub-Total	**£1,190,950**	Including acoustic releases
			Sub-Total	**£740,500**	Not including acoustic releases
	Acoustic device purchase	70	£3,500	£245,000	Includes spare devices. Large orders may trigger a discount (Evans & Thomas 2013)
	Analytical costs	2	£70,000	£140,000	2 x post-doctoral researchers
	Project management costs	1	£50,000	£50,000	Administration, logistics and reporting
			Total	**£1,625,950**	Including acoustic releases
			Total	**£1,175,500**	Not including acoustic releases

Caveats/points to consider

Costs are weather exclusive. Vessel will be capable of 10kts with lifting equipment and berths. No costs included for arranging licensing. Moorings will need components replacing annually.

B)

Option	Description	Ind. Quantity	Rate	Total amount	Comments
Year 2 and beyond 63 sites, 35km apart	Mooring Purchase (Each)	10	£3,500	£35,00	Includes Spar buoy and dahn flag but not Acoustic Release
	Acoustic Release Purchase	10	£7,150	£71,500	Pop-up release with rope canister to recover Cpod
	Mooring maintenance trip (Lump sum)	1	£156,000	£156,000	Assumes 17 ops days and £5k/day vessel costs
	Service Visit (Each)	3	£91,000	£273,000	Assumes 12 ops days to service 63 No. moorings
	Mooring maintenance	63	£1,500	£94,500	Includes components and labour
	Complete Mooring Replacement	0	£3,500	£0	Includes IALA compliant special mark
	Specialist labour to procure and assemble replacement mooring	0	£750	£0	Procure & assemble 1 No. replacement mooring only. To be used in the event of mooring loss.
			Sub-Total	**£384,300**	Including acoustic releases
			Sub-Total	**£312,800**	Not including acoustic releases
	Acoustic device purchase	10	£3,500	£35,00	Includes spare devices
	Analytical costs	2	£70,000	£140,000	2 x post-doctoral researchers
	Project management costs	1	£50,000	£50,000	Administration, logistics and reporting
			Total	**£609,300**	Including acoustic releases
			Total	**£537,800**	Not including acoustic releases

Caveats/points to consider

Costs are weather exclusive. Vessel will be capable of 10kts with lifting equipment and berths. No costs included for arranging licensing. Moorings will need components replacing annually.

5 Passive Acoustic Monitoring design

In this section, the ability of long-term monitoring studies using PAM sensors to detect changes in density is examined. Three detection scenarios were specified in Section 3 Project Objectives:

- a decline in the cSAC compared to no decline in the 'buffer';
- seasonal changes in usage within the cSAC; and
- short-term change in usage within the cSAC.

In Section 3.4.5 Power to detect declines, we introduced the concept of a power analysis and the context of detecting a trend using a simple linear model for illustration. However, the approach taken to address the project specific change scenarios listed above is more complex and uses a simulation tool designed for PAM sensors and exponential log-linear models.

5.1 Density estimation using PAM sensors

For PAM sensors, absolute density of animals ($D_{animals}$) is estimated from:

$$\hat{D}_{animals} = \frac{n_c(1-f)}{k\pi w^2 . \hat{p} . T . c . a_{perc}} \qquad (2)$$

where:

- n_c is the total number of cues (clicks);
- f is the proportion of incorrectly detected cues and so $(1-f)$ is the proportion of correctly detected cues;
- k is the number of points (PAMs);
- w is the radial distance and so $k\pi w^2$ is the covered area;
- $\hat{p}$ is the average detection probability of cues within the covered area, assuming all cues are detected at w=0;
- T is the acoustic recording length at each point (seconds);
- c is the cue rate (*e.g.* number of cues per second); and
- a_{perc} is the perception bias, the proportion of cues that are missed directly over the sensor.

In this project, absolute density was not required and so to estimate the relative density of animals $D_{relative}$ the above equation can be reduced as follows:

$$\hat{D}_{relative} = \frac{n_c}{k\pi w^2 . T} \qquad (3)$$

One implicit assumption in quantifying trends in $D_{relative}$ is that they reflect population trends (trends in *D*) – *i.e.* that the missing multipliers (*p* and *c*) are constant. We return to this in the discussion. Another assumption is that the density of animals is proportional to the density of cues/clicks.

5.2 Methodology

To investigate the change scenarios in relation to long-term monitoring studies using fixed PAM sensors, the simulation tools (called 'AVADECAF') developed by Booth *et al*. (2017) that were specifically designed for density estimation from fixed PAM sensors were used.

Due to the limited scope of this study, it was not possible to conduct a complete sensitivity analysis of every possible permutation of the parameters of the power analysis and monitoring programme considered. Therefore, instead, we have assessed some general trends of survey elements we can control (*e.g.* the number of sensors deployed, length of monitoring, the number of estimates generated per year) and those we cannot (*e.g.* the variation in cue rate of porpoises) – before considering some more specific scenarios as specified in the objectives.

The AVADECAF tool allows the user to specify true animal densities and some true change (dependent on the change scenario) over the survey period. A change scenario is composed of three elements:

- the study region size and shape;
- the survey design properties; and
- the characteristics of the species of interest.

Each of these elements needs to be defined by the user by parameterizing input variables. Data are then generated according to these values and an appropriate regression model fitted. In this application, a generalized linear model was fitted with a 'quasi-poisson' error distribution and log-link function (other error distributions/link functions could be used). A *t*-test is performed on the particular regression coefficient of interest and its significance (difference from zero) determined by α. This process is repeated many times and the results harvested to assess power. In this application, some elements were common to all scenarios and are described below; other parameters which were scenario specific are described in the appropriate section.

Where the change scenario included a decline, a decline of 25% or 10% was specified in the simulation (*i.e.* the population at the end of the study period was 75% or 90% of the population at the start, respectively). If the change included an increase, then an increase of 25% or 10% by the end of the study length, respectively, was specified. The scenarios assessing the long-term decline within the cSAC were simulated 5,000 times, however, for expediency, the other scenarios were simulated 1,000 times.

5.2.1 Characterising the study region

In this project, there were two regions of interest: the cSAC, and a buffer region of 50km around the cSAC and clipped to the EEZ (thus, splitting the buffer into disjunct areas, Figure 3). The areas of the cSAC and buffer were 36,951km^2 and 41,381km^2 (36,961 North + 4,420 South), respectively.

5.2.2 Survey design properties

Sensors were located throughout the regions of interest on a systematic grid with a random start point, thus the number required for a realization of a design will vary (by a few sensors) depending on the geographic start point in any given simulation. In Section 3.4.4 Survey Effort we indicated the (average) number of sensors required in the cSAC and buffer for a specified grid point spacing. It was envisioned that for a 35km x 35km grid, a total of 63 sensors would be required (30 in cSAC, 33 in buffer). We also explored for a limited set of scenarios the power associated with a 25km x 25km grid spacing (126 total sensors; 60 sensors in cSAC, 66 in buffer) and a 40km x 40km grid (49 total sensors; 23 sensors in cSAC, 26 in buffer). These grid spacing's were specified and plotted in the simulation tool from Booth *et al*. (2017).

For most scenarios, two lengths of monitoring programme were investigated: 6 and 12 years (specified by the steering group). In limited scenarios we also considered an 18 year monitoring programme.

5.2.3 Overview of the study population

5.2.3.1 Harbour porpoise density

In summer of 2016 the region was surveyed as part of SCANS-III (Hammond 2017). The results for the region showed that there was an average density of approximately 0.8 porpoise/km^2 (Table 9).

Table 9. Summary of results for survey blocks L and O from SCANS-III taken from Hammond *et al.* (2017). These blocks were surveyed by plane.

Block	Area (km^2)	Abundance	Density (animals/km^2)	CV
L	31404	19064	0.607	**0.38**
O	60198	53485	0.888	**0.21**
Total	***91602***	***72549***	***0.792***	***0.18***

Two regions based on the winter-summer usage of harbour porpoise have been defined (Figure 13). The southern region and a small section in the north-west were considered to persistently have higher densities in the winter than in the summer (Heinänen & Skov 2015).

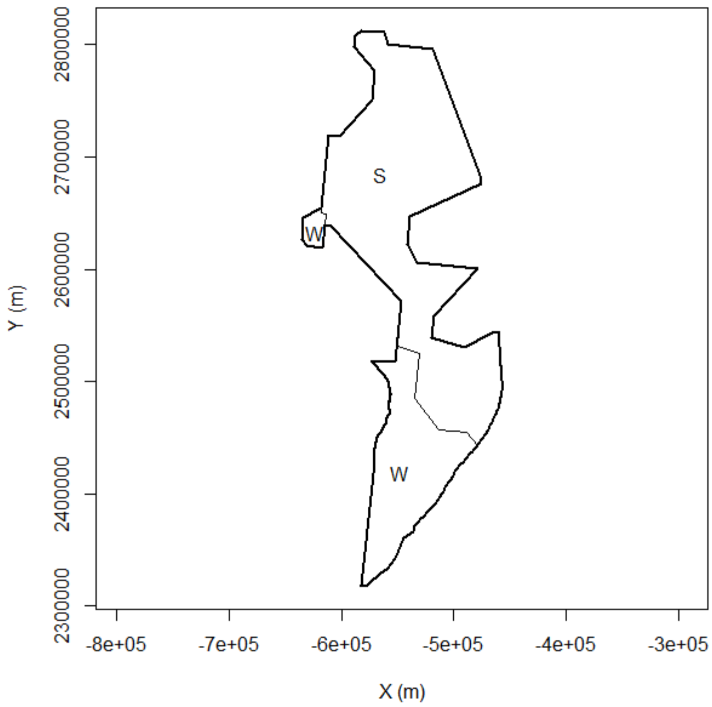


Figure 13: Boundaries based on seasonal usage: densities are persistently higher in winter than in the summer (in region W) and densities are persistently higher in the summer than in the winter (in region S).

5.2.3.2 Number of cues

Within the AVADECAF simulation package (Booth 2017), the number of cues at each sensor (n_{ci} where *i* indicates the sensor) were generated from

$$n_{ci} = \frac{\hat{D}_{animals,i} k \pi w^2 . \hat{p} . T . c . a_{perc}}{(1-f)} \quad (4)$$

where the parameters were obtained as follows:

- $\hat{D}_{animals,i}$ – density at sensor *i* (obtained from the specified density surfaces);
- truncation distance (w) - 400m (*i.e.* it was assumed that no HP click further than 400m can be detected);
- $\hat{p}$ was defined by a half-normal detection function ($g(y) = \exp(-y^2/2\sigma^2)$ where parameter - $\sigma = exp(4.5)$ Marques *et al*. (2013) suggested that for fixed sensors the largest component of a (density estimate) variance might be between sensor variability. This variability was incorporated by randomly varying the detection function between sensors (Figure 14);
- T is monitoring time (seconds). It was assumed that monitoring continues all day every day in the year, except for seasonal change scenarios (section 5.2.6) when density was estimated from data collected in '6 month' bins (*i.e.* the analysis was done on a seasonal (summer/winter) resolution, though the sensors would be deployed year round);
- cue production rate c - 10 clicks per second. No seasonal/yearly changes. This is likely to be a conservative estimate. Booth *et al.* (2017) found that cue rate did not have much effect on power and initial results (not shown here) indicated the same thing;
- perception bias a_{perc} - 0.8 (CV=0.1) representing the proportion of cues missed directly over the sensor. No seasonal/yearly changes. This value was chosen to reflect the fact that, although click detection is likely to be certain for porpoises directly over the sensor, clicks can be rejected at the classification stage, depending on the classifier used. Booth *et al.* (2017) demonstrated that varying the *f* value had little effect on power – that is, the power was not sensitive to the chosen *a* value;
- false positive rates f - 0.01 (CV=0.01). A low false positive rate was chosen to match the stringent classifier (Hel1) used in SAMBAH (SAMBAH 2016). As above, Booth *et al.* (2017) demonstrated that varying the *f* value had little effect on power.

The total number of cues was obtained from $n_c = \sum_{i=1}^{k} n_{ci}$ and density in the region of interest is obtained from equation 2.

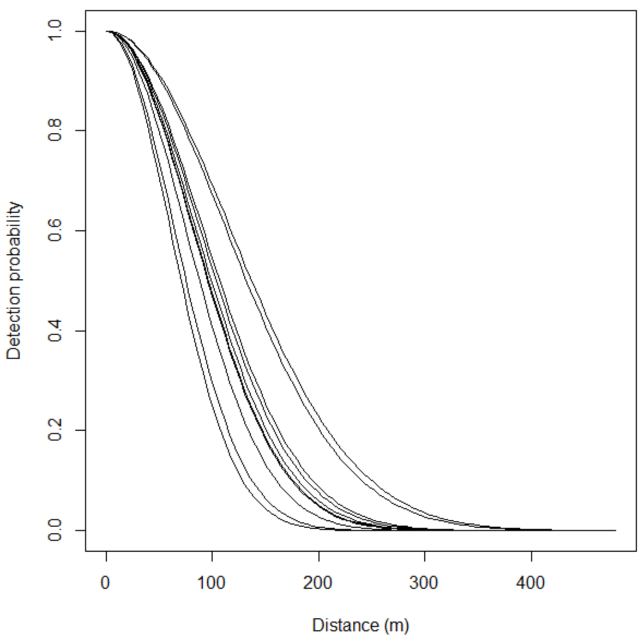


Figure 14. Half-normal detection function. Detection functions were selected at random for each sensor to incorporate likely variability between sensors.

5.2.4 A long-term decline in the cSAC

Prior to looking at the change scenarios listed above, the power of a study to detect a long-term decline in the cSAC was investigated using equation 1. Although not specifically requested, this scenario was included to provide a sensitivity of various parameters to put other results into context.

In this scenario, the sensitivity of the power to detect both a 25% decline and a 10% decline was investigated for different values of the following parameters:

- decline – equal proportion throughout the region (used for all scenarios);
- length of study – 6, 12 and 18 years;
- number of density estimates obtained per year - 1, 2 and 3 (assuming that data can be collected/processed at intervals throughout the year);
- spacing of PAM devices – 25km and 35km (and 40km for a limited set of simulations);
- variability of the cue rate, specified in terms of the CV - 0.05, 0.08, 0.1. This was used to specify five random realizations for cue production rate and the mean of the samples represented the estimated cue rate for each year and season. Sensitivity analysis in Booth *et al*. (2017) suggested that the CV of the cue rate was more influential on the power than the actual cue rate. This is not something we can control for in surveys and is a poorly understood topic for harbour porpoises (and most other cetaceans).

As a starting point, a density surface with some variation throughout the region, but with an average density overall of 0.8 animals/km^2 (based on the SCANS-III estimates, from surveys conducted during July/August) was generated (Figure 15).

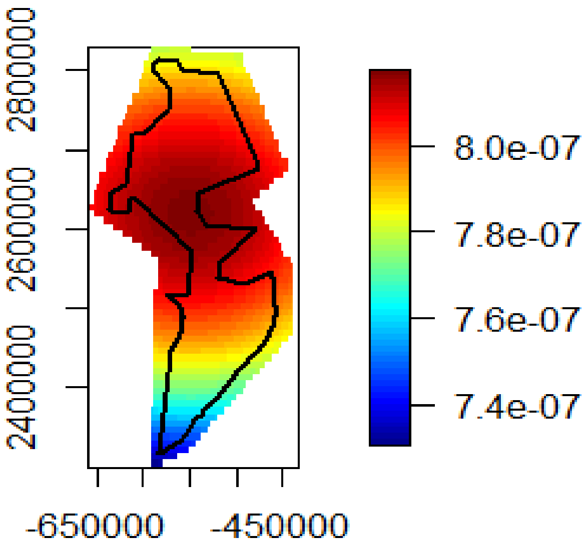


Figure 15. Density surface (colours indicate animals/m^2) in year 1, representative of 'summer' (based on SCANS-III). The thick black lines indicate the boundaries of the cSAC: the sensors were within the cSAC only and density was estimated for the cSAC.

5.2.5 Decline in the cSAC and no decline out with the cSAC

In this scenario, the study region was extended to include the buffer region and of interest was the power to detect a decline within the cSAC that did not occur in the buffer region (Figure 16). A density estimate was generated for each region (cSAC and buffer) for each year of the study with an imposed 25% decline (at the end of the study) in the cSAC and no change in the buffer. The regression model (Equation 1) was extended to allow for different regions (R):

$$D = \beta_0 + \beta_1 Y + \beta_2 R + \beta_3 Y.R + \epsilon \qquad (5)$$

where β_2 and β_3 were additional coefficients to be estimated from the fitted model. Thus, if there was a real difference in the trend between the two regions, the interaction term, β_3, would be non-zero.

An initial density surface was generated such that density was 0.8 animals/km^2 overall the total region but within the region densities varied (Figure 16).

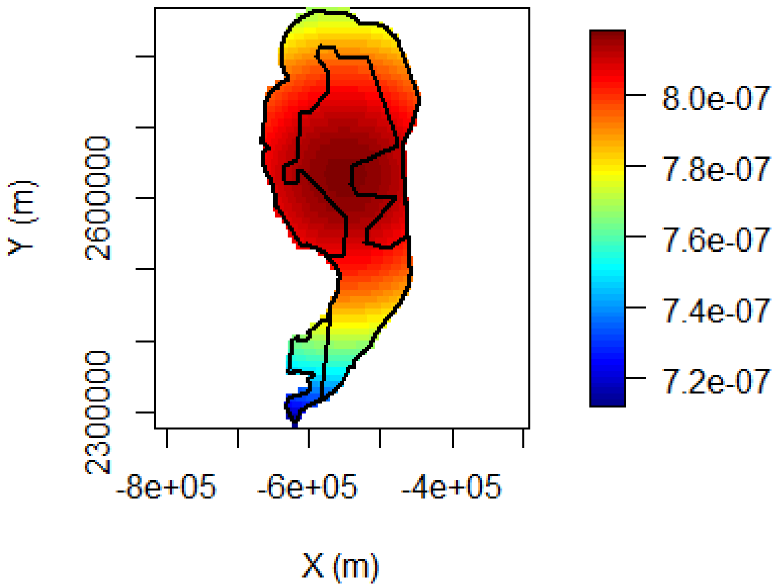


Figure 16. Density surface (animals/m^2) in year 1. The thick black lines indicate the boundaries of the cSAC and buffer.

The sensitivity of the power to different values of the following parameters was investigated:

- length of study – 6 and 12 years;
- variability of the cue rate, specified in terms of the CV - 0.05, 0.08 and 0.01;
- spacing of sensors – 25km and 35km.

5.2.6 Change of seasonal usage within the cSAC

Regions defining seasonal (winter and summer) usage have been specified within the cSAC (Figure 13) which more-or-less divided the cSAC into a northern and southern region. The small section in the north-west of the cSAC was treated as part of the southern region. Density is higher in the southern region in winter and higher in the northern region in the summer (Heinänen & Skov 2015). Scenarios were considered separately for each seasonal pattern (Figure 17 illustrates the initial densities used for the two seasons) and the envisioned changes related to densities in either the northern, the southern, or both regions, increasing, decreasing or staying the same (Table 10). Where a change was envisaged in a region (northern or southern), a 25% change (within the region) was specified; given the low power resulting for some of these scenarios (see later), a decline of 10% was not pursued.

For each seasonal pattern, estimated densities were generated for each region (northern and southern) based on monitoring for six months (to reflect a reduced amount of data used to obtain seasonal, rather than annual, estimates) according to the scenarios in Table 10. The density surfaces for year 1 for summer and winter are shown in Figure 17; the average densities were 0.8 and 1.5 animals/km^2 in the summer and winter, respectively. Equation (2) was used to fit the model, with the regions being the northern and southern regions (Figure 13). For scenarios 1 and 8 (same change in both regions), the regression coefficient tested was β_1- the coefficient associated with the trend over time. In order to limit the number of evaluated scenarios to a level feasible to implement in the available time, a grid spacing of 25km was specified. We explored the general pattern of changing the spacing (and therefore number) of sensors on power in section 6.3 below.

Table 10. Envisioned changes in density in the northern and southern regions (25% change in each region) defined by seasonal usage. The specified equation was fitted to the simulated data in order to test the change scenario.

Number	North	South
1	Decrease	Decrease
2	Decrease	No change
3	Decrease	Increase
4	No change	Decrease
5	No change	Increase
6	Increase	Decrease
7	Increase	No change
8	Increase	Increase

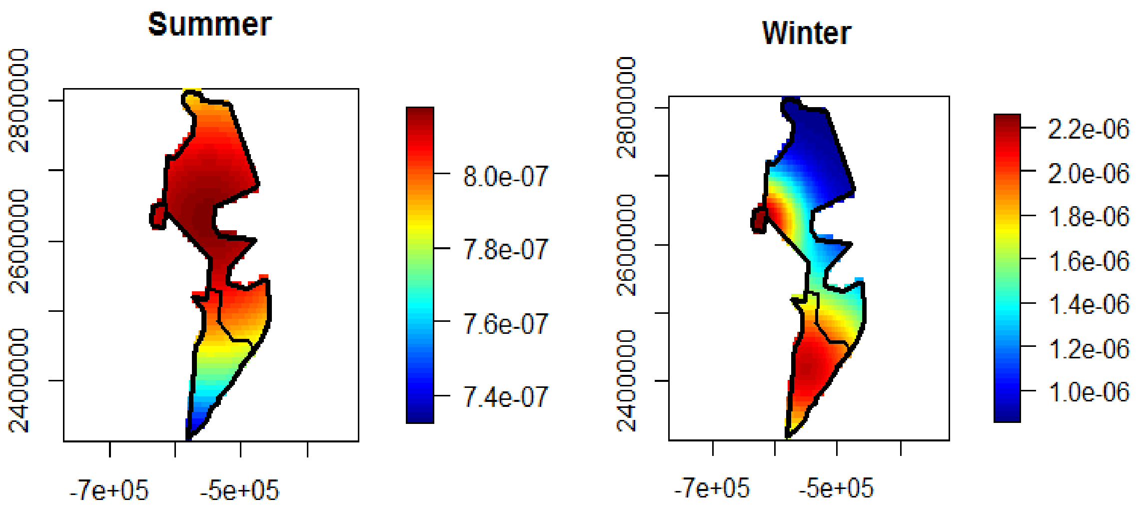


Figure 17. Density (animals/m^2) surfaces in year 1 for seasonal usage change scenarios.

5.2.7 Short-term changes in usage in cSAC

This scenario was motivated by considering possible porpoise reaction to the construction and operation of windfarms and therefore deviated from the classic scenarios we considered in sections 6.2.4-6.2.6 above. Carstensen *et al*. (2006) found that there was a decrease in porpoise acoustic behaviour within the construction area of an offshore wind farm. Assuming that echolocation activity was related to HP density, they contended that the decrease in echolocation activity was due to a reduction in harbour porpoise density. There were short-term effects due to specific activities during construction (*e.g.* ramming activity) and medium-term effects from operation: density had not recovered to pre-construction levels within the first year of operation (Tougaard 2005). To mimic this within the simulation tool, a density estimate was generated for each year of the study and the imposed change depended on construction phase (*i.e.* pre-, during and post-construction). Two example scenarios were considered for a six-year study:

1. Density was constant for two years, reduced by half for the third year and then increased by 10% for the next two years and by 5% in year six, such that at the end of six years it was 75% of the starting density.

2. Density was constant for two years, reduced by 30% in the third year and then increased by 10% for the next three years such that at the end of six years it had returned to the starting density.

Our interest here, was detecting a difference between the phases within the cSAC. Rather than consider year as the temporal variable, we used phase (*e.g.* pre-, during and post-construction) and the regression model was adapted as follows, where *P* represents phase of construction (which, in the scenarios specified, lasted different lengths of time – see the bullets above and section 6.3.4):

$$D = \beta_0 + \beta_i P + \epsilon \qquad (6)$$

The density surface generated in Section 5.2.4 (Figure 15) was used as the starting density and the CV of the cue rate was assumed to be 0.05 and a grid spacing of 25km was used in the simulation.

5.3 Results

5.3.1 General Patterns affecting power

Here the overall objective was to determine the best approach to monitoring harbour porpoise in the Southern North Sea cSAC using a series of power analyses to aid the assessment. There are a number of factors that affect the power of a survey and because it not possible to explore every permutation in this study, we have explored some general patterns (which are very likely to apply for the other analyses) to guide the monitoring design process.

Our results indicate that the length of the monitoring period had a marked impact on the power of surveys, with increasing power as the length of the monitoring period increased (*i.e.* from 6 years (black) to 12 (red) to 18 years (green lines), (Figure 18). To a lesser extent increasing the number of sensors (by reducing the spacing between points increased the power of the surveys (circles and triangles in Figure 18, also illustrated in Table 11). Whilst it is not possible to control for the variability of harbour porpoise cue rate, we determined that when porpoise click behaviour is more variable, this negatively affects power to detect changes (*i.e.* as variability increases, power decreases, Figure 18).

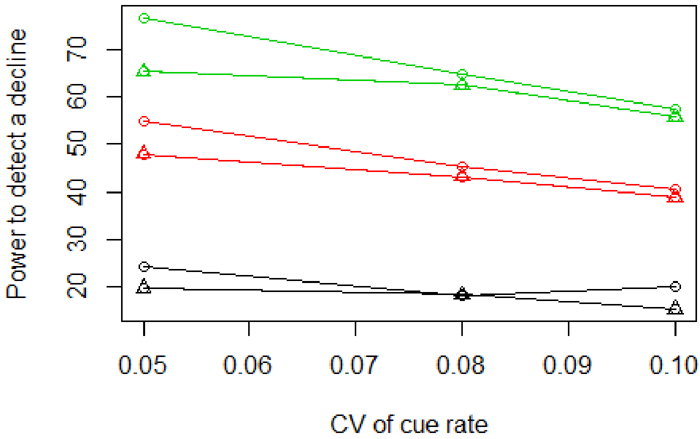


Figure 18. Power to detect a 25% decline in the SAC with a single estimate per year for a range of values for the CV of the cue rate, a study of length 6 years (black), 12 years (red) and 18 years (green) and sensors spaced at 25km (circle) and 35km (triangle).

As noted in section 3.4.6, the number of estimates generated in a year can affect the power to detect a change (in most scenarios we considered annual estimates to allow for comparison with published power estimates). We determined that increasing the number of estimates generated can significantly increase power. For example, for an 18-year monitoring programme with 30 sensors in the cSAC, increasing the number of estimates generated per year from 1, to 2 or 3 estimates resulted in power estimates of 48.0%, 82.1% and 93.9% respectively.

We expect that the power to detect smaller changes in population size in otherwise identical scenarios will be smaller than those for larger changes (as it is harder to reliably detect a smaller decline (see section 5.3.2).

Table 11. Exploring the effect of changing the number of sensors on the power. This scenario is only for the detection of a long-term decline in the cSAC (simulated 5,000 times) and therefore the number of sensors only relates to those deployed within the cSAC boundary.
*See Table 1 for the corresponding number of sensors to be deployed in the buffer region (for a corresponding spacing).

Number of years	Spacing	Sensors*	CV(cue)	Power with a 25% decline		
				1	2	3
6	25	59	0.05	24.4	53.8	74.7
12	25	59	0.05	54.2	87	96.8
18	25	59	0.05	75.9	97.5	99.7
6	35	30	0.05	22.4	47.6	68.5
12	35	30	0.05	49.5	81.6	95.2
18	35	30	0.05	69.5	95	99.5
6	40	23	0.05	19.8	44.1	63.1
12	40	23	0.05	46.4	78.9	92.7
18	40	23	0.05	65.6	92.9	98.9

5.3.2 A long-term decline in the cSAC

This section provides the results of the power to detect a long-term decline in the SAC and assess the sensitivity of the power to some key parameters.

The density surface generated for this scenario included some variation (approximately based on the SCANS-III estimated densities) throughout the cSAC but with an overall average density of 0.8 animals/km in year 1 (Figure 15). The best scenario for annual abundance estimates to detect a 25% decline over 6 years of monitoring was 24.4%, and 55% power following 12 years of monitoring. Even for the best scenario modelled; study length (12 years), number of sensors (n = 59) and the lowest CV of the cue rate (= 0.05), 55% power is fairly low.

Examination of the power results reveal that for annual abundance estimates; increasing the number of sensors in the study (*e.g.* 30 to 50) improves the power (19.8% to 24.4% over 6 years) but not as much as increasing the length of the study (19.8% or 48% for 30 devices over 6 and 12 years respectively) or reducing the CV (20.2% or 24.4% for 59 devices over 6 years for CV = 0.1 and 0.05 respectively). The influence of CV on the power to detect a decline in this scenario is illustrated in Figure 18. However, CV is not something we can control, the way that we can influence the power of the study is through manipulation of the number of sensors deployed and the length of the monitoring period. Management and budgetary considerations will need to be reviewed to determine what changes to the monitoring design can be made for the study to be able to detect a decline at the stated 80% power.

The largest improvement in power to detect a decline in the population is generated by increasing the number of density estimates per year (Table 12). For a 6-year monitoring programme with 59 sensors for CV = 0.05 power increased from one density estimate per year, 24.4% to 74.6% for 3 density estimates per year.

Table 12. Estimated power (as a percentage) of study to detect a 25% and a 10% decline in the cSAC for different number of density estimates per year (1, 2 or 3 estimates), length of study (years), spacing (km), CV of cue rate (CV(cue)) and number of sensors in the cSAC. The number of sensors is the average of the number of sensors generated for each simulation and in this scenario only relates to those deployed within the cSAC boundary (5,000 simulations were used for these scenarios).
*See Table 1 for the corresponding number of sensors to be deployed in the buffer region (for a corresponding spacing).

Number of years	Spacing	Sensors in cSAC	CV(cue)	Power with a 25% decline			Power with a 10% decline		
				1	2	3	1	2	3
6	25	59	0.05	24.4	53.8	74.7	6.5	11.1	15.3
6	25	59	0.08	20.1	45.3	64.0	5.5	9.6	13.9
6	25	59	0.1	17.6	40.0	57.3	5.8	8.8	11.9
6	35	30	0.05	22.4	47.6	68.5	6.4	10.0	13.8
6	35	30	0.08	19.2	40.9	58.0	5.3	9.3	12.6
6	35	30	0.1	17.0	36.1	51.6	5.2	8.7	11.1
6	40	23	0.05	19.8	44.1	63.1	6.3	9.9	12.7
12	25	59	0.05	54.2	87.0	96.8	11.9	21.0	29.8
12	25	59	0.08	44.8	79.5	93.7	10.4	17.9	25.1
12	25	59	0.1	41.4	71.4	88.4	9.3	15.2	21.2
12	35	30	0.05	49.5	81.6	95.2	10.7	17.9	26.5
12	35	30	0.08	40.0	74.3	90.6	9.0	16.4	21.3
12	35	30	0.1	36.8	68.5	85.2	8.9	13.0	18.5
12	40	23	0.05	46.4	78.9	92.7	10.3	17.2	24.3
18	25	59	0.05	75.9	97.5	99.7	16.2	30.1	42.0
18	25	59	0.08	66.5	94.3	99.0	12.7	24.6	34.4
18	25	59	0.1	58.7	87.2	97.3	12.2	21.5	30.0
18	35	30	0.05	69.5	95.0	99.5	15.2	26.1	36.8
18	35	30	0.08	60.8	90.1	98.0	13.2	22.9	31.3
18	35	30	0.1	54.2	86.6	96.1	11.8	18.8	27.4

5.3.3 Change of usage within the cSAC

With the cSAC more-or-less divided into a northern and southern region depending on seasonal use, 8 change scenarios were envisioned with a 25% change in each region, where a change was specified. The power to detect any change was as expected greater for any study which was for 12 years over 6 years, *e.g.* for a decrease in both the north and south regions the power to detect change in summer was 26.4% over 6 years and 48.2% over 12 years (Table 13). For the scenarios where the change was large, *e.g.* a 25% increase in one region and a 25% decrease in the other region (scenarios 3 and 6) the power was greatest *i.e.* >62% for a study of 12 years. For all other scenarios the power decreased in line with the decrease in percentage change of the scenarios (Table 13). The spacing of sensors (25km) and the CV = 0.05 remained the same for each change in seasonal usage and the power in this case is directly linked to the amount of change which is detectable.

Table 13. Estimated power (%) for envisioned changes in density in the northern and southern regions (25% change in each region, simulated 1,000 times) defined by seasonal usage. Spacing of sensors (25km) and CV = 0.05 remained constant for each scenario.

Scenario	Region		Number of years	Power	
	North	South		Summer	Winter
1	Decrease	Decrease	6	26.4	31.0
			12	48.2	54.9
2	Decrease	No change	6	14.0	12.7
			12	29.6	26.3
3	Decrease	Increase	6	34.9	30.3
			12	67.7	62.9
4	No change	Decrease	6	15.6	15.2
			12	27.9	27.3
5	No change	Increase	6	9.8	9.4
			12	19.3	18.5
6	Increase	Decrease	6	35.7	35.3
			12	67.9	66.9
7	Increase	No change	6	10.6	9.0
			12	18.7	18.7
8	Increase	Increase	6	17.5	23.2
			12	33.4	39.6

Whilst we have only considered a subset of the possible variables in these power analyses, we expect that increasing the length of the monitoring period and the number of estimates generated per year are likely to markedly increase the power, whilst changing the number of sensors is likely to have a smaller impact on power.

5.3.4 Short-term decline in the cSAC

As highlighted in section 6.2 we explore a different set of scenarios considering short term (and larger scale declines) declines as a consequence of disturbance from offshore construction activities. Two example scenarios were considered for a six-year study only:

1. Density was constant for two years (pre-construction), reduced by half for the third year (during construction) and then increased for the next three years (post-construction) such that at the end of six years it was 75% of the starting density.

2. Density was constant for two years (pre-construction), reduced by 30% in the third year (during construction) and then increased by 10% for the next three years such that at the end of six years it had returned to the starting density (post-construction).

The power to detect difference in phases for scenario number 1 (large differences between phases) was 90.2% and for scenario number 2 (smaller differences between phases) was 36.5% (Table 14). This high power for scenario 1 is perhaps not surprising given the dramatic change in density we imposed during the construction phase. As with the scenarios in sections 6.3.1-6.3.4 we expect the general patterns observed to apply here.

Table 14. Estimated power (%) for the detection in phases for 2 change scenarios; a 50% and a 30% decline and staged recovery over six years (sensor grid spacing 25km and cue rate CV = 0.05, simulated 1,000 times).

Scenario	Power (%)
1 – 3rd year 50% reduction in abundance	90.2
2 – 3rd year 30% reduction in abundance	36.5

6 Discussion

In this study, we conducted a series of simple power assessments of the different survey methods using the TRENDS program (Gerrodette 1987, 1993), AVADECAF (Booth 2017) and Emon tool (Barry 2017). We predicted the power of annual estimates from line transect surveys to detect different harbour porpoise population declines using a range of CV values, including those achieved from SCANS III aerial and ship-based surveys (Hammond 2017). This analysis showed that the power to detect a 25% decline over six years of monitoring was only 29%, and only 48% following 12 years of monitoring using the SCANS III aerial survey CV of 0.17. This means that given these survey CV values, following 12 years of monitoring you would have a ~50% chance of failing to detect a 25% decline in the population. This simple analysis is in line with the conclusions of Berggren *et al*. (2006a) that for populations of marine mammals that are decreasing they may reach critically low levels before the downward trend could be statistically detected because of the high variability and low power in the data and methods used in marine mammal monitoring schemes.

Using a more complex analytical approach we selected the AVADECAF tool which is specifically designed to conduct power analyses for cetacean density estimated from passive acoustic fixed sensors. Initially we assessed the ability of static PAM to detect a long-term decline in the cSAC and subsequently the scenarios which were specified in Section 3 Project Objectives:

- a decline in the cSAC compared to no decline in the ‘buffer’;
- changes in seasonal usage within the cSAC; and
- short-term change in usage within the cSAC.

With a sensor grid spacing of 25km (equivalent to approximately 60 sensors in the cSAC) and a low variability in cue rate (= 0.05) the best scenario for detecting a 25% decline in the cSAC in isolation was over an 18 year monitoring programme and had 76.6% power. When designing the monitoring plan for the cSAC and ‘buffer’ we considered the projected budget (estimated at £1,000,000 year one and with diminishing budget for subsequent years) and designed two grid spacing options 25km and 35km spacing. We then compared a change in density (25% decline) inside the cSAC that was not reflected in the ‘buffer’ outside the cSAC. Not surprisingly we found that a longer monitoring period, lower CV of cue rate and smaller spacing between sensors achieved the best power; 35.7% for a 12-year study, CV(cue) = 0.05km and 25km grid spacing. From these two large scale, yet simple designs we could see that increasing the study length and increasing the number of sensors was the only managable way to improve the power as the CV of cue rate (though influential in determining power) is not directly controllable.

Examining change scenarios inline with the existing approximate north-south change in seasonal abundance of harbour porpoise in the cSAC we found that the highest power was achieved in the scenarios with the largest change. For example there was >62% power to detect a 25% increase in one region and a 25% decrease in the other region over a 12-year study period. For our analysis of a short term decline, again the best power achieved was for the scenario with the greatest difference in animal density at year 3 (scenario 1, 50% decline). The power to detect this decline was 90.2% over 6 years, though a reduction in density of only 30% at year 3 reduced the power to 36.5%.

There is a body of scientific literature exploring the general power of monitoring marine mammal populations (e.g. Berggren 2006a) which show that, in general populations of marine mammals (most commonly cetacean species) may reach critically low levels before the population decline could be statistically detected. Overall, the power to detect small changes (*i.e.* 25% over 12 years (~2% per year)) that we have presented throughout the study is achievable and cost effective using static PAM. It is important to note that detecting smaller changes (*e.g.* 1% per annum) are likely not attainable for cryptic, highly mobile cetacean species such as the harbour porpoise. Ways to increase the power to detect a trend in a population being monitored by static PAM include; increasing the monitoring length and increasing the number of sensors, and the number of estimates per year, whilst conceding that variable environments, distribution and animal behaviour will all negatively impact power.

In general, for a study which has a low power to detect a difference, there will be a high risk of a type 2 error (failing to detect a change when one has occurred). One of the best ways to reduce this risk when CV is high is by collecting more data. However, increasing sample size through combining survey effort does not necessarily result in sufficient power to detect trends. Jewell (2012) examined survey effort across a global scale and because of the extent of variability across surveys, species and oceans, power was not increased. Such retrospective power analysis though controversial can be helpful for estimating the size of an effect that could be detected in a study using the observed variance (Thomas 1997) and for understanding the challenges facing managers of marine mammal populations. In their review of decades of marine mammal monitoring data, Taylor (2007) found that agencies had almost no statistical power to detect even catastrophic declines in abundance in many stocks. Given the frequency and precision of the U.S. monitoring effort a precipitous decline of >50% abundance over a 15 year period would not be detected in 72% of studies of baleen whales, 90% for beaked whales, and 78% for dolphins/porpoises (based on a one-tailed t-test, = 0.05, Taylor 2007). Recommendations made to increase the likelihood of detecting precipitous population declines included; increasing survey extent and frequency (Taylor 2007). Similarly, Jewell (2012) recommend repeated dedicated surveys designed specifically for the species and geographical region of interest should be used to inform conservation and management. Tyne *et al*. (2016) found that based on boat-based photo-ID surveys it would take 9 years to detect a 5% annual change in abundance of a small, genetically isolated spinner dolphin (*Stenella longirostris*) population, equivalent to a 37% decrease in overall population using a CV=0.09 and power of 80%. Furthermore, from shore based census surveys of eastern North Pacific gray whales (*Eschrichtius robustus*) a population increase of 46% over the survey period (14 surveys over 13 years) would need to take place before a significant change could be detected (Turnock & Mizroch 2002). Both of these studies are limited to annual estimates from data collected over a temporally discrete time period. For static PAM, data will be collected almost continuously allowing more estimates per year to be generated cost effectively. As we have demonstrated above, in these simulations, this provides an increased level of power of static PAM surveys without significantly increasing the cost of collecting and analysing data (as is the general case with snapshot vessel based and aerial surveys; visual or PAM). Booth *et al.* (2017b) also explore other monitoring approaches by which early warning signals of population change might be monitoring in marine mammal populations.

The evaluation of monitoring methods for cetaceans and the exploration of the effect of survey frequency and duration on the ability to detect trends in abundance is a contemporary challenge facing wildlife managers. Decisions should be based on robust science and rigorous monitoring regimes however, this often conflicts with limited financial resources. Funding limitations for abundance estimates generally equate to a reduction in the precision of those estimates and this in turn has implications for the power of detecting trends in abundance (Thomas 2010). However, here we believe static PAM can provide a cost effective means by which to robustly monitor for changes in harbour porpoise usage of the SNS cSAC.

6.1 Recommended Monitoring Approach for SNS and wider area

Having reviewed the pros and cons, resolution, utility (via power analyses), practicalities and costs of each of the survey methods in line with the stated objectives for monitoring harbour porpoise in the SNS we suggested at the IAMMWG meeting (January 2018) that an array of static PAM loggers was the best approach for long term monitoring at the site relative to the detection scenarios:

- a long-term decline in the SNS cSAC relative to the wider area; we defined the wider area as a 50km 'buffer' around the whole cSAC, clipped to land and the UK exclusive economic zone (EEZ);
- persistent seasonal changes in abundance with increased use of the north of the cSAC in the summer and the south of the cSAC in the winter;
- short-term changes in usage due to human impacts.

Static acoustic monitoring has been used to monitor and assess the status of a range of species around the world (Rayment 2010; Gallus 2012; Brandt 2016; Tregenza 2016) and specifically in the UK (Thompson 2014; Nuuttila 2017; Palmer 2017; Williamson 2017). These studies showed that static PAM can be used to detect temporal changes in habitat use by harbour porpoise over, annual, seasonal, diurnal or tidal cycles. Static PAM makes this possible as monitoring can be conducted around the clock over extended periods of time. An additional benefit of static PAM, is its effectiveness in monitoring temporal changes in habitat use by harbour porpoise over a range of spatial and temporal scales (*e.g.* Gallus 2012; SAMBAH 2016), in a range of habitats (*e.g.* Carlström 2005; Todd 2009; Tougaard 2009), This method has been used for monitoring harbour porpoise acoustic behaviour in the wild (Carlström 2005) around offshore installations and monitoring the effects of offshore construction (de Haan 2007; Todd 2009; Tougaard & Carstensen 2011; Dähne 2017) and is widely employed in European jurisdictions (*e.g.* (BSH 2003). Therefore its feasibility as a proven cost efficient, medium term, large scale monitoring option is well established.

We observed that the power achievable with the different survey methodologies was broadly comparable given observed overall CV values (see Section 3.4.4) for annual estimates. Static PAM provides 24/7 monitoring with the opportunity to generate a number of estimates in each year which results in an increase in the power to detect change. As noted above, this is a simulation where we are able to control for a number of factors. In real data there are always a range of factors driving the patterns observed. It will be important that the data collected are analysed in a sensible manner such that any non-independence in errors is adequately captured in the correlation structure of analyses, and suitable set of variables considered to maximise what can be said about results. Whilst the same might be achievable from quarterly aerial surveys (for example) or vessel-based approaches, these represent more snapshot approaches and are limited to the number of surveys conducted each year (*i.e.* if there are four surveys per year, it is not possible to generate more than four estimates in that year). Because static PAM offers continuous monitoring for a large number of points (*e.g.* 49, 63, 124 - depending on spacing), this provides maximum flexibility in the analysis stage to generate robust estimates and ensure surveys have sufficient power to achieve their objectives. Though we acknowledge detecting small changes will still be extremely challenging for this species, no matter what monitoring method is employed. Continuous monitoring also allows for assessment of short term displacement and shifts in distribution patterns to be observed (which is critical for a highly mobile, patch-exploiting species like the harbour porpoise). In addition, the foraging 'buzzes' of harbour porpoises can be interrogated using PAM data to better understand foraging behaviour at different sites and under different conditions (if known).

Like all monitoring approaches there are benefits and costs to each method. In our recommendations, it is important to stipulate some of the assumptions and caveats of the use of static PAM. For example, without adjustment, PAM data provides an index of vocalisation detections and not abundance. As with other survey approaches, animal behaviour may be variable and impacted by environmental and anthropogenic factors. In the case of static PAM, animals may change vocalise more when encountering a prey patch, or potentially less when disturbed by noise (as suggested in Dähne 2013; Pirotta 2014). Of course the same is true for other survey methods where visual sighting rates may be affected by changes in dive behaviour or surfacing behaviour (*e.g.* when foraging or engaged in other behaviours, Westgate 1995; Teilmann 2007). As highlighted in section 5, power can be increased by generating multiple estimates per year, but there is an important assumption that these estimates are independent.

6.1.1 Suggested monitoring design for SNS cSAC

Based on the review and power analyses conducted herein, we recommend the deployment of an array of static PAM units to monitor harbour porpoises in the SNS cSAC. Given the PAM systems considered, we'd recommend that CPODs and/or Soundtrap units are deployed. The former is well established as a static PAM tool for harbour porpoises, however there are known limitations which must be accounted for in design and maintenance of a monitoring programme. Soundtraps provide the additional benefit of being able to record noise, but present additional costs for non-standardised analysis and the devices are currently unproven for long-term monitoring of harbour porpoises. However, as a solution, a combination of CPODs and a noise recording device like the Soundtrap or SM3M (or others) to monitor harbour porpoise and noise levels concurrently would be valuable. These devices could be paired on all moorings, or a subset of locations to reduce costs. In addition, noise monitoring from other contemporary efforts may provide useful contextual information or data to be used as environmental modelling covariates.

We recommend that a sufficient number of units are deployed to ensure power to detect meaningful changes. From the power analyses, we determined that the spacing (and so number) of devices had less of an effect on power than other factors (such as length of monitoring and number of estimates per year) but that more sensors would result in higher power. Because there are cost implications to the number of sensors deployed, we recommend that a spacing of 35km or 40km between units be used, resulting in 63 or 49 sensors acros both the cSAC and buffer, respectively. There is a relatively small difference in power between scenarios run with these spacings, but a difference in total cost (affecting capitol costs and analysis). We recommend that 'Spar buoy' (or similar) mooring systems like those used in the German North Sea (Figure 8) are deployed. These moorings often use acoustic releases. These should be considered, but are known to have issues with fouling. meaning the unit cannot be retrieved and/ or premature release where loud impulsive sound can result in the unintended release of the device leading to loss (P. Thompson, pers. comm). In addition, acoustic releases are an expensive component and therefore their use should be carefully considered with mooring specialists in planning phases, as their inclusion may increase project cost and risk (they have been included in indiciative costs here for completeness). Whilst more inexpensive moorings (*e.g.* simple surface markers and lightweight mooring components (*e.g.* those suggested by Evans & Thomas 2013)) could be employed to save on costs, this would result in an increased project risk (as less robust moorings can easily be damaged by collision or bad weather often resulting in loss of equipment and data). In addition, having robust moorings and suitable surface markers might allow for other sensors to be deployed (*e.g.* meteorological instruments *etc*.) on the surface markers and/or for upgrade to systems capable of transmitting data in the future (if costs are reduced and efficacy is demonstrated). Such an approach would require funds in the region of ~£3 million over the first three years of the monitoring programme, with yearly costs in the region of ~£600,000 (covering data retrieval and analysis *etc*.). Finally, we recommend that sufficient analysis budget is made available to allow for as many (independent) estimates per year as possible. This is a key way to increase power.

In summary, based on the best available information and the power analyses conducted in this study, the following monitoring programme is recommended:

- archival recording systems (*e.g.* CPODs, Soundtrap *etc*.) deployed on a spacing of 35km x 35km (*e.g.* total ~63 sensors) or 40km x 40km grid (total ~49 sensors), serviced every three months.;

- noise recordings collected *in situ* from at least a subset of locations;

- spar buoy moorings (potentially with acoustic releases where dependable) to ensure robust moorings to withstand the elements, the long monitoring duration and other marine users;

- a significant yearly analysis budget, to allow for all data to be processed and analysed (with appropriate QA on a subset of data) each year, to allow for multiple estimates of relative abundance to be calculated (to ensure higher power to detect changes). Analysis budget should also allow for PAM data to be analysed at different temporal and spatial scales (*i.e.* to address different questions: *e.g.* long-term declines, short term changes, hotspot/distribution patterns).

In addition, separate, but concurrent research efforts could be funded to try to determine absolute abundance of porpoises using static PAM (*e.g.* tagging of animals to determine cue rate and CV, dive/vocal behaviour informing availability bias, *etc*.) and make use of contemporaneous monitoring efforts to maximise the value of monitoring harbour porpises in the SNS cSAC.

6.2 Current and contemporaneous monitoring of harbour porpoise

To fulfil the monitoring and management obligations of government for the cSAC a dedicated monitoring program is recommended and we have outlined our recommended approach above. Of course, in order to extract maximum value from SNS monitoring for harbour porpoise, it makes sense to capitalise on other concurrent efforts which are either directly (*e.g.* surveying porpoise populations) or indirectly (*e.g.* monitoring the environment) improve our understanding of harbour porpoise use of the SNS cSAC. Specifically, any concurrent monitoring for research, conservation or development purposes within the cSAC or wider southern North Sea could complement information collected through a dedicated program and could help inform the wider context for the species and site, however, this must not be necessary to fulfilling the monitoring and management obligations. As such, we would recommend engaging with other contemporaneous North Sea monitoring projects which may enhance knowledge and context of harbour porpoise distribution and abundance in the SNS cSAC. Below we highlight a number of projects of note which might provide such data and/or information:

- **Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS)[6].** The aim of the project is to develop a framework for a fully operational joint monitoring programme for ambient noise in the North Sea and to facilitate the incorporation of the effects of ambient noise in assessments of the environmental status of the North Sea, and to evaluate measures to improve the environment. Marine Scotland Science and

[6] http://northsearegion.eu/jomopans/.

CEFAS have an active role in this project. Given the concern over harbour porpoise sensitivity to noise, collaboration with such programs could provide valuable contextual information and/or covariates to be used when interpreting data, to better understand patterns driving the distribution of the species.

- **An alternative framework to assess marine ecosystem functioning in shelf seas (AlterEco)[7].** The aim of this project is to better understand how changing physical and chemical conditions in UK Shelf Seas affects the marine ecosystem and ocean health. Through the deployment of small fleets of AUVs and surface vehicles continuous measurements in the North Sea will be conducted between November 2017 and January 2019. The project will deliver improved spatial and temporal understanding of key shelf drivers for the investigation of the shelf sea ecosystem functioning. Such studies may provide useful covariates with which to evaluate the observed patterns of porpoise occurrence, to help better understand how the species utilises the cSAC region on a fine temporal scale.

- The **Small Cetaceans and European Atlantic waters and the North Sea (SCANS)[8].** The primary objective of SCANS surveys is to estimate the absolute abundance of cetacean species in shelf and oceanic waters in the European Atlantic. As we have highlighted above, the monitoring consists of a series of large scale aerial and boat-based surveys which have taken place on an approximately decadal time scale; 1994, 2005 and 2016. It is important to stress, however, that this is not a programme of surveys, but that each of the three surveys (SCANS I, SCANS II and SCANS III) have been developed independently. There is no guarantee of additional surveys of this type occurring as funding will be required.

- **Site specific baseline and potentially post-consent monitoring of offshore windfarm developments** within the cSAC may be another source of spatially explicit data. In addition, specific scientific studies might provide useful contextual information to aid SNS monitoring objectives (*e.g.* cue rates from tagged porpoises as part of the **DEPONS** project).

[7] http://www.altereco.ac.uk/.
[8] https://synergy.st-andrews.ac.uk/scans3/.

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9 Glossary of Terms, Acronyms and Abbreviations

Term	Description
AU	Assessment Unit (AU) is a term developed by OSPAR for reporting purposes under the Marine Strategy Framework Directive. They reflect a geographical area occupied by a population and so are divisions based on biology/ecology rather than management. These areas vary by species, *i.e.* they are not the same within a regional sea for different species.
AUV	Autonomous Underwater Vehicle
AVADECAF	Assessing the ViAbility of DECAF
cSAC	candidate Special Area of Conservation
DECAF	Density Estimation for Cetaceans from Passive Acoustic Fixed Sensors
Duty-cycling	A duty cycle is the fraction of one period in which a signal or system is active. Duty cycle is commonly expressed as a percentage or a ratio. A period is the time it takes for a signal to complete an on-and-off cycle.
IAMMWG	Inter-Agency Marine Mammal Working Group
ICES	International Council for the Exploration of the Seas
JNCC	Joint Nature Conservation Committee
MS	Member States
MU	Management Unit (MU) typically refers to a geographical area in which the animals of a particular species are found to which management of human activities is applied. An MU may be smaller than what is believed to be a 'population' or an 'ecological unit' to reflect spatial differences in human activities and their management. If MUs are defined at a smaller spatial scale than the population, it is important that management takes into account the rates of interchange of individuals between MUs; that is, the MUs should not be treated as if they were demographically independent.
MSFD	Marine Strategy Framework Directive
OSPAR	Oslo/Paris convention (for the Protection of the Marine Environment of the North-East Atlantic
PAM	Passive Acoustic Monitoring
SAMBAH	Static Acoustic Monitoring of the Baltic Sea Harbour Porpoise
SCANS	Small Cetaceans in European Atlantic waters and the North Sea
SNCB	Statutory Nature Conservation Body
SNS	Southern North Sea
Statistical terms	***Description***
α	Used to denote the probability of a Type I error.
β	Used to denote the probability of a Type II error.
Coefficient of variation (CV)	a measure used to describe the amount of variation in an estimator given by the standard error of the estimator divided by itself (Buckland *et al*. 2001).
One-tailed test	used to test whether there has been either an increase or a decrease.
Null hypothesis (H_0)	hypothesis to be tested (in this context H_0: $\beta = 0$).
Power	$1 - \beta$
Quasi-Poisson	mean-variance relationship is relaxed so that $\mu = c\sigma^2$ where *c* is estimated from the data.
t-test	statistical hypothesis test in which the test statistic follows a *t*-distribution under the Null hypothesis.
Type I error	incorrectly concluding that a trend has occurred.

Type II error	incorrectly concluding that no trend has occurred.
Two-tailed test	used to test whether there has been a trend (regardless of whether it is an increase or a decrease).

Appendix 1: Estimated costing for 40km x 40km static PAM array

Estimates of cost for a static PAM arrays using a Spar buoy mooring system (based on Figure 8) were developed in collaboration with marine mooring equipment specialists. The cost estimates are based on supply, deployment and 4 x servicing of this 40 km x 40 km mooring system (caveats listed beneath the table).

Option	Description	Ind. Quantity	Rate	Total amount	Comments
49 sites, 40km apart	Mooring Purchase (Each)	49	£3,500	£171,500	Includes Spar buoy and dahn flag but not Acoustic Release
	Acoustic Release Purchase	49	£7,150	£350,350	Pop-up release with rope canister to recover Cpod
	Deployment (LS)	1	£135,000	£135,000	Assumes 14 ops days and £5k/day vessel costs
	Service Visit (Each)	4	£77,000	£308,000	Assumes 10 ops days to service 49 No. moorings
	Complete Mooring Replacement	0	£3,500	£0	Includes IALA compliant special mark
	Specialist labour to procure and assemble replacement mooring	0	£750	£0	Procure & assemble 1 No. replacement mooring only. To be used in the event of mooring loss.
			Sub-Total	**£964,850**	Including acoustic releases
			Sub-Total	**£614,500**	Not including acoustic releases
	Acoustic device purchase	55	£3,500	£192,500	Includes spare devices
	Analytical costs	2	£70,000	£140,000	2 x post-doctoral researchers
	Project management costs	1	£50,000	£50,000	Administration, logistics and reporting
			Total	**£1,347,350**	Including acoustic releases
			Total	**£997,000**	Not including acoustic releases

Caveats/points to consider

Costs are weather exclusive. Vessel will be capable of 10kts with lifting equipment and berths. No costs included for arranging licensing. Moorings will need components replacing annually.