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Noise sensitivity of animals in the Baltic Sea

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Preface

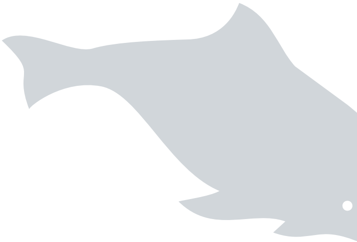
The Baltic Sea holds some of the busiest shipping lanes in the world as well as some of the largest cities in Northern Europe. There is furthermore a large range of off-shore construction work and other human activities in this area (see e.g. Baltic SCOPE project). Increasing noise levels can be problematic to species relying on sound for most parts of their life cycle. Noise may disrupt behaviours, mask important signals and can reduce the hearing sensitivity either temporarily or permanently in an individual (Richardson *et al.*, 1995; Southall *et al.*, 2007). By causing disturbance to single individuals the effects of noise have the potential to decrease fitness which could lead to reduced recruitment to the next generation and thereby affect a population.

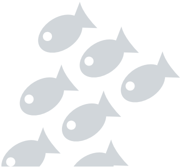
As a response to the awareness of increasing underwater noise, the 2013 HELCOM Copenhagen Ministerial Declaration commits the Contracting Parties to "take further measures, initiatives or efforts to reach a healthy marine ecosystem supporting a prosperous Baltic Sea region, including addressing pollution of the marine environment by litter, as well as impacts on marine organisms from underwater impulsive and continuous noise".

In the 2013 Ministerial Declaration it was furthermore agreed that "the level of ambient and distribution of impulsive sounds in the Baltic Sea should not have negative impact on marine life and that human activities that are assessed to result in negative impacts on marine life should be carried out only if relevant mitigation measures are in place".

At European level, the Marine Strategy Framework Directive (MSFD, 2008/56/EC) includes a Descriptor (number 11) specifically concerned with the introduction of energy, such as underwater noise, into the marine environment. Both the HELCOM Ministerial commitment and the MSFD aim to ensure the achievement of a good environmental status (GES) for Baltic and European marine waters, respectively. For underwater noise this means that human induced noise levels should not adversely affect the population. Although there is increasing knowledge on noise impacts on individual fish and marine mammals (see Popper and Hawkins, 2012 2016), the extent to which this could affect an animal's fitness is still unknown, making it difficult to define the maximum level of underwater noise that is consistent with good environmental status at the population level.

During the last two years HELCOM has worked on improving knowledge and understanding of sources of underwater noise and their impacts on Baltic Sea species. This report identifies Baltic species which have the potential to be impacted by noise based on the hearing capabilities of the animals as well as on how they use and react to sound. The document also provides a prioritized list of noise sensitive species in the Baltic Sea. For each of the prioritized species the distribution of species and biologically sensitive areas is presented based on available data.





1. Introduction

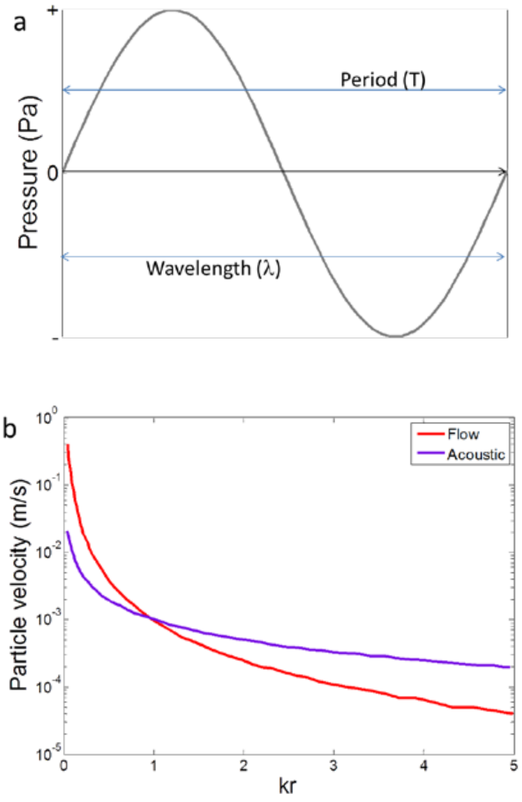


Figure 1: a. An acoustic wave as a function of distance gives the wavelength, and as a function of time gives the period. **b.** Close to the sound source ($r \leq \lambda$) the total particle is larger than the acoustic particle velocity due to added particle velocity (flow) i.e. the local flow caused by the sound source moving the water directly (modified from Wahlberg and Westerberg, 2005).

1.1. Sound

A sound wave is a spreading pressure fluctuation caused by local particle movements in an elastic medium, such as air or water. When particles of the medium are displaced, for example by a loudspeaker or a calling fish, this creates local volumes of low and high pressure, where the density of particles increases and decreases, respectively. These fluctuations, which can be measured either as particle movements or pressure fluctuations, are travelling away from the sound source with a speed, which is dependent on the medium (1500 m/s in water). Marine mammals are sensitive to the pressure of the sound wave and most probably also particle motion. Fish and many aquatic invertebrates, on the other hand, are sensitive only to the local particle movements of the sound field, even though some species are capable of detecting the sound pressure fluctuations as well (see below). This distinction is important, as the pressure and particle motion components of the sound field behave differently close to a sound source and near a boundary such as the sea floor or the water surface.

A given acoustic signal consists of certain wavelengths; a wavelength is the spatial extension of one cycle of increasing and decreasing pressure (Figure 1a). The time it takes to complete one pressure cycle is called the period, and the reciprocal of the period is the signal's frequency. The wavelength (λ, measured in meters, m) and the frequency (f, in Hertz, Hz) are related through the speed of sound (c, in m/s) of the medium. The intensity of the frequencies composing a certain signal can be measured with signal analysis using the so-called Fourier transform, which decomposes the signal into frequency components of different amplitude. Animals are sensitive to different frequencies, making frequency an important parameter when evaluating acoustic signals in relation to how animals react to the signal in question.

The magnitude of the acoustic signal is a crucial feature when considering animal hearing and sound sensitivity. The magnitude can for example be the peak-pressure, the particle velocity, or most often the intensity which is a combination of the two. The acoustic intensity is defined as the power travelling through a unit area, and is calculated as the product of the local pressure fluctuation and the local particle velocity. A higher sound intensity increases both sound detectability and possible risk of negative impacts of sound (see below).

The pressure component of a sound is measured in Pascal (Pa), and can be measured with a pressure sensitive device, a so called hydrophone (underwater microphone). At long ranges from the sound source (range much larger than the wavelength of the sound) the particle velocity can be calculated from the local pressure measurements, making it possible to calculate the sound intensity using pressure measurements only. At closer ranges however there is additional particle motion which adds to the local particle movement (Figure 1b, Wahlberg and Westerberg, 2005). Therefore, at a close range or close to a boundary like the water surface or the bottom, particle motion needs to be measured directly.

As sound travels through the medium it gets attenuated and distorted. The intensity of the sound decreases as the area over which the sound energy is spread increases. This is called geometric spreading. Sound energy is also absorbed by the medium. In seawater the absorption is frequency dependent with higher frequencies being absorbed more than lower frequencies, but as salinity goes down this frequency dependent absorption also decreases. In the inner parts of the Baltic Sea the higher frequencies therefore do not attenuate as fast as in Kattegat and the Belt Sea (Andersson and Johansson, 2013). Another effect that decrease attenuation of sound in the Baltic Sea is the formation of sound channels which is a typical effect in stratified water bodies such as the Baltic (Klusek and Lisimenka, 2016). The occurrence of sound channels is not predictable and relates to parts of the spectrum only.

The animal ear and hearing system detects and integrates sound signals over a wide range of sound intensities. As a first approximation, our perception of sound intensity is a logarithmic function of the sound intensity. Therefore, “sound pressure intensities” are usually calculated as Sound Pressure Level (SPL) in decibels (dB) using the following equation:

$$SPL = 20log10(\frac{p}{p_0})$$

where $\boldsymbol{p}$ is the sound pressure and $\boldsymbol{p_0}$ is the reference value. In underwater acoustics the reference sound pressure is 1 µPa. One decibel roughly corresponds to the smallest difference in sound intensity that a human, and many terrestrial animals, can discern.

The pressure p can either be the peak to zero or peak to peak pressure (the highest pressure of the signal, or the difference between the highest and lowest pressure of the signal, respectively), or the average pressure of the signal where the average is usually calculated as the root-mean-square (rms) pressure over a well-defined time interval of the signal. Values can vary more than 15 dB depending on which choice of SPL definition is used in the calculation (for terminology, see ISO 18405:2017).

For animals detecting particle motion, particle motion can be quantified either as displacement, velocity or acceleration. The hair cell, the sensory cell in the inner ear responsible for sound detection, is a displacement detector (displacement measured in meters, m). However, the combined passive mechanical properties of the inner ear act as an accelerometer (measured in meters per second squared, m/s2) at low frequencies (Kalmijn, 1989). Above a few hundred Hertz this changes and particle velocity (measured in meters per second, m/s) becomes the adequate stimulus (Kalmijn, 1989).

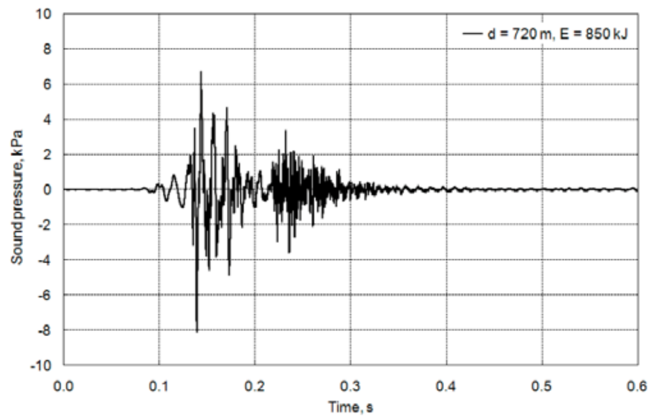


Figure 2: Example of impulsive noise with a fast rise time. Waveform of an acoustic signal from 850 kJ hydraulic hammer measured at 720 m (from Betke, 2008).

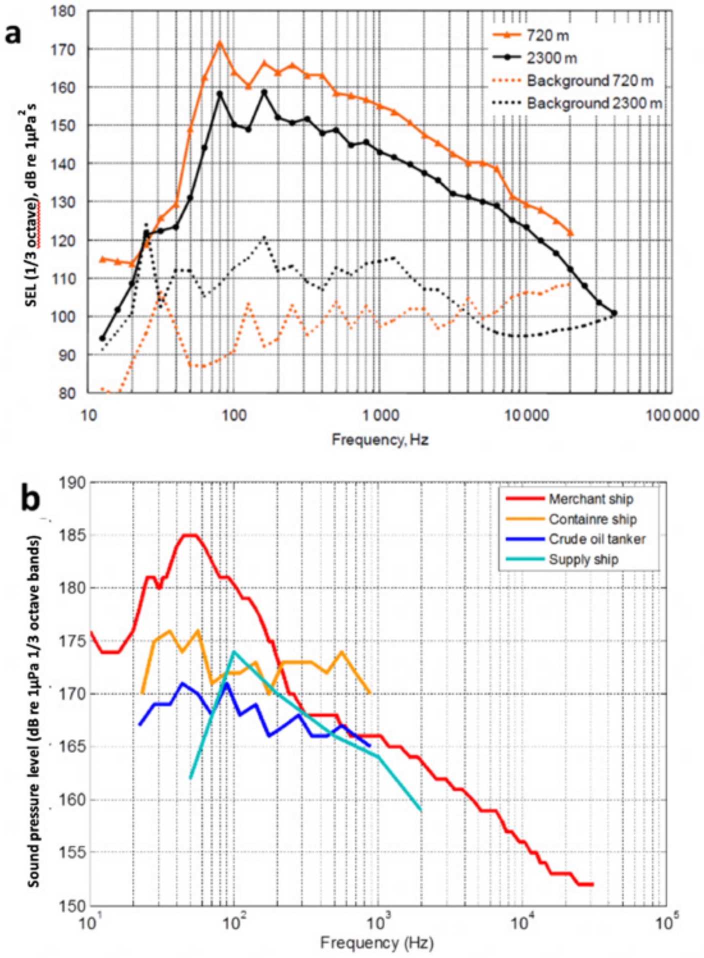


Figure 3: a, Power spectral density of two kinds of noise sources. a, 1/3 octave power spectral density of impact pile-driving noise averaged over 24 pile strikes with 850 kJ hammer, measured at 720 m and 2300 m from the pile, and background noise levels at the same distances (from Betke, 2008).
b, 1/3 octave power spectral densities of four types of vessels. Merchant ship (red line, modified from Arvenson and Venditis, 2000), container ship (orange line, modified from McKenna *et al.*, 2012), crude oil tanker (dark blue line, modified from McKenna *et al.*, 2012), and supply ship (light blue line, modified from Richardson *et al.*, 1995).

1.2. Noise

Noise is generally defined as unwanted sound which clutters and masks sounds of interest (Richardson *et al.*, 1995). Noise can largely be divided into two categories; continuous noise and impulsive noise, though there often is some overlap between the categories. The two differ greatly in a number of properties. Impulsive sound is characterized by a short duration, and a fast rise time. An example of impact noise from pile-driving can be seen in Figure 2 (Betke, 2008). Continuous sound from a source can be constant, fluctuating, or slowly varying over a long time interval (ISO 1996-1:2016). At long distances from a pile driving site, the piling noise can have more of a continuous character due the propagation affects (Bailey *et al.*, 2010).

The intensity of the different frequencies also known as the power spectral density (PSD) is a very important parameter when describing different noise sources. Comparing the PSD of a noise to the hearing sensitivity and sound production frequencies of different animal species aids in identifying animals at risk of experiencing adverse effects from noise.

The PSD of a sound can be presented in 1 Hz frequency bands or in 1/3 octave frequency bands. The latter is the most commonly used when evaluating possible noise impact in animals, as it more closely resembles how the sound will be perceived by an animal (see Chapter 2 for details).

PSD is presented for impulsive noise from pile-driving (Figure3a; Betke, 2008), and for continuous noise from vessels of different sizes (Figure3b; Richardson *et al.*, 1995; Arveson and Venditis, 2000; McKenna *et al.*, 2012).

2. Hearing sensitivity and sound production in animals: the case of the Baltic Sea

Many aquatic animals have elaborate anatomical structures for detecting sound. Baltic marine mammals (the grey, harbour and ringed seals, and the harbour porpoise) have acute underwater hearing abilities (Kastelein *et al.*, 2010, Reichmuth *et al.*, 2013). Some of the Baltic fish species such as herring and cod also hear well, mostly at low frequencies (Enger, 1967, Sand and Enger, 1973), produce sounds (Wahlberg and Westerberg, 2003, Wilson *et al.*, 2004, Hawkins and Rasmussen, 1978) and react to sounds (Wilson and Dill, 2002, Thomsen *et al.*, 2012). For other Baltic fish species, as well as for the majority of the Baltic invertebrates, little is known about how they hear and make use of sound, even though for the vast majority of species sound is most likely playing a role in their lives during some part of their life cycle (e.g. Popper *et al.*, 2001, Tolimieri *et al.*, 2000).

Sound propagates well over long distances in the aquatic environment whereas light attenuates rapidly (Medwin and Clay, 1998), and many aquatic animals rely on sound for communication, orientation and finding prey. Animals use sound for communication between conspecifics and during different specific activities e.g., mating, spawning, schooling and aggression. Sound is used for navigation through passive listening (e.g., by fish and seals) or echolocation (by harbour porpoises). Sound and low frequency vibrations are important sensory cues in predator/prey interactions, whether a predator is trying to locate a prey, or a prey is trying to avoid detection and capture (Dehnhardt *et al.*, 2001, Karlsen *et al.*, 2004).

Audiograms present an animal's hearing thresholds as a function of frequency and sound intensity (Figures 4, 5 and 6 below). Audiograms are the result of psychoacoustic testing under low-noise laboratory conditions, leading to absolute or slightly masked hearing thresholds, depending on the noise levels in the test situation. However, only a limited number of species, as well as individuals, has been tested for their hearing sensitivity to pressure and even fewer for sensitivity to particle motion and generalization between species should be avoided.

In the following hearing sensitivity and sound production parameters will be presented for central marine species in the Baltic Sea where hearing sensitivity has been investigated.

2.1. Marine mammals

Marine mammals have evolved from terrestrial mammals which probably had hearing systems well-adapted for air-born sound (Hoelzel, 2002). Cetaceans such as harbour porpoises have adapted to a fully aquatic life style and their hearing apparatus has been adapted to register sound pressure underwater (Nummela, 2008). Some of the lowest hearing thresholds in animals are found in the underwater hearing of some cetaceans, such as the harbour porpoise (Kastelein *et al.*, 2010). Pinnipeds, such as harbour, ringed and grey seals on the other hand have maintained an amphibious life style, where important aspects of their life cycle (e.g. giving birth and molting) take place on land, resulting in the ability to detect sound in air as well as under water (Reichmuth *et al.*, 2013).

Sound production is also very different in cetaceans and seals. Cetaceans use echolocation, where they emit intense ultrasonic calls or clicks, and use the returning echoes reflected by objects impinged by the sound to navigate and locate prey (Au, 1993). Some cetaceans like dolphins also produce different types of whistles and calls for communication (Richardson *et al.*, 1995, Madsen *et al.*, 2012), but harbour porpoises are only communicating acoustically with their high-frequency clicks (Clausen *et al.*, 2010). Seals mainly produce sound for communication (Schusterman and Van Parijs, 2003, Schusterman *et al.*, 2000). Communication sounds in air are very important for group coherence, mother-offspring relations, and during mating season for species breeding on land (Schusterman and Van Parijs, 2003). Underwater sound plays an important role during mating season for species breeding in water, where males produce a variety of sounds to either attract females, or establish territorial boundaries (Van Parijs *et al.*, 2000, 2003a and b, Van Parijs, 2003), though sound is likely produced year round (Andersson *et al.*, 2015, Stirling, 1973).

2.1.1 Cetaceans

Harbour porpoise **(Phocoena phocoena)**

Hearing is the key sensory modality for harbour porpoises for most aspects of their life. Their hearing sensitivity is very good and covers a wide frequency range (Figure 4; Andersen, 1970, Popov *et al.*, 1986, Kastelein *et al.*, 2002, 2010). The frequency analysis performed by the auditory system can be described as using a series of bandpass filters. Above 1 kHz the bandwidth of these filters is approximately 1/3 of an octave for humans (Moore, 2012) as well as for harbour porpoises (Kastelein *et al.*, 2009). However this may be more complicated at very high ultrasonic frequencies (Popov *et al.*, 2006). In addition, harbour porpoise hearing becomes increasingly

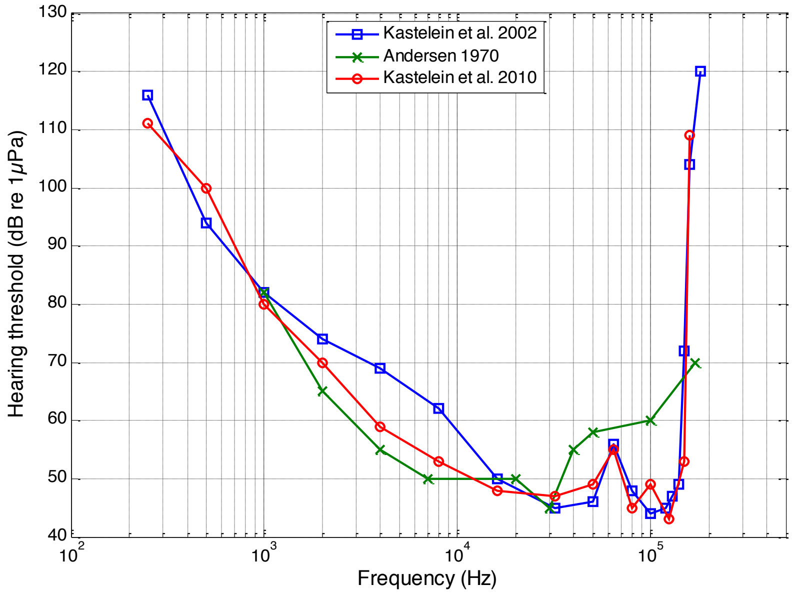


Figure 4: Harbour porpoise hearing sensitivity from Andersen, 1970, and Kastelein *et al.* 2002 and 2010.

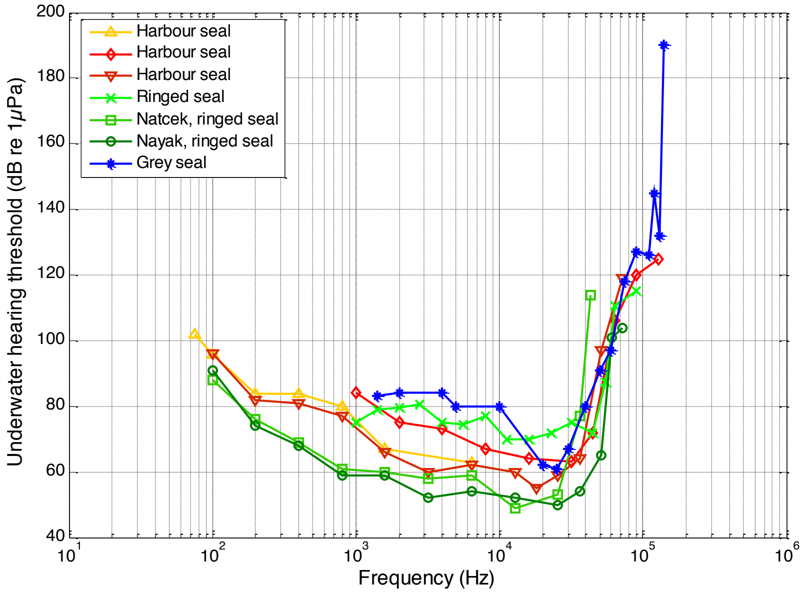


Figure 5: Underwater hearing sensitivity for harbour seal (orange line from Kastak and Schusterman, 1998, red line from Møhl, 1968 and dark red line from Reichmuth *et al.* 2013); ringed seal (light green) from Terhune and Ronald, 1975, and ringed seal (darker green lines) from two individuals, a young female (Nayak) and an older male (Natcek) from Sills *et al.*, 2015; grey seal (blue line) from Ridgway and Joyce, 1975. The audiogram from Ridgway and Joyce (1975), is based on data obtained using an electrophysical method, and is therefore not directly comparable to the other data presented here, which is obtained through behavioural methodology.

directional with higher frequencies (Kastelein *et al.*, 2005). This directionality improves their echolocation capabilities by making them less susceptible to background noise and clutter (i.e. returning echoes from other objects other than the intended target; Kastelein *et al.*, 2005).

Harbour porpoise echolocation clicks have a frequency content centred around 130 kHz and peak to peak source sound pressure levels around 200 dB re 1μPa (Villadsgaard *et al.*, 2007). They also seem to use echolocation clicks for communication, but at significantly lower sound pressure levels (140-160 dB re 1 μPa; Clausen *et al.*, 2010).

2.1.2 Seals

Harbour seal (Phoca vitulina vitulina)

Harbour seals have acute hearing under water as well as in air due to their amphibious lifestyle. They are sensitive to a wide range of frequencies in both media; their underwater hearing sensitivity is shown in Figure 5. (Møhl, 1968, Terhune, 1988, Kastak and Schusterman, 1998).

During the mating season in the summer, male harbour seals maintain underwater territories through long- lasting low-frequency rumbles ranging in frequency from around 250 Hz to around 1.4 kHz with most energy at approximately 650 Hz (Van Parijs *et al.*, 2000). Similar sounds have also been recorded outside the mating season, but with unknown behavioural significance (Anderssons *et al.*, 2015). Van Parijs *et al.* (2000) recorded vocalizations from Scottish harbour seals, but there may be slight differences in frequency content from different populations, as there are differences in dialect between harbour seals from different areas (Van Parijs *et al.*, 2003a). As sound travels further than light under water the reproductive success of the male is therefore more dependent on him being heard than seen.

Baltic ringed seal (Phoca hispida botnica)

Ringed seal hearing sensitivity was found to be comparable to and even slightly more sensitive than that of harbour seals (Sills *et al.*, 2015).

Ringed seal underwater vocalizations have been recorded in ice covered habitats, when seals maintain breathing holes and during mating season (Stirling and Thomas, 2003). Vocalization of ringed seals is versatile. Several types of calls have been described for ringed seals: low and high pitched barks, yelps and chirps knocks, clicks and woofs. The frequency content is between 100 Hz and 5 kHz (Stirling, 1973; Rautio *et al.*, 2009; Jones *et al.*, 2014; Mizuguchi *et al.*, 2016).

Grey seal (Halichoerus grypus)

The underwater hearing of grey seals has only been investigated, to our knowledge, in a single study (Figure 5; Ridgway and Joyce, 1975). The study was conducted using auditory evoked potentials, which are not directly comparable to the psychophysical data obtained from harbour seals and ringed seals. Grey seal hearing may not be as sensitive as that of the other two seal species, but whether this reflects the difference in methodology used in the different studies is difficult to evaluate.

Grey seals have been found mating both on land and in water (Van Parijs, 2003). Underwater vocalizations of grey seals have been described as low frequency growls with a frequency content of 100-500 Hz, guttural "rups" with a frequency content of 100 Hz to 3 kHz, and clicks at a frequency of approximately 3 kHz (Asselin *et al.*, 1993).

2.2. Fish

Hearing in fish differs from marine mammals in various ways. Where marine mammals are sensitive to the pressure component of a sound wave, fish are, as mentioned earlier, generally sensitive mainly to the particle motion of the sound wave. For frequencies below a few hundred Hz all fish species, regardless of their hearing apparatus anatomy, detect the particle motion (Kalmijn, 1989, Karlsen *et al.*, 2004), and for fish with no swim bladders (e. g. flatfish, mackerel) or with little air in the swim bladder (e.g. salmonids) this is the range of their hearing (Chapman and Sand, 1974, Hawkins and Johnstone, 1978). At higher frequencies species with a gas filled cavity can detect sound pressure, as a pressure wave impinging on a gas filled cavity causes an increase in the particle motion stimulating the inner ear (e.g. gadoids; Sand and Enger, 1973; Fay and Popper, 1974).

Some species have special adaptations to detect the pressure component as well, which gives them a wider frequency sensitivity and lower hearing thresholds (e.g. clupeids and carp fishes; Enger, 1967, Fay and Popper, 1974). A few species are even capable of detecting sound in a higher frequency range (up to 100 kHz) than most species (shads (*Alosa alosa* and *Alosa fallax*)) however only at high sound intensities (> 140 dB; Wilson *et al.*, 2008, 2011, Gregory and Clabburn, 2003).

Examples of hearing sensitivity and communication are presented for four fish families in the Baltic Sea representing different degrees of adaptation to sound detection.

2.2.1 Salmonids

Though salmon (*Salmo salar*) does possess a swim bladder, it does not significantly improve its hearing sensitivity as it does in e.g., gaoids (Hawkins and Johnstone, 1978). Salmon is mainly sensitive to low frequency sound (below 500 Hz) but only of relatively high intensities (Figure 6; Hawkins and Johnstone, 1978, Knudsen *et al.*, 1992, 1994).

Sound production, to our knowledge, has not been studied in salmon.

2.2.2 Gadoids

The Atlantic cod (*Gadus morhus*) possesses a swim-bladder, but has no special coupling between the swim-bladder and the inner ear. Hearing of Atlantic cod has been investigated by Chapman and Hawkins (1973) and Offutt (1974). The audiograms from these studies are shown in Figure 6.

Atlantic cod produces sound by contracting muscles associated with the swim-bladder, thus vibrating the swim-bladder walls. As part of its mating behaviour Atlantic cod produces "grunts". These grunts have short duration, typically less than 300 ms and are composed of a series of pulses with the main energy at 45-500 (Hawkins and Rasmussen, 1978, Finstad and Nordeide, 2004). The grunt has a fundamental frequency ranging between 45 to 90 Hz with two to three overtones, but the source level of these calls is not known. Atlantic cod has also been documented to produce a click sound associated with anti-predator behaviour. These sounds have a peak frequency of 6 kHz and a source level of 153 dB re 1µPa (Heike *et al.*, 2004).

2.2.3 Clupeids

In the Atlantic herring (*Clupea harengus*) the swim-bladder extends to the head, where it is directly connected to the inner ear (Blaxter *et al.*, 1981). The audiogram of Atlantic herring was measured by Enger (1967), showing that it is sensitive to higher frequencies than cod and salmon (Figure 6).

The Atlantic herring produces sound by releasing air bubbles from the anal duct (Wahlberg and Westerberg 2003, Wilson *et al.*, 2004). This creates a pulsed chirp consisting of a series of pulses with centroid frequencies ranging from 3 to 5.1 kHz and a source level ranging from 55 to 90 dB re 1 µPa rms (Wahlberg and Westerberg, 2003). The biological relevance of these sounds is still unclear, but it may be associated with group coherence in schooling behaviour (Wilson et al 2004).

Shads, such as allis shad (*Alosa alosa*) and twaite shad (*Alosa fallax*) belong to a Clupeid (herring family) subfamily (Alosinae). This subfamily is remarkable as it contains the only fish species that has been documented to detect ultrasound (Mann *et al.*, 2001). Hearing has not, to our knowledge, been investigated in allis shad or twaith shad, however the hearing sensitivity of the American shad (*Alosa sapidissima*) has been investigated and is presented in Figure 6 (Mann *et al.*, 1997).

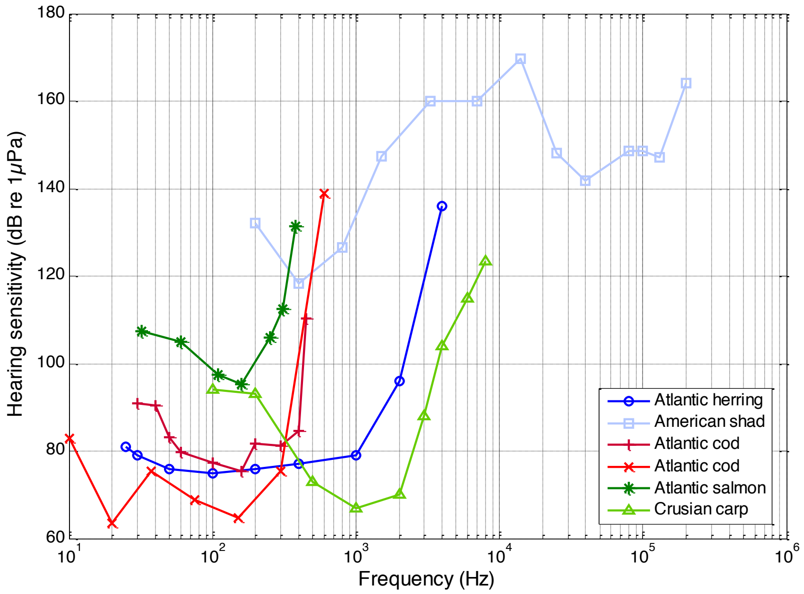


Figure 6: Hearing sensitivity for five Baltic Sea fish species: Atlantic salmon (green line; Hawkins and Johnstone, 1978), Atlantic cod (red lines; Chapman and Hawkins, 1973; Offut, 1974), Atlantic herring (dark blue line; Enger, 1967), American shad (light blue line; Mann *et al.*, 1997), and crucian carp (light green line; Siegmund and Wolff, 1973).

At low frequencies its hearing sensitivity is likely masked resulting in increased thresholds compared to Atlantic herring, but though the threshold is relatively high at high frequencies, allis and twaith shad have been documented to react behaviourally to ultrasonic clicks in the frequency range mimicking an oncoming predator (Wilson *et al.*, 2008, 2011; Gregory and Clabburn, 2003).

Sound production in shad has, to our knowledge, not been studied.

2.2.4 Cyprinids

The crucian carp (*Carassius carassius*) is a representative of the cyprinid family found in the inner parts of the Baltic Sea (HELCOM, 2012). Cyprinids are part of the Otophysi group which are characterized by having a series of small bones called the Weberian ossicles connecting the swimbladder to the inner ear. This connection increases the hearing sensitivity and the hearing frequency range markedly (Popper and Fay, 2011).

Its hearing has been investigated in a single study (Figure 6; Siegmund and Wolff, 1973). The crucian carp is more sensitive at higher frequencies than any other fish species presented in this document.

Sound production has, to our knowledge, not been documented for this species.

2.3. Diving birds

There are numerous species of birds in the Baltic Sea area, both resident and wintering, that dive to forage under water (e.g. Great cormorants (*Phalacrocorax carbo*) and common eiders (*Somateria mollissima*)) (HELCOM 2013, Skov *et al.*, 2011).

While in-air hearing has been investigated in several terrestrial species (Fay, 1988, Dooling *et al.*, 2000), very little is known about underwater hearing in diving birds. A recent study by Therrien (2014) has investigated the underwater hearing in the long-tailed duck (*Clangula hyemalis*), a species also found in the Baltic (Skov *et al.*, 2011). They were however not able to identify exact hearing thresholds due to a high degree of variation in test exposure levels (50 dB range of variation, Therrien, 2014).

Underwater hearing of the great cormorant has been investigated in a pilot study by Johansen *et al.* (2016), these data, however, remain to be verified in a more controlled experimental set-up.

3. Impact of noise on marine animals

The effects of noise depend on different properties of noise such as frequency content and duration. The scale of the effect largely depends on the animal's proximity to the sound source with increasing impact the closer the animals is to the source. An animal moving towards a noise source will, at some point, come within detection distance of the noise. At shorter distances effects from noise range from masking, behavioural changes/cessation of ongoing behaviour, physiological stress effects, temporary or permanent changes in hearing sensitivity, and physical injury in non-auditory tissue.

The range of the different impacts is ideally defined by a species specific threshold for each effect, creating species specific zones of impact. Figure 7 shows how the different zones are contained within each other. In reality these zones are not sharply defined, and there is a large overlap between the different zones, as impacts are depending on a number of variables like age, sex and general physiological and behavioural states of the individuals all of which will be different for each individual within a species (Popov *et al.*, 2011, Southall *et al.*, 2007). The existing background noise level is also an important factor for determining the extent of the zones of impact.

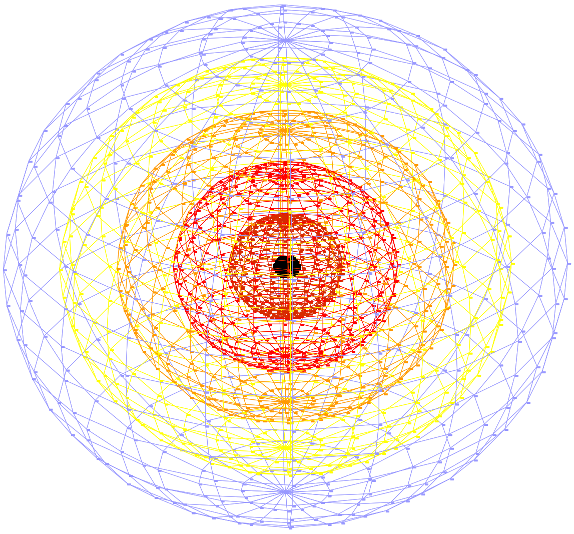


Figure 7: Zones of noise impact. The noise point source (black) is at the centre of the sphere. As the distance to the noise source increases, the severity and number of different effects experienced by an animal decreases. Injury and PTS (dark red) only occur closest to the sound source. TTS (red), behavioural reactions and stress (orange) can also occur further away along with masking (yellow), and furthest away from the sound source an animal is just able to detect the sound (blue). These zones of impact are, however, not as sharply defined as depicted here and there is a large degree of overlap between some of the zones.

3.1. Detection

The distance at which an animal is able to detect a sound source depends on the animals' hearing ability under noisy conditions. In addition to the absolute hearing thresholds presented above, another important parameter in determining detection thresholds is the critical ratio. The critical ratio is defined as the lowest signal-to-noise ratio at which an animal is just able to detect a tone in broadband masking noise (Kastelein *et al.*, 2009). The lower an animal's critical ratio is for a given frequency, the better it is at detecting a signal in noise.

Harbour porpoise critical ratios have been measured by Kastelein *et al.* (2009), and auditory filters have been investigated at high frequencies (22.5 to 140 kHz) by Popov et al (2006). At low frequencies (<4 kHz) critical ratios were around 18 dB. Critical ratios increased with increasing frequency and at frequencies between 125 kHz and 150 kHz the critical ratio was around 39 dB. The study by Kastelein *et al.* (2009) suggests that harbour porpoises are good at, but not specially adapted to, detecting signals in noise through improved critical ratios at certain frequencies. However, Popov *et al.* (2006) show results indicating that harbour porpoises may indeed have adaptations for detecting high frequency signals, which has otherwise only been seen in a few species of bats (Long, 1977).

Harbour seal critical ratios have been investigated for frequencies between 100 Hz and 2500 Hz (Southall *et al.*, 2000). The results show ratios increasing with frequency with values between 13 dB at 200 Hz and 17 dB at 2.5 kHz. This suggests that harbour seals are good at detecting low frequency signals in noise, but are not specially adapted to specific frequencies (Southall *et al.*, 2000). Sills *et al.* (2015) measured critical ratios in ringed seals at 100 Hz to 25.6 kHz and found similar results to those of harbour seals, suggesting that ringed seals can efficiently extract signals from background noise across a broad range of frequencies.. Critical ratios have not, to our knowledge, been investigated in grey seals.

In salmon the critical ratio was measured at the best frequency of hearing (160 Hz), and was found to be approximately 24 dB (Hawkins and Johnstone, 1978). In Atlantic cod critical ratios were measured at frequencies ranging from 50 Hz to 380 Hz, and are in the range of 16 to 21 dB (Chapman and Hawkins, 1973). Atlantic cod's ability to detect signals in noise at very low frequencies (<400 Hz) may therefore be comparable to that of marine mammals in their best frequencies. Critical ratios have not been investigated in herring, shad or crucian carp.

There is no data available of critical ratios or effects of underwater noise on any of the diving bird species at this time.

With increasing noise levels it becomes increasingly difficult for animals to detect signals of importance (masking, see below), and increasingly difficult to evade noise signals such as noise from impact pile-driving.

3.2. Masking

Sound processing in the mammalian ear happens in what can be viewed as a series of band-pass filters (Patterson, 1974), and the bandwidth of the filters increases with the frequency of the sound to be processed. One-third-octave band filters are good approximations for the proposed auditory filters of many mammals at higher frequencies (120 kHz, Lemonds *et al.*, 2011), and may also be a valid assumption for fish with swim bladder such as herring and cod (Fay, 1988) if no other information is available. Analysing noise using one-third octave band filters gives an idea of what these animals would experience. Masking of signals can occur, if there is an overlap in frequency between the signal in question and the 1/3 octave noise level. A decrease in detection distance can happen at ranges where the one-third octave band sound pressure level of the masking sound exceeds the critical ratio within the critical band of the signal of interest for the animal (Frisk *et al.*, 2003). Masking is a naturally occurring phenomenon in the environment. However in areas with human activities, detection ranges for important signals may be further reduced due to anthropogenic noise levels.

Porpoises rely heavily on acoustic signals for all aspects of foraging and navigation, and acoustic signals are crucial during e.g. sexual displays and in communication between the mother and the calf (Clausen *et al.*, 2010). Though there is very little overlap in frequency between the main frequencies of known noise sources (see section 1.2) and echolocation and communication clicks, there may still be enough energy at the higher frequencies (Hermansen *et al.*, 2014) to potentially change click production in harbour porpoises in some situations (Sarnocińska, 2016). The role of passive listening in harbour porpoises is not yet understood, but masking of naturally occurring sounds could potentially be an issue for harbour porpoises when navigating as well.

Underwater signals are particularly important in courtship and mating behaviour in seals and cod and for school coherence in herring (Van Parijs, *et al.*, 2003a and b, Van Parijs, 2003, Rowe and Hutchings, 2004, Wilson *et al.*, 2004). Masking of underwater sounds used by male seals during mating season, and by cod during spawning season has the potential to negatively affect the reproductive success of individual animals, and this could in turn affect recruitment to the next generation. Since many fish species migrate over considerable distances and may rely on acoustic cues from the surrounding environment (Van Opzeeland and Slabbekoorn, 2012) increased noise levels could potentially also affect fish ability to find vital areas such as spawning grounds.

Compensation mechanisms to overcome masking of communication signals have been described in several marine mammal species either increasing the amplitude of their signal or shifting the frequency of the signal (Lombard effect; Holt *et al.*, 2009, Parks *et al.* 2011). Masking can also be overcome by increasing the call duration or call rate making it more probable that a signal is detected or by waiting for the noise to cease (Brumm and Slabbekoorn, 2005). Increased call duration has been documented in killer whales (Foote *et al.*, 2004). Fluctuation in the time/frequency structure of the masking noise can result in a release from masking known as comodulation masking release, which has been demonstrated in the bottlenose dolphin (Branstetter and Finneran, 2008) and goldfish (Fay, 2011). These compensatory mechanisms have not been investigated in seals, but spatial release from masking due to directional hearing has been found in a sea lion (Holt and Schusterman, 2007), and one study has shown that signals composed of a number of different frequencies are more readily detectable by pinnipeds in quiet and masked conditions than predicted from the audiogram and critical ratio (Cunningham *et al.*, 2014). Increasing amplitude or shifting frequency has not been investigated in fish, but in Atlantic cod sound production is an important factor in mate selection (Rowe and Hutchings, 2004), and changing sound parameters could thus affect mating success for males, thus altering natural selection. Finally mere detection of the signal may not be enough for successful communication, and an excess of signal of some dB above the detection threshold may be required (Erbe *et al.*, 2016).

3.3. Behavioural changes

Behavioural changes range from very strong reactions, such as panic or flight, to more moderate reactions where animals may orient themselves towards the sound or move slowly away. It may also be the cessation of normal ongoing behaviour. But behaviour is inherently difficult to evaluate especially in animals living under water where observations are difficult. Animal reactions may also vary with season, initial behavioural state (e.g. motivation, foraging, migrating or nursing), age, sex, and with different intensities, frequencies and time structures of the noise. Linking short term reactions to long term impact is one of the greatest challenges for science today.

Behavioural changes in harbour porpoises have mainly been investigated in relation to impulsive noise. Lucke *et al.* (2009) were able to induce consistent behavioural changes in a captive harbour porpoise when it was exposed to noise levels of 174 dB (peak-peak) re 1µPa (or a SEL of 145 dB re 1 µPa^{2}s) from a single airgun. Harbour porpoises in the wild have shown to flee noise from impact pile-driving, where aversive reactions have been documented up to 20 km from the pile-driving site (Tougaard *et al.*, 2009, Brandt *et al.*, 2011, Dähne *et al.*, 2013, Pirotta *et al.* 2014). In some areas porpoises returned after a maximum of a few days (Brandt *et al.*, 2011, Dähne *et al.*, 2013) and in one area population figures did not return to pre-pile-driving values after more than 10 years after constructing a windfarm where pile driving was carried out only for the transformer station (Teilmann and Carstensen, 2012). However, harbour porpoises have also shown to respond with strong behavioural reactions to medium and high frequency components (250 Hz to 63 kHz) of shipping noise at relatively low levels (123 dB re 1 µ Pa rms, Dyndo *et al.*, 2015).

Harbour porpoises have also shown strong reactions to acoustic deterrent devices developed to keep seals away from aquaculture (Olesuik *et al.*, 2002, Brandt *et al.*, 2013, Coram *et al.*, 2014). Deterrence has been observed up to 7 km from the active device (Brandt *et al.*, 2013).

Previous studies did not observe behavioural changes corresponding to strong avoidance in seals as a direct result of human activities (Harris *et al.*, 2001, Blackwell *et al.*, 2004, Southall *et al.*, 2007). However, more recently an aerial survey programme conducted during a five-year period spanning wind farm construction, revealed a significant post-construction decline in harbour seal haul-out counts (Skeate *et al.*, 2012). Also, Russell *et al.* (2016) found that during piling (without noise mitigation), seals usage (abundance) was significantly reduced up to 25 km from the piling activity. Seals are generally known to habituate fast, even to relatively loud sound levels (Fjälling *et al.*, 2006). However, a study by Götz and Jannick (2011) demonstrates that repeated startle responses induced by intense noise with a fast rise time, can result in noise sensitization and fear conditioning, causing animals to leave an area otherwise associated with food.

Changes in behaviour as a consequence of noise have been investigated for a number of fish species exposed to different kinds of sound with varying intensity, and sound that may deter some fish species, can have an attracting effect on others (for reviews see Wahlberg, 1999, Popper and Hastings, 2009).

A laboratory study by Voellmy *et al.* (2014) found that increasing noise levels in the test tanks reduced feeding success in the three-spined stickleback (*Gasterosteus aculeatus*) and reduced feeding behaviour in the European minnow (*Phoxinus phoxinus*).

Engås *et al.* (1996) reported lower catch rates of Atlantic cod and haddock (Melanogrammus aeglefinus) for five days after seismic exploration using air-guns at up to 33 km from the activity. Atlantic herring and blue whiting (*Micromesistius poutassou*) also appeared to avoid or to move to a greater depth in an area where air-guns were used (Slotte *et al.*, 2004). These studies suggest that noise from seismic surveys may induce avoidance of an area in wild fish populations at least for a limited time period.

The effects of pile-driving noise were investigated in Atlantic cod and sole (*Solea solea*) in a study by Mueller-Blenkle *et al.* (2010). They found significant movement responses in sole at received sound pressure levels of 144-156 dB re 1µPa peak, and movement responses in Atlantic cod and received levels of 140-161 dB re 1µPa peak. They also measured the particle acceleration of the stimulus with reactions occurring at levels between 8.62x10-4 and 6.51x10-3 m/s2 peak. Behavioural reactions to play-backs of sound mimicking impulsive noise sources (main energy between 50 and 600 Hz) have also been investigated in schools of sprat (*Sprattus sprattus*) and Atlantic mackerel (Scomber scombrus) in the wild (Hawkins *et al.*, 2014). The lowest sound level where a reaction was detected in sprat schools was 140 dB re 1 µPa (peak-peak), and for Atlantic mackerel the minimum sound pressure level to elicit behavioural reactions was 143 dB re 1µPa. The behavioural reactions found in sprat schools were a lateral dispersal of individuals breaking up the school and often a reforming of the school at lower depths. Mackerel more often responded by a change in depth. As the reactions were proportional to the sound pressure level measured, dose-response curves were prepared. Through these curves it was determined that a sound pressure level of 163 dB re 1µPa (peak-peak) and cumulative SEL of 145 dB re 1µPa2s will elicit reactions in 50 % of the sprat schools. For Atlantic mackerels reactions are also elicited in 50 % of the schools at 163 dB re 1µPa (peak-peak), but at a cumulative SEL of 152 dB re 1µPa2s. For fish without or with a deflated swim-bladder such as the mackerel the relevant stimulus for hearing is particle motion, and to estimate one aspect of the particle motion the particle velocity of the played back sound was calculated under the assumption of a free acoustic field. The single noise pulse particle velocity estimated to elicit reactions in 50% of the mackerel schools was calculated to -80.4 dB re 1 m/s or particle velocity exposure level of -101.7 dB m2/s. The particle velocity values are likely to be conservative estimates, as the assumptions used in the calculations are somewhat uncertain.

Infrasound, sound below 20 Hz, is likely detectable to all aquatic species with the ability to register particle acceleration (Sand and Karlsen, 2000). Intense infrasound at 10 Hz with a particle acceleration of 0.01 ms-2 produced spontaneous avoidance in juvenile salmon and salmon smolt (Enger *et al.*, 1993, Knudsen *et al.*, 1992, 1994). The same was found for the European eel (*Anguilla Anguilla*, Sand *et al.*, 2000), suggesting that this may be a more generalized reaction to infrasound.

A study of juvenile European eel showed that shipping noise did not adversely affect individuals in good physical condition, but caused less effective anti-predator behaviour in individuals in poor physical condition (Simpson *et al.*, 2015, Purser *et al.*, 2016). The physical state of an individual may thus also influence the scale of noise effects.

3.4. Physiological stress

Changes in behaviour are one aspect of responding to noise, but other processes within the body of the individual are also set in motion. All these responses are collectively known as the integrated stress response (Bonga, 1997). The stress response is initially an adaptive response to avoid the negative effects of a stressor, such as noise. In fish the increase in hormones (e.g. cortisol) associated with the stress response (Wysocki *et al.*, 2005) causes an increased oxygen uptake, and redistribution of blood and oxygen to necessary tissues (Bonga, 1997). However, in marine mammals, where the ability to restrict oxygen consumption is vital to their diving abilities, the hormonal stress response is somewhat different (Atkinson *et al.*, 2015).

Stress hormones also cause allocation of energy resources from long-term investments, like growth and reproduction, to the more immediate needs for survival (Schreck, 1996, Wingfield, 2003, Atkinson *et al.*, 2015).

Prolonged or often re-occurring exposure to noise can result in a chronic state of stress, with constant high levels of stress hormones. Negative effects of increased cortisol levels have been demonstrated in terrestrial mammals (Wingfield, 2013), however, this effect remains to be investigated in marine mammals (Atkinson *et al.*, 2015). For marine mammals in areas such as the Baltic Sea, where individuals still have increased levels of contaminants in the tissue (Aguilar *et al.*, 2002, Routti *et al.*, 2005), things may be even more complicated, as contaminated individuals may be more vulnerable to stress from noise than in other areas (Atkinson *et al.*, 2015).

Prolonged high levels of cortisol have negative effects on various parts of the immune system in fish (Schreck, 1996). In the brown trout even relatively small increases in cortisol concentrations, significantly affected the survival, through increased susceptibility to infection and disease (Pickering and Pottinger, 1989). Dror *et al.* (2006) demonstrated that handling stress significantly increased the susceptibility to ulcerative disease in the goldfish. Cortisol has shown to have inhibitory effects in the release of reproductive hormones in rainbow trout (*Oncorhynchus mykiss*, Pankhurst and Dedual, 1994), and in Atlantic cod daily exposure to linear up-sweeps (100 Hz to 1 kHz) during the spawning window resulted in reduced egg production and fertilization, and ultimately caused a more than 50 % reduction in viable embryos (Sierra-Flores *et al.*, 2015). Stress has also shown to have a negative effect on the development of larvae in the Atlantic cod, with more abnormal developing larvae in eggs from stressed females (Morgan *et al.*, 1999), and cod larvae exposed to noise developed lower body width–length ratios, making them easier to catch in a predator-avoidance experiment (Nedelec *et al.*, 2015). Slower growth rates have been shown in rainbow trout in the first months of exposure to noise in an aquacultural setting (Davidson *et al.*, 2009). All these studies imply that noise effects on physiological parameters such as development and growth also differ depending on life stage.

3.5. Hearing sensitivity threshold shifts

Intense noise levels can lead to noise-induced changes in animal detection thresholds either temporarily (TTS) or permanently (PTS) through fatiguing, damaging or even killing sensory cells in the inner ear (Popper and Hastings, 2009, Ketten, 2012). Due to their protective status noise-induced PTS in marine mammals has only been documented in a single laboratory study, where PTS was accidentally induced. Even though underwater explosions can very likely cause PTS at a distance of a few km (Koschinski 2011), it is probably not very common in wild populations, as the animals need to be very close to the sound source for most kinds of anthropogenic sound sources. Hearing loss is therefore more often temporary with the animal regaining its original detection abilities after a recovery period. The recovery period can be critical for an animal because its communication, navigation, prey detection or predator avoidance can be impaired for some time (Lucke *et al.*, 2009). Sound intensity, frequency, and duration of exposure are important factors for the degree and magnitude of hearing loss, as well as the length of the recovery time (Popov *et al.*, 2011). Prolonged exposures to noise, where the ear is re-exposed to TTS inducing sound pressure levels before it has had time to recover from previous TTS, may result in a building TTS, and TTS of 50 dB or more which will often result in permanent hearing damage (Ketten, 2012).

PTS has not been investigated in harbour porpoises, but PTS was accidentally induced in a harbour seal after two consecutive 60 s exposures to a 4.1 kHz pure tone fatiguing stimulus. This initially induced a threshold shift in hearing sensitivity at 5.8 kHz of more than 50 dB, and more than two months later 7-10 dB threshold shift was still measurable (Kastak *et al.*, 2008).

Lucke *et al.* (2009) measured TTS in harbour porpoises exposed to a single sound pulse from a single airgun. TTS of more than 6 dB was measured after a single exposure to 200 dB (peak-peak) re 1µPa or SEL of 164 dB. The exposure was repeated after two days and induced a 15 dB TTS. This suggests the hearing sensitivity was not completely recovered after the first exposure before the second exposure commenced. Investigating the cumulative effect of multiple pile-strikes, Kastelein *et al.* (2015) exposed a harbour porpoise to playbacks of pile-driving sounds. During exposure sessions, the average received SEL of a single pulse was 146 dB re 1 µPa2s. Within each exposure session, the animal was exposed to 2760 playbacks of pile driving strikes with an inter-pulse interval of 1.3 s, resulting in a total exposure duration of 60 min (i.e., a cumulative sound exposure level of 180 dB re 1 µPa2s. The maximum TTS found after 1 h exposure was 3.6 dB at 8 kHz, and the hearing recovered within 48 min of exposure. Extrapolating between different impulsive noise sources may thus not be appropriate. Kastelein *et al.* (2012a) also induced TTS in a harbour porpoise using longer noise durations of lower intensity octave band noise centred around 4 kHz, where an exposure of SPL of 124 dB re 1 µPa for 120 min caused a TTS of 6 dB. The cumulated SEL was therefore 163 dB re 1 μPa^2s. TTS in another Phocoenoid species, the Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*) was studied by Popov *et al.* (2011). When exposed to continuous half octave band noise centred at 32 kHz, 45 kHz, 64 kHz or 128 kHz for 30 min, TTS could be induced at sound pressure levels as low as 140 dB re 1 µPa. TTS happens close to the main frequency of the impact sounds for continuous tones (Kastelein *et al.*, 2013).

TTS in a harbour seal exposed to longer duration noise was investigated twice (Kastak *et al.*, 2005, Kastelein *et al.*, 2012a). Kastak *et al.* (2005)

were able to induce 6 dB TTS after 25 min exposure to 152 dB re 1 µPa using octave band noise centred at 2.5 kHz. Kastelein *et al.* (2012b) found that TTS of approximately 6 dB was induced after 60 min exposure to 136 dB re 1 µPa octave band noise centred around 4 kHz.

Popper *et al.* (2005) investigated TTS in three species of fish, northern pike (*Esox lucius*), Lake chub (*Couesius plumbeus*), and broad whitefish (*Coregonus nasus*), when exposed to high intensity noise from a seismic air-gun. TTS was found in northern pike and lake chub, but not broad whitefish, and hearing fully recovered within 24 hours of exposure. Scholick and Yan (2001) tested the effect of white noise (0.3-4.0 kHz) at 143 dB re 1 µPa on the fathead minnow (*Pimephales promelas*), a cyprind fish species. They were able to show significant TTS even after relatively short exposures (1 hour), and longer exposures (24 hours) produced TTS that was still significant after two weeks.

Noise has also been shown to cause injury directly to the hearing sensory epithelium in fish (Popper and Hastings, 2009). Enger *et al.* (1981) found damaged cells in the sensory epithelium of Atlantic cod exposed to between 1 and 5 hours of pure tones (50 Hz to 400 Hz at 180 dB re 1 µPa). McCauly *et al.* (2003) found extensive damage to the hearing epithelium in pink snapper (*Pagrus auratus*), after exposure to intense seismic air-gun noise. A later study has however not been able to replicate this study in another fish species (Popper *et al.*, 2007).

3.6. Physical injury in non-auditory tissue

High intensity sounds have been proposed as the cause of bubble formation in the tissue of some cetaceans (Jepson *et al.*, 2003; Tal *et al.*, 2015). Furthermore, Tal's *et al.* 2015 results indicate a deleterious interaction between intense underwater sound fields and the vital body functions either directly or via nitrogen bubble growth. The study indicates a significant contribution of the noise to the development of a neurologic insult, in addition to the dysfunction by decompression sickness. Though physical injury after noise exposure has not been investigated in porpoises, it has been proposed as the cause of some cetacean mass-strandings after exposure to military mid-frequency sonar (Balcomb and Claridge, 2001). A study by Kvadsheim *et al.* (2010) examined possible tissue damage in hooded seals after exposure to naval sonar, but found no evidence of tissue damage.

Mimicking exposure to pile-driving two fish species hybrid striped bass (*Morone chrysops* X *Morone saxatilis*) and Mozambique tilapia (*Oreochromis mossambicus*), were exposed to 210 dB re 1µPa2s that caused barotrauma such as a ruptured swim bladder, herniations and hematomas in several organs (Casper *et al.*, 2013). Similar findings were described for lake sturgeon (*Acipenser fulvescenss*) and Nile tilapia (*Oreochromis niloticus*), though the same study did not find damage in hogchoker (*Trinectes maculatus*), a fish with no swim bladder exposed to similar noise levels (Halvorsen *et al.*, 2012). The study found a correlation between the types of swim bladder and the degree of tissue damage at high sound intensities (Halvorsen *et al.*, 2012). Barotrauma in juvenile chinook salmon (*Oncorhynchus tshawytscha*) exposed to pile-driving was investigated by Halvorsen *et al.* (2011). Based on these results a dual criteria for predicting barotrauma was devised. Exposures above 179 dB re 1 µPa2s per strike for exposures of 1920 pile- strikes and 181 dB re 1 µPa2s per strike for exposures of 960 pile-strikes, combined with a cumulative exposure criteria of 211 dB re 1µPa2s integrating the energy of all the pile-strikes in the exposure, would elicit barotrauma severe enough to reduce fitness. Injuries in fish from explosives have been documented up to distances of 100 m from a blast site (Continental, 2004, dos Santos *et al.*, 2010).

4. Criteria for identifying noise–sensitive species

Several aspects are considered in order to identify the Baltic species most sensitive to noise:

- **Hearing sensitivity.** For a species to be susceptible to impacts of noise outside of the immediate vicinity of the sound source it must be able to detect sound. Hearing sensitivity of the different species (see chapter on hearing sensitivity and sound production) is therefore considered.
- **Impact of noise.** A species might be able to detect and produce sound within a range of frequencies (see chapter on hearing sensitivity and sound production), but it may not be very sensitive to noise disturbance, or it may react to noise even if the frequency spectrum is outside the frequency of best hearing or sound production of the species (see chapter on noise impacts). Potential noise impact on the species is considered.
- **Threat status.** Populations already threatened by impacts from other sources, such as eutrophication or hazardous chemicals, may be more susceptible to detrimental effects from noise. Threat status is therefore also evaluated based on information from the HELCOM red list of Baltic Sea species in danger of becoming extinct (HELCOM, 2013).
- **Commercial value.** Noise effects on species with high commercial value can potentially affect the economy of an industry such as the fishing industry or on a smaller scale recreational industry relying on the presence of marine mammals. Commercial value is therefore also included as a parameter.
- **Data availability.** If little or no knowledge is available on either, hearing sensitivity or noise impact or if little or no data are available on spatial distribution, a species is not included at this stage. Data supplied at a later stage may warrant a species to be considered a priority species. Data availability is thus a continuing factor for choosing priority species.

A list of noise sensitive species is proposed based on the five criteria, where data availability at this stage is concerning hearing sensitivity and potential noise impact (Table 1). Each criteria is ranked based on relevance according to available knowledge as: high, medium, low, negligible or unknown. The subsequent chapter will further narrow down the list based on availability of spatial distribution data, and finally propose a list of priority sound sensitive species.

Previous chapters identify the harbour porpoise, harbour seal, ringed seal and grey seal as highly sensitive to sound in a wide frequency range. Harbour porpoises are found to be especially sensitive to noise disturbance from impulsive noise, however continuous noise may also prove to be an issue in some instances (Dyndo *et al.*, 2015), and though some of the world's highest densities of porpoises are found in the Belt Sea, which also contains some very busy shipping lanes (Sveegaard *et al.*, 2011 a and b), there is also a risk of negative long-term effects of physiological stress responses from noise both impulsive and continuous.

The three seal species may be impacted by continuous noise particularly during the mating season and especially for harbour seals and ringed seals, as underwater communication may play a key role in their mating behaviour. Impulsive noise may also have an effect through eliciting series of startle responses ultimately causing aversive behaviour (see chapter above), and possibly the negative long-term effects of physiological stress responses.

Harbour porpoises are divided into two subpopulations in the Baltic. The Baltic Proper subpopulation is considered critically endangered (CR), and the Western Baltic subpopulations is evaluated as vulnerable (VU). Harbour seals exhibit a high degree of site fidelity (Dietz *et al.*, 2012), and seals hauling out in Kalmarsund do not overlap with harbour seals in the Southern Baltic, but are considered a separate subpopulation (Härkönen and Isakson, 2010). The Kalmarsund subpopulation is considered vulnerable, whereas seals in the Southern Baltic subpopulation are considered of least concern (LC). The Baltic ringed seal subspecies is considered vulnerable, and the grey seal population in the Baltic is evaluated to be of least concern.

Cod and herring are sensitive to sound in a much narrower frequency range than marine mammals, but at the lower frequencies, where anthropogenic noise contributes significantly. Burbot, a member of the gadoid family, is not as sensitive to sound as Atlantic cod (Cott *et al.*, 2013a). However, both cod and burbot may be vulnerable to masking by continuous noise in the spawning season, where communication sounds likely play an important role (Cott *et al.*, 2014). Furthermore cod and herring are sensitive to disturbance during migration where both continuous and impulsive noise could possibly affect movement patterns for instance through causing acoustic barriers, as well as during spawning, where noise could cause disruption of important behaviour. Negative long-term effects of physiological stress responses are also a concern for cod and herring in several life stages. Cod and herring are fished commercially in the Baltic with cod listed as vulnerable in the HELCOM red list. Burbot has been fished to some extent in the inner parts of the Baltic, and is listed as near threatened (NT) with declining population size (HELCOM, 2013). Baltic herring is however, currently evaluated as of least concern.

Sprat is a commercially important species in the Baltic. The hearing sensitivity of sprat has not yet been investigated. However, sprat is a close relative of herring, and anatomical studies show that the structure of the hearing apparatus is very similar to that of herring (Allen *et al.*, 1976). Using the hearing sensitivity of herring as an approximation of sprat hearing therefore seems to be a justifiable assumption when considering noise impacts on sprat. Hawkins *et al.* (2014) showed that schools of wild sprat react to sound mimicking pile-driving noise, which could have consequences for the survival of individual sprat, since a breaking up of the school makes them more vulnerable to predation, as well as it increases energy consumption.

European eel is sensitive to sound only at very low frequencies (<200 Hz), and its sensitivity is comparable to that of salmon (Jerkø *et al.*, 1989). European eel is critically endangered therefore any possible disturbance to this population could be detrimental.

Though shads and cyprinid fish are sensitive to sound over a broad frequency range, based on their threat status and low commercial value they are not included as priority species at this stage.

The long-tailed duck along with other diving birds such as the red-throated diver (*Gavia stellate*) and the common scoter (*Melanitta nigra*) are considered endangered in the Baltic, but the lack of data on hearing sensitivity and noise impact on diving birds in general prevents any species of diving bird to be included as a priority species at this stage.

Table 1: List of noise sensitive species based on the five criteria: 1) Hearing sensitivity, 2) Impact of noise, divided into impulsive and continuous, 3) Threat status, critically endangered (CR), vulnerable (VU), near threatened (NT), and least concern (LC), 4) Commercial v/alue, and 5) Data availability. Each criteria is ranked based on relevance according to available knowledge as: **high (🔴/€€€/★★★), medium (🟡/€€/★★), low (🟢/€/★), negligible/not applicable (–), or unknown (?)**.

		Hearing sensitivity	**Impact of impulsive noise**	**Impact of continuous noise**	**Threat status**	**Commercial value**	**Data availability**
Marine mammals	Harbour porpoise (*Phocoena phocoena*)	🔴	🔴	🟡	CR/VU	–	★★★
	Harbour seal (*Phoca vitulina vitulina*)	🔴	🔴	🟡	VU/LC	–	★★★
	Baltic ringed seal (*Phoca hispida botnica*)	🔴	🔴	🟡	VU	–	★★★
	Grey seal (*Halichoerus grypus*)	🔴	🔴	🟢	LC	–	★★
Fish	Cod (*Gadus morhua*)	🟡	🟡	🟡	VU	€€€	★★
	Burbot (*Lota lota*)	🟡	?	?	NT	€€	★
	Baltic herring (*Clupea harengus membras*)	🟡	🟡	🟢	LC	€€€	★★
	Sprat (*Sprattus sprattus*)	?/🟡	🟡	🟢	–	€€€	★★
	European eel (*Anguilla Anguilla*)	🟢	🟢	🟢	CR	€€€	★

4.1. Spatial distribution of noise sensitive species

Spatial distribution of a species is important when considering the potential risks of impacts from noise. It provides information of where individuals of a species can be found across seasons, and is invaluable in identifying areas of high density and likely high importance for a species. Noise effects such as masking and behavioural changes are often associated with particular areas and at certain times of the year. Identifying these biologically sensitive areas and times for priority species, would help reduce noise impact on the different species at particularly sensitive periods in their lifecycle (e.g. spawning, calving, nursing, and mating). Marine protected areas such as Natura 2000 areas and HELCOM marine protected areas, have been designated based on special types of habitat and based on the areas of importance for several species of marine organisms. Kallundborg fjord in Denmark has been identified as an area with high porpoise density (Sveegaard *et al.*, 2011a and b), and as a high importance area for calving and nursing (Loos *et al.*, 2010), and has since 2011 been included in the Natura 2000 site, "Røsnæs, Røsnæs Rev, og Kalundborg Fjord", with harbour porpoises as part of the designation basis. Information on marine protected areas with the above listed species in the designation basis, can therefore aid in pinpointing areas of concern.

The risk of hearing damage is not limited to a special time or particular habitat, but rather to an individual's proximity to the sound source and can thus occur over the entire distribution range. To address this risk several countries (e.g. Germany, United Kingdom and Denmark) have adopted national regulations for reducing noise levels from activities with high levels of impulsive noise (e.g. pile-driving, and seismic exploration, S. Werner, 2010, JNCC, 2010a and b, MMWG, 2015). However, information on distribution can provide information on areas with high and low occurrence, making it possible to avoid high density areas.

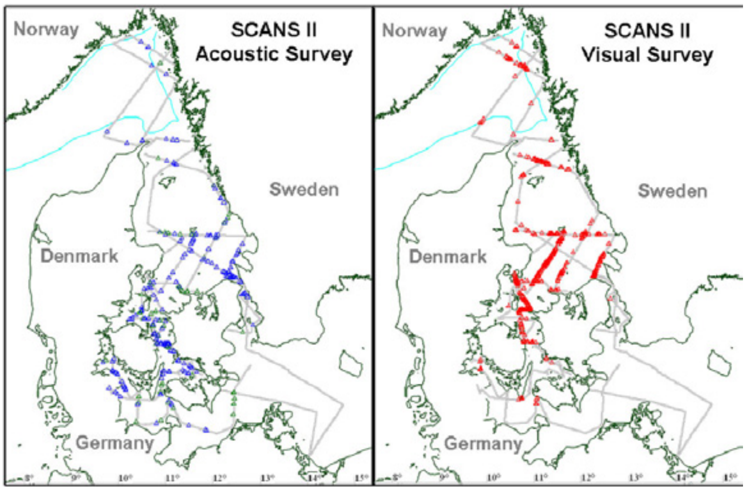


Figure 8: Survey plot from the vessel 'Skagerrak' during the SCANS-II survey 29th of June to 14th of July 2005. Acoustic detections are shown with blue triangles on the left panel. Visual sightings are shown with red triangles on the right panel. The sailed route is shown as a grey line. From Teilmann *et al.*, 2008.

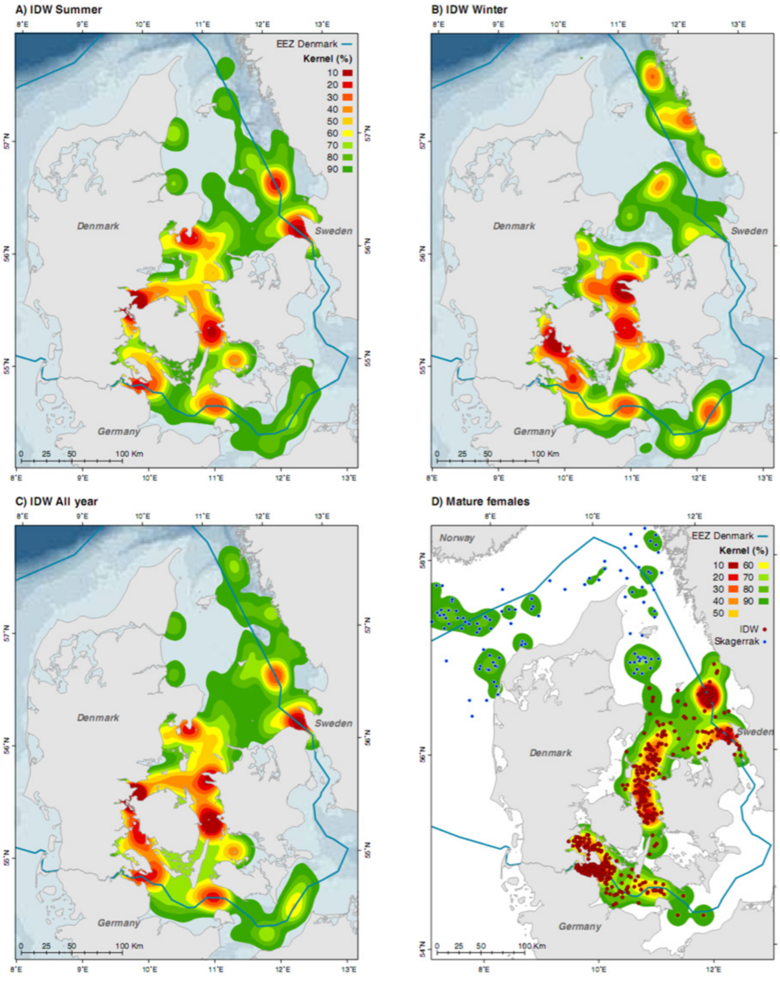


Figure 9: Distribution of harbour porpoises from satellite taggings of 37 animals in inner Danish waters 1997–2007. Colour scale is based on kernel density estimations of 10 intervals. A) Distribution during summer, B) Distribution during winter, C) All year distribution, and D) Kernel and transmitted locations for 8 of the satellite tracked individuals (tracked all year and all females). From: Teilmann *et al.*, 2008.

4.2. Marine mammals

4.2.1 Cetaceans

***Harbour porpoise* (Phocoena phocoena)**

The harbour porpoise is the only cetacean commonly found in the Baltic Sea, and is the only species known to use these waters for all aspects of its life cycle (Viquerat, 2014). As a species listed in Annex IV in the Habitat Directive (1992), marine protected areas (MPAs) have been established in the Baltic Sea where harbour porpoises have been found in high densities, or areas that are suspected to be of high importance.

Harbour porpoises are usually found in coastal waters where the water depth is <200m, and though they can dive to depths of down to at least 220 m and stay submerged for up to five minutes, most dives are shallow with a duration of two minutes or less (Otani, 1998, 2000, Bjørge, 2009). They are mostly found swimming alone or in small groups of 2-3 individuals, often comprised of a mother and her calf. The mating period is in August. With a gestation period of 10-11 months females give birth to a single calf every 1-2 years in June-July (Lockyer, 2003). New-born calves start suckling right away and are nursed for at least 8 months before weaning (Bjørge, 2009).

There are two main subpopulations of harbour porpoises in the Baltic Sea, the Western Baltic subpopulation, and the Baltic Sea subpopulation (Teilmann *et al.*, 2008). This is supported genetically to some extent (Wiemann *et al.*, 2010) and by geometric morphometry (Galatius *et al.*, 2012). The population size estimates of the Western Baltic subpopulation come with a large degree of uncertainty. SCANS II estimates around 20,000 individuals (Hammond *et al.*, 2013), whereas Viquerat *et al.* (2014) estimate twice as many individuals in a slightly smaller area. However neither of these studies covers the entire range of the Western Baltic subpopulation. Estimates of the Baltic Sea subpopulation have been made through the EU LIFE+ funded project Static Acoustic Monitoring of the Baltic Sea Harbour Porpoise (SAMBAH) which estimated ca. 500 individuals (95% CI 80-1,091) (SAMBAH, 2015).

Large-scale visual and acoustic surveys of the species were conducted all through European waters in the summers of 1994 and 2005 (Figure 8, Hammond *et al.* 2002, 2013, Teilmann, 2008). Data collected from satellite-tagged individuals indicate southern Kattegat and the Belt Seas as important habitats for harbour porpoises of this subpopulation (Figure 9, Teilman, 2008, Sveegaard *et al.*, 2011b). This is supported by acoustic monitoring of the area (Sveegaard *et al.*, 2011a) as

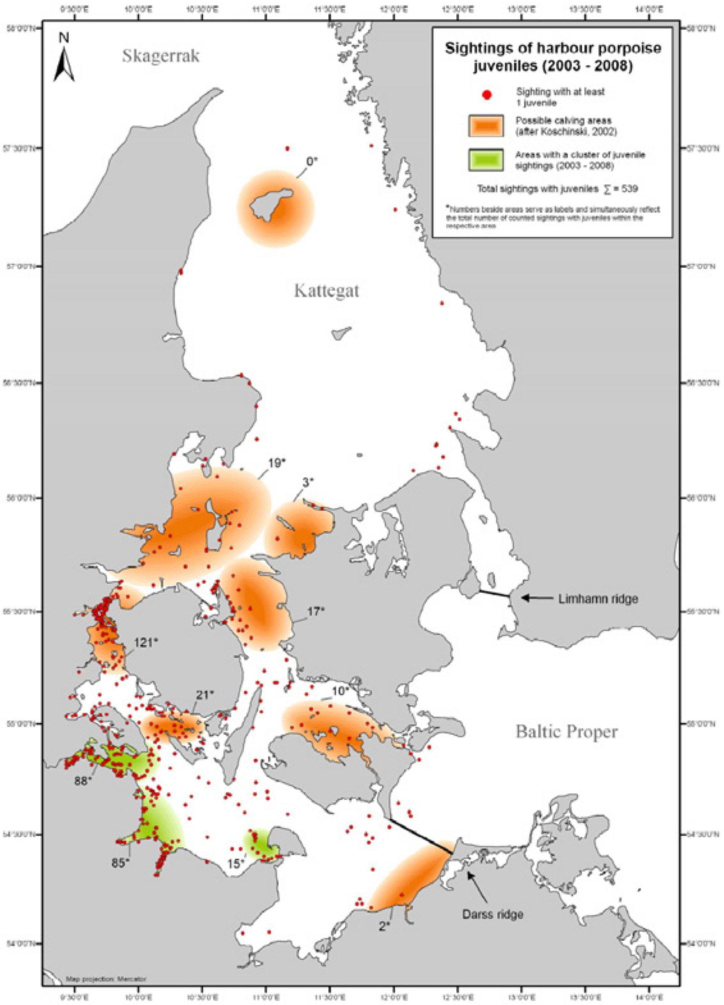


Figure 10: Sightings of harbour porpoises with juveniles and proposed calving and nursing grounds. From Loos *et al.*, 2010.

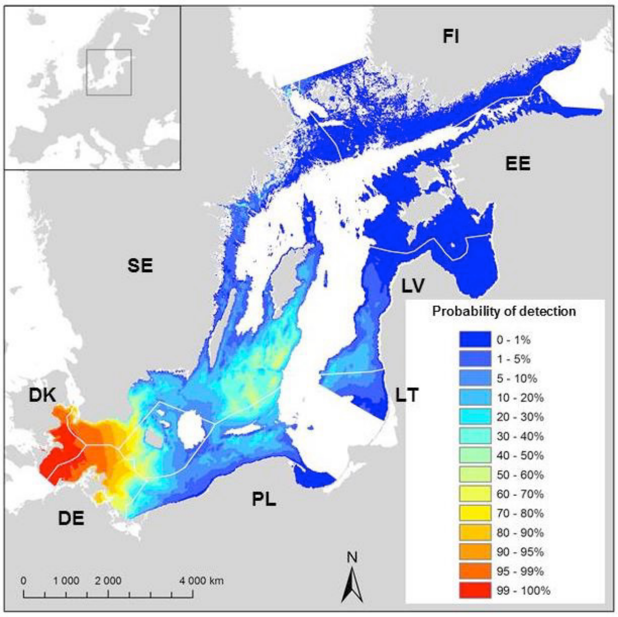


Figure 11: Distribution of Baltic harbour porpoise subpopulation modelled as the probability of detecting click trains in August. From SAMBAH, 2015.

well as by opportunistic observations of porpoises (Gilles *et al.*, 2006). Models using satellite-tag data, together with environmental variables that served as a proxy for prey abundance, also predicted southern Kattegat and the Belt Seas to have a high prevalence of harbour porpoises during all seasons (Edrén, 2010). Loos *et al.* (2010) propose important calving and nursing grounds for the Western Baltic subpopulation (Figure 10) based on juvenile sightings.

The distribution of the Baltic Sea harbour porpoise subpopulation has previously been investigated through visual and acoustic surveys (e.g. Gillespie *et al.*, 2005) and through opportunistic records of bycaught animals (Kuklik and Skóra, 2003), but so far the very few sightings has made it difficult to give any concrete knowledge on the distribution or population size. Data from the SAMBAH project (a large passive acoustic monitoring study during two consecutive years throughout the Baltic) has provided more detailed information on the distribution of the Baltic Sea harbour porpoise subpopulation. There is a clear separation of the two subpopulations during summer with the Baltic harbour porpoise subpopulation mainly found in swallower waters south of Gotland (Figure 11, SAMBAH, 2015). This separation coincides with calving and mating periods, suggesting no cross-breeding between the two subpopulations. In winter animals are more dispersed and seem to mix with the Western Baltic subpopulation. Areas of special interest to this subpopulation are therefore mainly based on the summer distribution (Figure 12, Carlström and Carlén, 2016).

The data available at this stage should be sufficient to identify some biologically sensitive areas for the Western Baltic harbour porpoise subpopulation, but additional data may at a later stage warrant adding more areas.

For the Baltic Sea harbour porpoise subpopulation, biologically sensitive areas can be identified from data from the SAMBAH project, data should be sufficient to identify some biologically sensitive areas though additional areas could be added at a later stage.

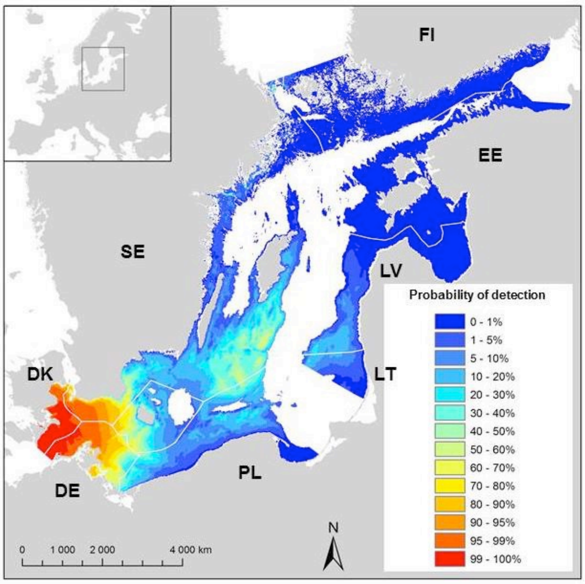


Figure 12: Areas important for the Baltic Sea harbour porpoise presented per quater for 30% of the entire population and a 20% detection probability (from Carlström and Carlén, 2016). The dashed line east om Bornholm is the proposed management line for the Baltic Sea harbour porpoise subpopulation based on summer distribution from Sveegaard *et al.*, 2015. The black polygon is an early version of a proposed expansion of already existing Natura 2000 sites Hoburgs bank och Norra Midsjöbanken to incompas the new results of Baltic harbour porpoise distribution.

4.2.2 Seals

Harbour seals, ringed seals, and grey seals are all listed in both Annex II and V in the Habitat Directive (1992). The amphibious lifestyle of seals means that they are found both in the water and hauled out on various sites on land. Areas of importance for seals can be identified both from data on known haul-outs as well as on tracking of individual seals.

Baltic harbour seal **(Phoca vitulina vitulina)**

Harbour seals are found in coastal waters mainly in the boreal and temperate regions of the Northern hemisphere (Burns, 2009). They are divided into five different subspecies based on distribution and genetic information, with the Baltic harbour seals belonging to the subspecies *Phoca vitulina vitulina*. In the Baltic Sea harbour seals are divided in two subpopulations, the Southern Baltic subpopulation, and the Kalmarsund subpopulation, that are genetically distinct from one another (Härkönen and Isakson, 2010). Recent counts of harbour seal in the Southern Baltic subpopulation estimate it to be approximately 12,000 in 2013 (HELCOM seal database). This observed decline may partly be the result of an outbreak of bird-flu in several areas (Søgaard *et al.*, 2015). The Kalmarsund subpopulation went through a severe bottleneck in 1970's (Härkönen and Isakson, 2010), but is showing a steady increase in individuals with the latest count being roughly 800 individuals in 2013 (HELCOM seal database). This number is not a direct subpopulation estimate. However as the survey was carried out at the peak moulting period, when the proportion of hauled out individuals is considered the highest, it may be considered as minimum population estimates, as some part of the population will always in the water and thus will not be included in the count.

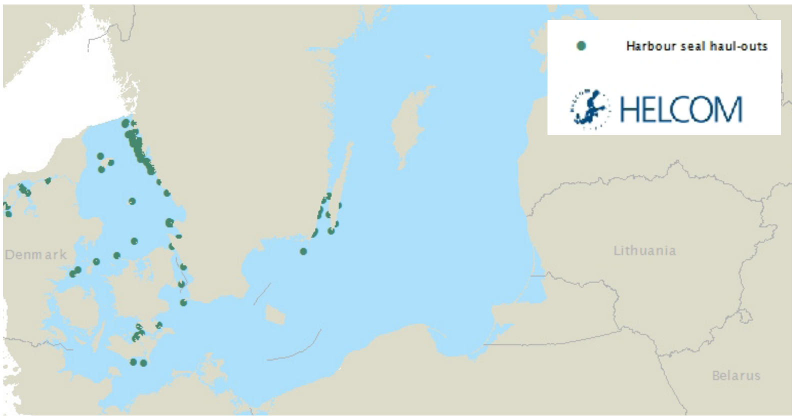


Figure 13. Haul-outs for both harbour seal subpopulations in the Baltic Sea (HELCOM SEAL EG, 2015, for the HELCOM core indicator on "Distribution of Baltic seals" (unpublished, http://www.helcom.fi/baltic-sea-trends/indicators/distribution-of-baltic-seals/contributors-and-references/)).

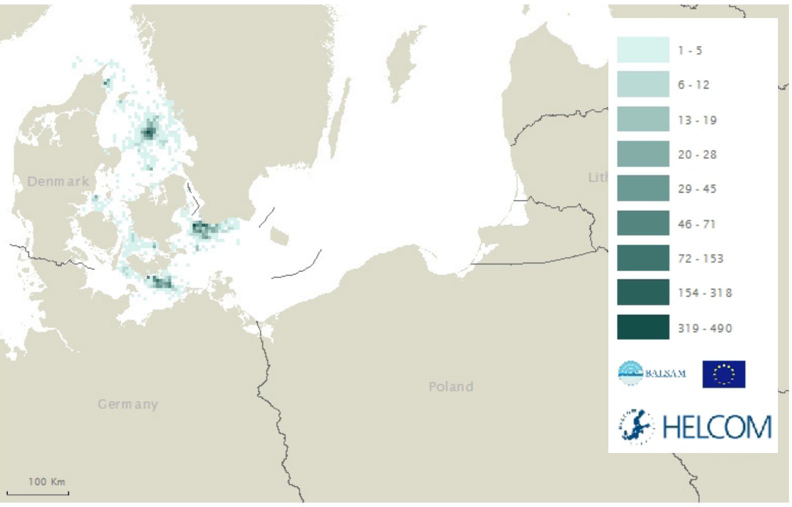


Figure 14: Distribution observations of harbour seals based on GPS tracks from single tagged individuals (HELCOM, 2015). Numbers signify the number of locations in each 5x5 km grid.

Most mature females give birth to a single pup each year, and in the Southern Baltic subpopulation births take place in June (Jørgensen, 2003). Harbour seal pups are born with a water-proof fur, which enables them to follow their mother into the water shortly after birth, though pups are nursed on land for four weeks (Burns, 2009). Mating takes place after the nursing period, primarily in July-August in the Southern Baltic subpopulation (Jørgensen, 2003) and though actual mating sites are unknown, mating is thought to occur in the water relatively close to haul-outs (Søgaard *et al.*, 2015), although some studies indicate that it may also occur in nearby feeding sites (van Parijs *et al.*, ?). In August adult seals moult which requires longer periods on land, as the skin must be dry for this process (Burns, 2009, Søgaard *et al.*, 2015).

Harbour seals exhibit a high degree of site fidelity, and will often remain relatively close to haul-out sites (Dietz *et al.*, 2013, Olsen *et al.*, 2014). They usually feed rather close to their haul-outs as well (Dietz *et al.*, 2012). Harbour seal haul-outs for both subpopulations in the Baltic Sea can be seen in Figure 13.

Information on distribution is available for the Southern Baltic subpopulation based on tagging of single individuals (Figure 14), but does not provide information on the distribution of the whole subpopulation. There is currently no tagging data available for the Kalmarsund subpopulation.

Due to their high degree of site fidelity the data available at this stage should be sufficient to identify some biologically sensitive areas for harbour seals in relation to haul-outs, but a representative data set would require tagging of seals at each haul out, which is still very far off. Therefore as for harbour porpoises additional data may warrant adding more areas at a later stage.

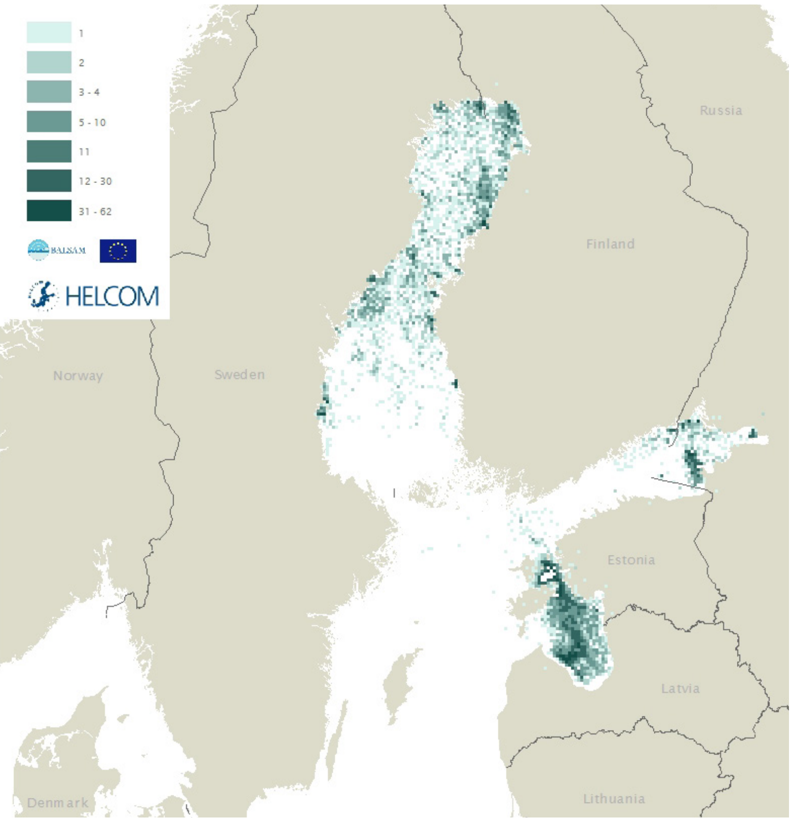


Figure 15: Distribution observations of ringed seals based on GPS tracks from single tagged individuals (HELCOM, 2015). Numbers signify the number of locations in each 5x5 km grid.

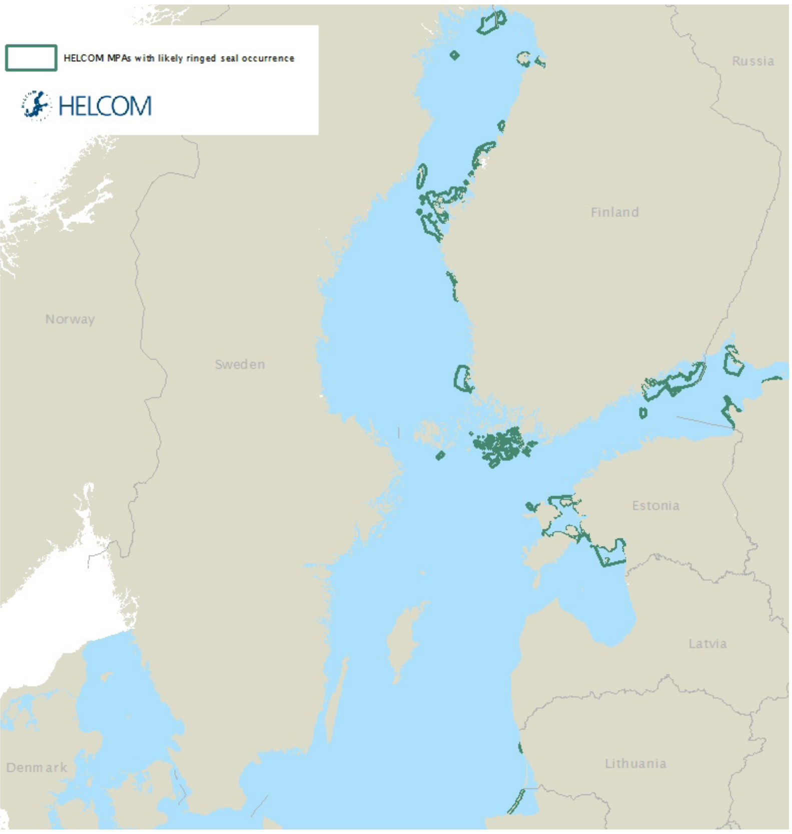


Figure 16: Marine protected areas in the HELCOM area (2016) with ringed seals as part of the designation basis (HELCOM MPA database).

Baltic ringed seal (Phoca hispida bothnica*)*

Ringed seals are closely associated with ice for essential parts of their life cycle. They are therefore very vulnerable to changes in the ice cover due to global warming (Hammill, 2009, Sundqvist *et al.*, 2012). In 2014 the estimated count of ringed seal in the Bothnian Bay was 8119 individuals (HELCOM seal database). In the southern parts of their distribution range such as the Gulf of Finland and Gulf of Riga, ice cover will likely be decreasing more and more in the coming years (Sundqvist *et al.*, 2012), This will likely lead to reduced population growth in those sub-populations (HELCOM, 2018).

Females give birth to a single pup each year. The pup is born with a white lanugo fur, which prohibits it from following its mother into the water. Pups are born on the fast ice in February-March (Sinisalo *et al.*, 2008) in small lairs under the snow that mothers excavate close to a breathing hole. The pups shed the white lanugo coat after 2-3 weeks (Hammill, 2009), but nursing continues for 4-6 weeks (Sinisalo *et al.*, 2008). Breeding is thought to take place during the nursing period, with males defending underwater territories, and mating taking place under the water. Moulting season for ringed seals is from mid-April to early May (HELCOM, 2013).

Information on areas occupied by ringed seals is available based on tagging of single individuals (Figure 15). Ringed seals are more sensitive to masking during mating season in April and May, but as pupping, nursing and in some respect mating is associated with ice-cover in ringed seals identifying areas that are biologically sensitive in terms of mating is not possible at this stage. However, this information together with marine protected areas with ringed seals as part of the designation basis does provide an estimate of main areas of interest for ringed seals in the Baltic.

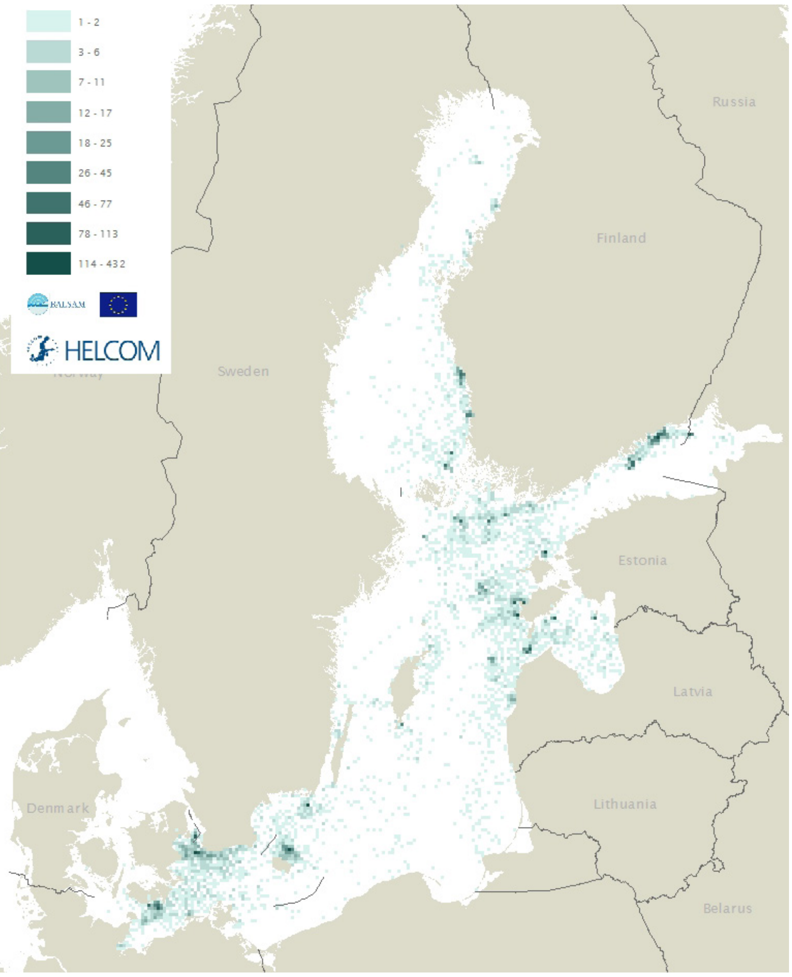


Figure 17: Distribution observations of grey seals based on GPS tracks from single tagged individuals (HELCOM, 2015).

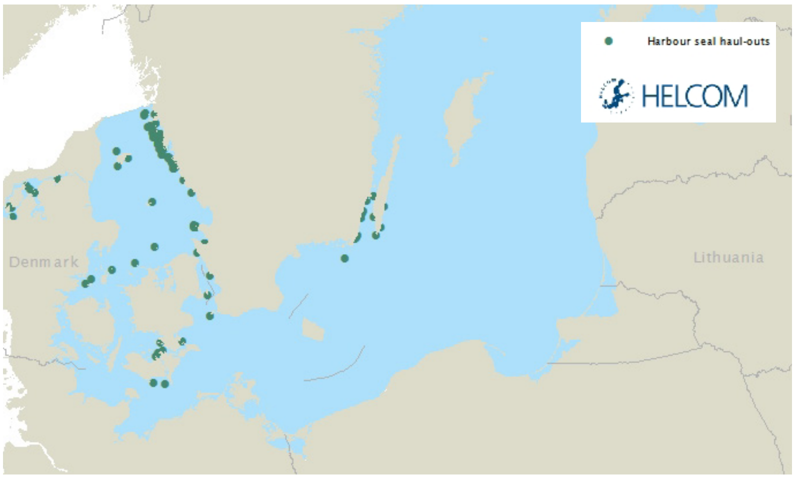


Figure 18: Grey seal haul-outs in the Baltic Sea (HELCOM SEAL EG, 2015, for the HELCOM core indicator on "Distribution of Baltic seals" (unpublished, http://www.helcom.fi/baltic-sea-trends/indicators/distribution-of-baltic-seals/contributors-and-references/)).

Baltic grey seal **(Halichoerus grypus)**

The number of counted grey seals in the Baltic Sea is estimated to be around 32,000 individuals based on the latest seal count from 2014 (HELCOM seal database). Dietz *et al.* (2003) used satellite tags to track the movements of six grey seals from Rødsand seal sanctuary. Results show that individual grey seals migrate through the Baltic proper to the inner Baltic Sea, which also supports findings that grey seals have relatively large foraging ranges compared to harbour seals (Thompson *et al.*, 1996).

Most females give birth to a single lanugo covered pup each year in February-March (Bonner, 1979). The pup is weaned after 17-18 days, and then the female goes into oestrous. Mating likely takes place in the water at the time of weaning (Hall, 2009). During moulting from May to June (HELCOM, 2013) grey seals remain closer to the haul-out, and may be more sensitive to disturbance in these areas in this period, as they congregate around the haul-outs.

Information on areas visited by grey seals are available from tagging of single individuals (Figure 17). However the data represents rather few tagging sites and as a result may be heavily skewed. Grey seals do not exhibit the same degree of site fidelity as harbour seals, but are much more mobile (Dietz *et al.*, 2012). Still information on haul-outs (Figure 18) gives an estimate of the main areas of interest in relation to mating, moulting and pupping with the latter taking place on land or the ice, when it is present in the Northern part of the Baltic.

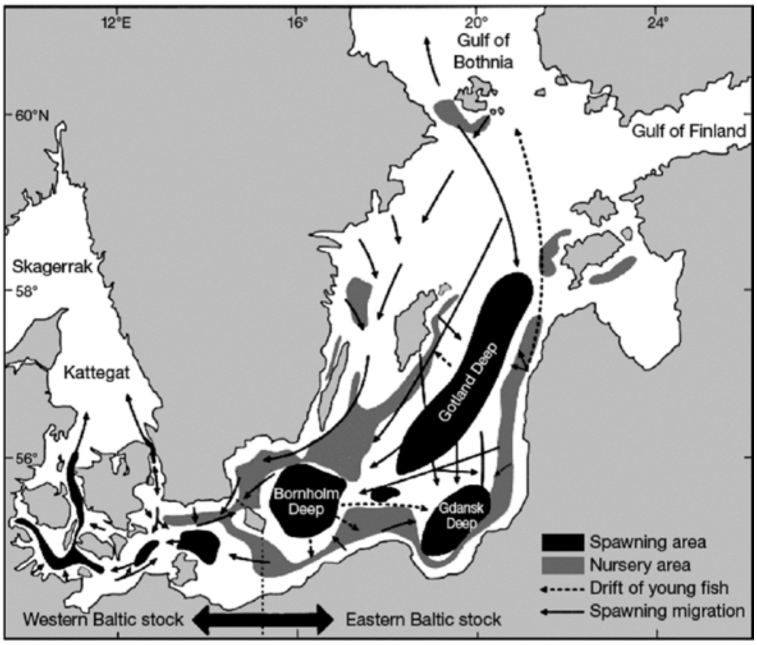


Figure 19: Historical spawning and nursery grounds for the Eastern and Western Baltic cod stocks. From HELCOM, 2013.

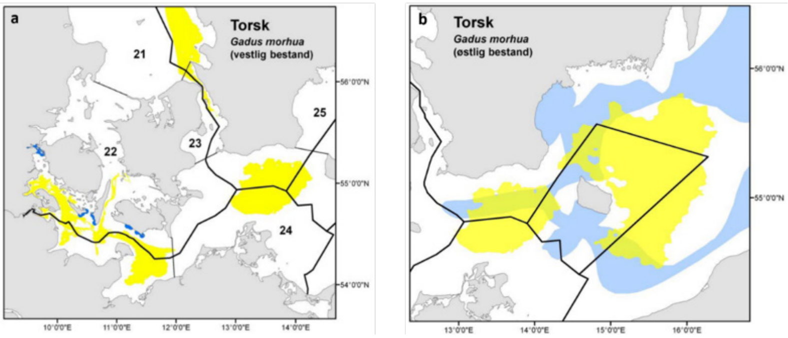


Figure 20: Spawning areas (yellow) and recruitment grounds (blue) for: a) the Western Baltic cod stock, and b) the Eastern Baltic cod stock.

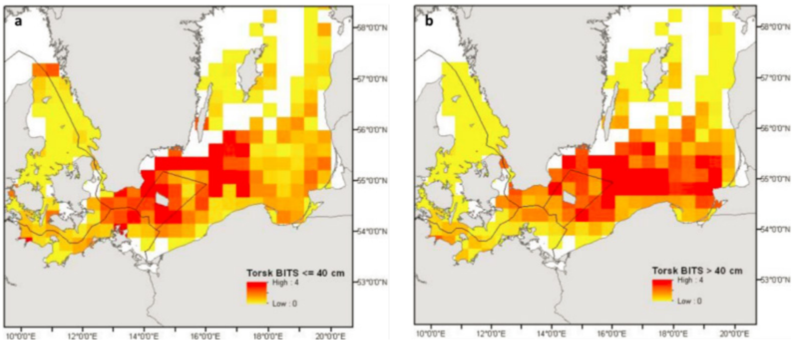


Figure 21: Cod distribution and abundance in the Baltic Sea based on data from BITS 2001–2010. a) Distribution and abundance of cod smaller than 40 cm, and b) distribution and abundance of cod larger than 40 cm. From Warnar et al., 2012.

4.3. Fish

4.3.1 Cod (*Gadus morhua*)

The HELCOM area contains two subspecies of Atlantic cod, in three separate management stocks. The Kattegat stock belongs to the subspecies *Gadus morhua morhua*, and the Eastern and Western Baltic Sea ones to the subspecies *Gadus morhua callarias*. Cod distribution and abundance based on data from the Baltic International Trawl Survey (BITS) covering the period 2001-2010 is shown in Figure 21a for cod smaller than 40 cm and larger than 40 cm in Figure 21b (Warnar *et al.*, 2012). The total cod stock in the Baltic Sea and Kattegat has decreased by 46% between 1971 and 2012 (HELCOM, 2013). This decrease is largely due to overexploitation of the stocks (ICES, 2012a and b), but for the Eastern Baltic stock, hydrographical conditions like low salinity and hypoxia in the water has also halted recruitment, as cod eggs require a minimum salinity of 11 psu, an oxygen concentration of at least 2 ml/L and a temperature higher than 1.5°C (BALANCE, 2007). Historical records show three main spawning sites for the Eastern Baltic cod stock (Figure 19; HELCOM, 2013, *Gadus morhua*) and two out of three spawning sites in the inner Baltic Sea have been lost, leaving the Bornholm Deep as the main spawning ground in the east and Arkona basin in the west (Figure 19, Warnar *et al.*, 2012). For the Kattegat stock only one or two spawning sites are left in the central and Southern part of Kattegat and the Belt Sea waters (Warnar *et al.*, 2012). As cod exhibit strong homing behaviour towards spawning sites once a site is lost, reestablishment is unlikely to occur (Svedäng *et al.*, 2010).

Spawning takes place between May and December, with spawning in the Arkona basin occuring in spring, in the Bornholm basin during summer, and in winter/early spring in Kattegat. Winter/early spring spawning is also seen in Atlantic cod in the North Sea (BALANCE, 2007, Warnar *et al.*, 2012).

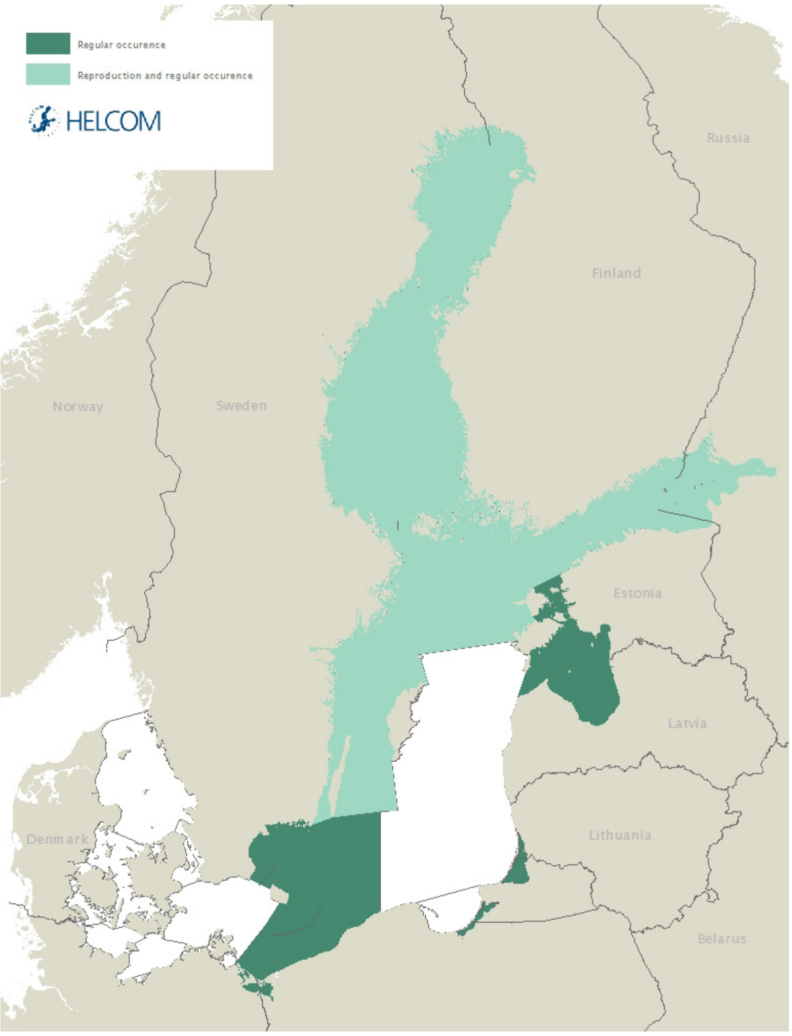


Figure 22: Burbot distribution in the Baltic Sea at the level of sub-basin (HELCOM, 2013).

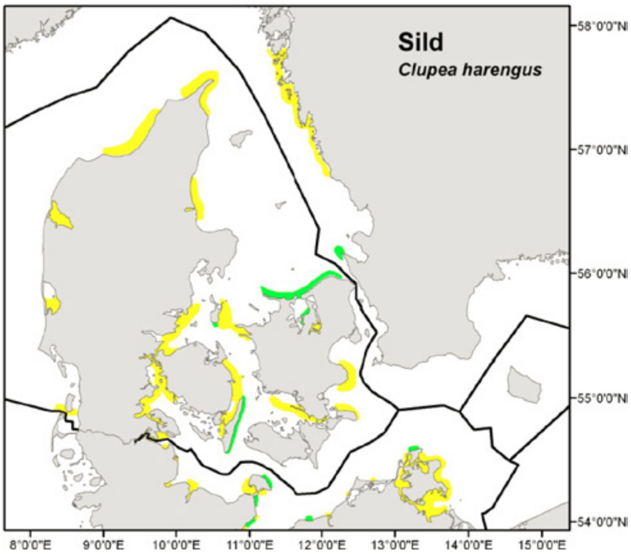


Figure 23: Spawning areas for herring in the Western Baltic, Belt Sea and Kattegat. Yellow areas are for spring spawners, and green areas are for autumn spawners from Warnar et al., 2012.

4.3.2 Burbot (*Lota lota*)

Burbot is the only gadoid species found in freshwater, and in the Baltic it is found in estuaries in brackish water. Its main distribution range is in the Northern Baltic Sea in the Gulf of Finland and in the Gulf of Bothnia (Figure 22).

Burbot spawns at night below the ice from November to March, where they form larger groups (Cott *et al.*, 2013b).

4.3.3 Baltic herring (*Clupea harengus membras*)

In the Baltic, herring is found in two separate stocks with different spawning periods. Autumn spawners are predominantly found in the Western and Southern Baltic Sea, and spring spawners are predominantly found in the North-eastern parts of the Baltic Sea basin (HELCOM, 2013 *Clupea harengus*, Warnar *et al.*, 2012), though there is a large degree of overlap in distribution between the two groups. Spawning areas for herring in the Western Baltic, Belt Sea and Kattegat are shown in Figure 23, where green areas are spawning grounds for autumn spawners, and yellow areas are for spring spawners (Warnar *et al.*, 2012). The area around the island of Rügen in Germany is of particular importance for the spring spawners (Warner *et al.*, 2012). Herring is usually found as pelagic schools in the top 250 m of the water column (Jørgensen, 2003), but for spawning it migrates to shallower waters (10-20 m in depth). The fertilized eggs sink to the bottom where they stick to the substrate forming dense beds on the sea floor in habitats with coarse substrate types such as gravel or coarse sand. In the Baltic however, herring also spawns on vegetation (HELCOM, 2013, *Clupea harengus*).

The distribution and abundance of herring in the outer Baltic was estimated based on BITS covering the period 2001 to 2010. Results are shown in Figure 24a, for herring smaller than 20 cm and larger than 20 cm in Figure 24b (Warnar *et al.*, 2012). There is a high variability in egg and larvae mortality due to predation and environmental factors. This leads to a high degree of variability in yearly recruitment, resulting some very strong year-classes in years where the environmental factors have been favourable, and the opposite when environmental factors have been particularly unfavourable (Warner *et al.*, 2012, Jørgensen, 2003).

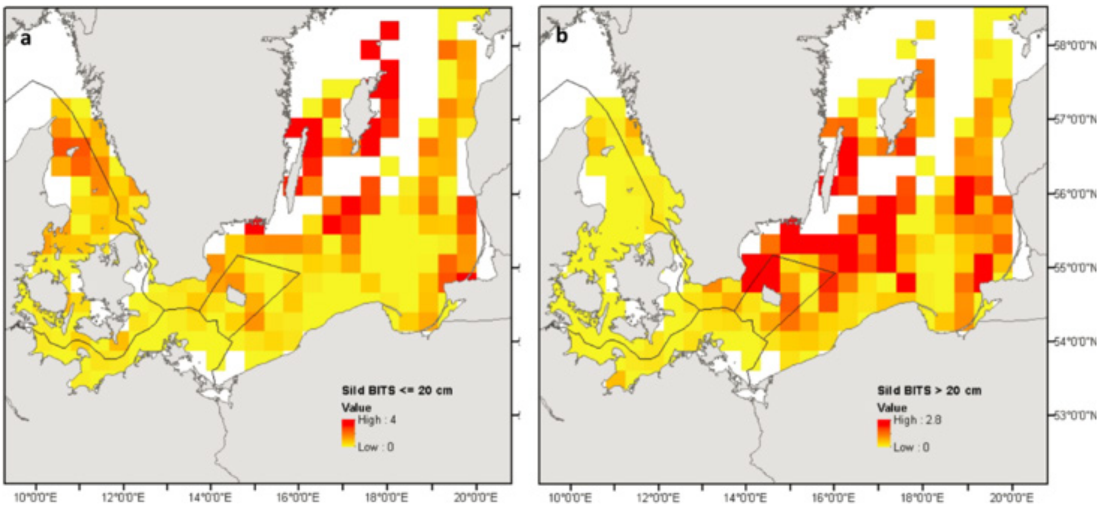


Figure 24: Herring distribution and abundance in the Baltic Sea based on data from BITS 2001–2010. a) Distribution and abundance of herring smaller than 20 cm, and b) distribution and abundance of herring largr than 20 cm. From Warner et al., 2012.

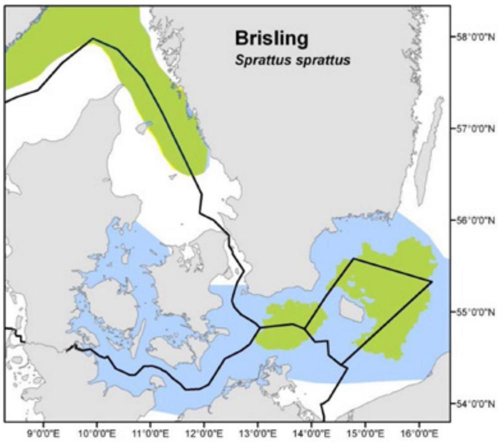


Figure 25: Spawning (green) and recruitment (blue) areas for sprat in the Western Baltic, Belt Sea and Kattegat. From Warner et al., 2012.

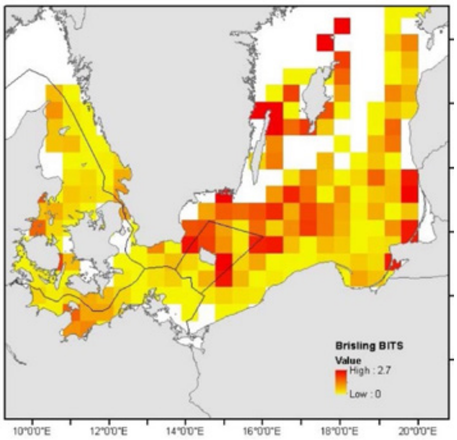


Figure 26: Sprat distribution and abundance in the Baltic Sea based on data from BITS 2001–2010. From Warnar et al., 2012.

4.3.4 Sprat (*Sprattus sprattus*)

Sprat is a close relative of herring, but unlike herring sprat population consists of a single stock (Warner *et al.*, 2012). The spawning period for sprat in the Baltic Sea is usually between March and August (BALANCE, 2007). Sprat is a batch spawner, and spawns in the same areas as cod, the Bornholm deep and Arkona basin (Figure 25, Warner *et al.*, 2012), but have also been found to spawn in the outer part of the Gulf of Finland, in the Gulf of Riga, in the Northern Deep, the Gotland Deep, and the Gdansk Deep (Ojaveer and Kalejs, 2010). Sprat eggs require a salinity of more than 6 psu, and an oxygen content of more than 0.7-1 ml/L to survive, and have a temperature optimum between 5 and 13°C. They have a higher buoyancy than cod eggs and are found higher up in the water column (BALANCE, 2007).

The distribution and abundance of sprat in the southern and western part of the Baltic Sea was estimated based on BITS covering the period 2001 to 2010. Showing a high abundance especially in the central part of the Baltic proper (Figure 26, Warner *et al.*, 2012). As seen in herring there is high degree of variability in yearly recruitment of sprat, largely coupled to water temperature and predation by cod (Ojaveer and Kalejs, 2010).

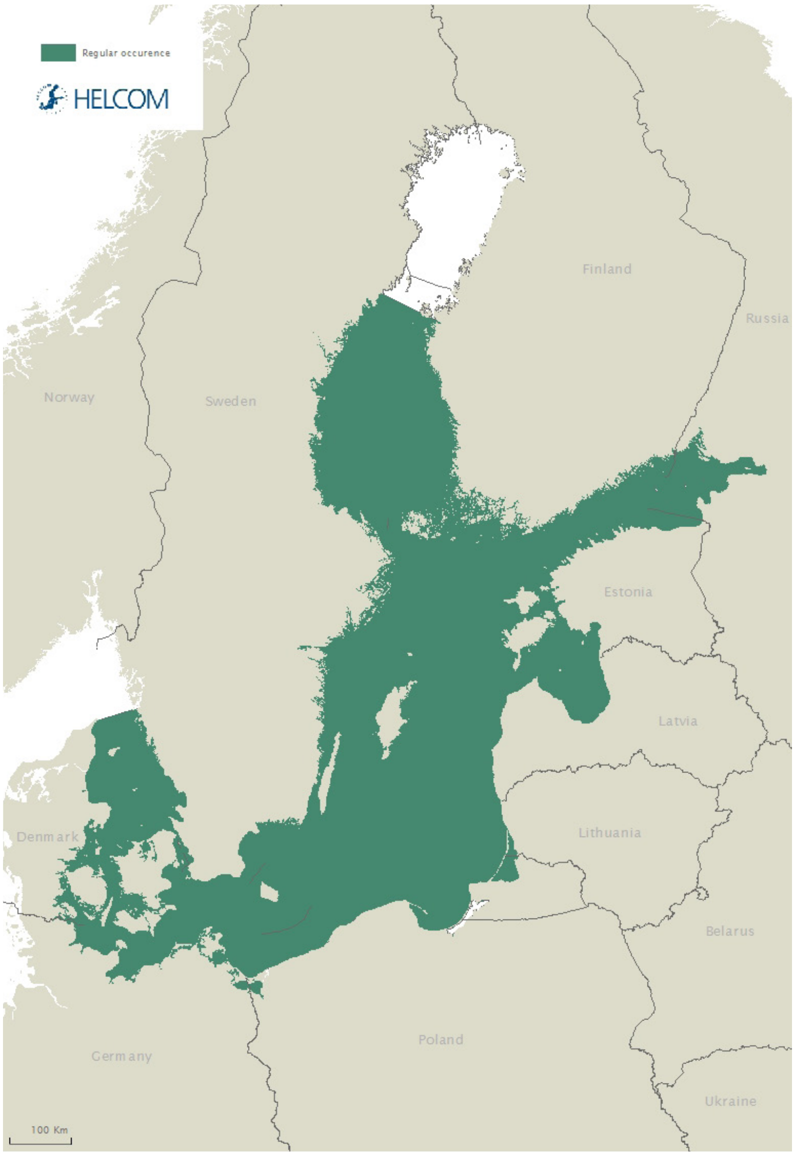


Figure 27: Occurrence of European eel at the level of sub-basin in the HELCOM area (HELCOM, 2013).

4.3.5 European eel (*Anguilla Anguilla*)

The European eel spawns in the Sargasso Sea in the tropical part of the Western Atlantic. Larvae follow the Gulf Stream across the Atlantic to the European continent where they metamorphose into glass eel. They rely on rivers, stream and coastal areas for maturing including the Baltic. The Baltic Sea is thus part of the migratory route for glass eel going towards rivers, streams and important coastal habitats and for adult eels migrating towards spawning grounds. Occurrence of European eel in the Baltic is shown at the level of sub-basin in Figure 27.

Even though the European eel is considered critically endangered only one marine protected area has European eel listed as part of the designation basis (Lundåkrabukten on the Swedish coast of the Sound), but the status of European eel is not known even for this area.

4.4. Priority Noise Sensitive Species

Data on species distribution and areas of biological importance is most well established for the two harbour porpoise subpopulations as it is based on several large scale surveys. Information available to HELCOM on areas occupied by seals is currently based on GPS tracking of single individuals and the location but not importance of haul-outs, and does not provide data for distribution of the whole population or across seasons. Distribution data for burbot and European eel are limited to sub-basin wide occurrence, and data on spawning and nursing grounds in the Baltic are only available for cod limited to two stocks, and for sprat and herring in the outer Baltic, but not for burbot.

Based on existing knowledge and available data harbour porpoises in the Baltic are more sensitive to noise disturbance during calving and nursing periods in June to Septemer and through the fall months. Figure 10 identifies areas of importance for calving and nursing in the Western Baltic subpopulation, and Figure 12 identifies areas of importance during calving and mating periods in the Baltic subpopulation. Figure 9 identifies areas of high harbour porpoise density based on tagging of individuals and further corroborated by acoustic surveys in the Western Baltic subpopulation.

Harbour seals, ringed seals, and grey seals are more sensitive to masking during mating season, as masking could potentially reduce mating success, and thus affect the population. For harbour seals mating takes place from May to July, for ringed seals it is in April and May, and for grey seals in late March and early April. For harbour seals and grey seals some areas of importance are identified from marine protected areas with the species as part of the designation basis, but as pupping and mating is associated with ice-cover in ringed seals, areas of biological importance can only be identified for ringed seals from data on marine protected areas, where this species is included as part of the designation basis.

For the fish species at this stage the Bornholm Deep, and Arkona basin can be identified as areas of high interest for cod and sprat during spawning (in spring and summer), and for sprat the Northern deep, Gotland deep, and Gdansk deep can also be identified during the spawning period. For herring several spawning areas can be identified from Figure 23, but the area around Rügen is of particular importance. For burbot and European eel there is insufficient data at this time to identify biologically sensitive areas.

Due to little available knowledge on noise sensitivity, and distribution for European eel and burbot, as well as low commercial importance for burbot, these two species are not included in the final proposed list of noise sensitive priority species presented in Table 2 for marine mammals and Table 3 for fish.

Biologically significant periods for each of the priority noise sensitive species presented in Table 2 and Table 3 is presented in Table 4.

A preliminary map of biologically sensitive areas that can be identified at this stage, based on available information of distribution, and biologically significant periods (Table 4) is presented in Figure 28. For harbour porpoises the identified areas are based on established and proposed marine protected areas (HELCOM, 2016, Calrström and Carlén, 2016) identified as important areas based on tagging and acoustic survey data (Teilman, 2008, Sveegaard *et al.*, 2011a and b, SAMBAH, 2015, Calrström and Carlén, 2016). For the Baltic harbour porpoise sub-population, it is possible to specify further by comparing the data from SAMBAH (2015) to information in Table 4 down to identify areas where animals are present during the most sensitive periods (calving and nursing). For harbour seals and grey seals the identified areas are based on data on identified haul-outs (HELCOM SEAL EG, 2015, for the HELCOM core indicator on “Distribution of Baltic seals” (unpublished, http://www.helcom.fi/baltic-sea-trends/indicators/distribution-of-baltic-seals/contributors-and-references/)). Though the data used in the map shows only haul-outs on land, this may still be used as a preliminary proxy for sensitive areas, as the periods identified as sensitive (pupping, mating and moulting, Table 4) are closely related to haul-outs. For ringed seals, due to lack of detailed knowledge, at this stage the identified areas are based on data from marine protected areas, where this species is included as part of the designation basis (HELCOM, 2016).

For cod and sprat the Arkona basin and Bornholm deep are important during spawning in spring and summer (Warner *et al.*, 2012), and for sprat the Northern deep, Gotland deep, and Gdansk deep are also important during the spawning period (Table 4, Warner *et al.* 2012, Ojaveer and Kalejs, 2010). The extent of the area is defined by parameters such as salinity, temperature and oxygenation, which can show great variation from year to year, and also change within the spawning period. The areas are therefore marked on the map, but markings do not necessarily represent the actual shape of the area. For herring the area around Rügen is identified as of particular importance for spawning in spring (Table 4, Warner *et al.*, 2012).

This is a preliminary working map, where areas may be added or changed, as more information becomes available.

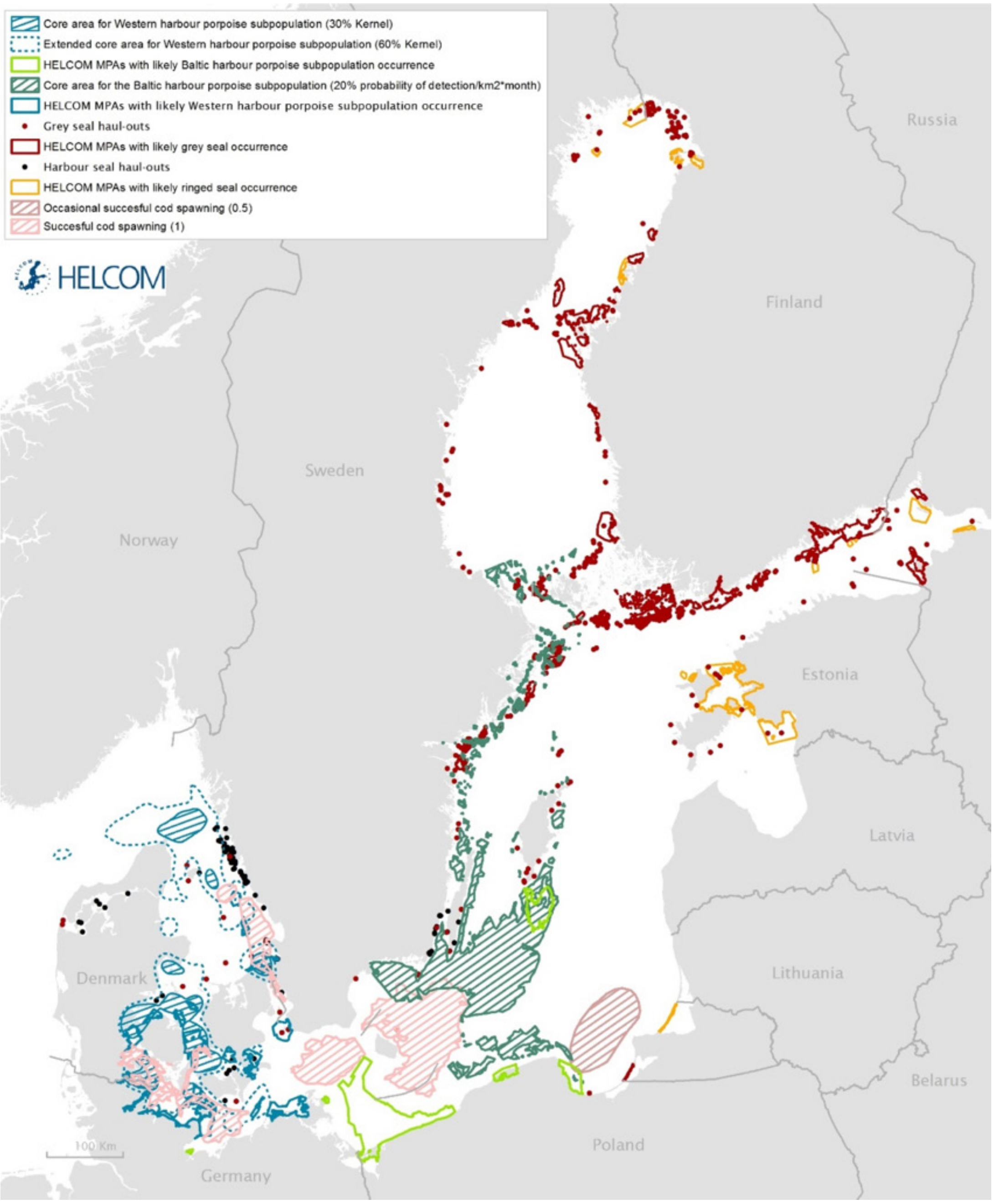


Figure 28 – Noise sensitive areas derived from biological data on species sensitive to underwater noise so far identified. For harbour porpoises important areas are based on established marine protected areas (MPA) where this species occur as well as recent findings. For the Western Baltic subpopulation, important areas are based on tagging and acoustic survey data (Teilmann et al., 2008; Sveegaard et al., 2016) and MPA where this species occur (HELCOM MPA database). For the Baltic subpopulation important areas are based on acoustic survey data (ASCOBANS, 2016) and MPA where this species occur (HELCOM MPA database). For harbour seals and grey seals, areas are based on data of identified haul-outs (from the HELCOM core indicator report on "Distribution of Baltic seals"), and for grey seals also on MPA where the species occurs (HELCOM MPA database). Harbour seals and grey seal haul-outs are used by seals only for a few weeks and this does not reflect the full range of marine areas used by harbour seals nor grey seals. This gap in data should be addressed in future reports. Important areas for ringed seals are based on MPA where the species occurs (HELCOM MPA database). For the fish species important areas are based on known spawning grounds. Cod spawning grounds (HELCOM HOLAS II Dataset: Cod spawning areas, 2017). For migrating species it may be necessary to take measures to ensure migration without physical or acoustic barriers. More sites may be added as data becomes available, i.a. important foraging areas and other fish species. Continuous sound (such as from ships) and its effects on marine life needs further investigation. Contracting Parties are encouraged to support further research.

Table 2: List of priority noise sensitive marine mammal species based on the five criteria: 1) hearing sensitivity, 2) impact of noise, 3) threat status, critically endangered (CR), vulnerable (VU), near threatened (NT), and least concern (LC), 4) commercial value, and 5) data availability. Each criteria is ranked based on relevance according to available knowledge and data as: high (red), medium (yellow), low (green), negligible (grey) or unknown (white).

	Hearing sensitivity	References	Impact of impulsive noise	Impact of continuous noise	References	Threat status	Commercial value	Data availability	References
Harbour porpoise (*Phocoena phocoena*)	Range of best hearing sensitivity covering a wide frequency range (4-150 kHz)	Andersen, 1970, Kastelein *et al.*, 2002 and 2010	TTS and behavioural changes have been investigated in relation to two types of impulsive noise (pile-drining and air-gun), as well as in relation to acoustic harrasment devices	TTS and behavioural changes have been investigated in relation to longer duration octave band noise. Low levels of high frequency noise from shipping can also induce strong behavioural responses in harbour porpoises	Lucke *et al.*, (2009), Kastelein *et al.*, 2012b, Popov *et al.*, 2011, Tougaard *et al.*, 2009, Brandt *et al.*, 2011, Dähne *et al.*, 2013, Teilmann and Carstensen, 2012, Olesuik *et al.*, 2002, Brandt *et al.*, 2013, Coram *et al.*, 2014, Dyndo *et al.*, 2015	CR/VU	NEGLIGIBLE	Data is available for the Western Baltic harbour porpoise subpopulation, and the Baltic Sea subpopulation, in summer	Hammond *et al.* 2002, 2013; Teilmann, 2008; Sveegaard *et al.* 2011a and b Carlström and Carlén, 2015
Harbour seal (*Phoca vitulina vitulina*)	Range of best hearing sensitivity covering a wide frequency range (2-30 kHz)	Kastak and Schusterman, 1998, Møhl, 1968, Reichmuth *et al.*, 2013	PTS and TTS have been investigated in relation to impulsive noise. Startle and avoidance responses have been documented in harbour seals to sounds with a high rise time, and a high degree of "roughness"	PTS and TTS have been investigated in relation to noise of longer duration. Studies have described communication sounds in harbour seals, and critical ratios have been described for this species, making it possible to conservatively estimate masking occurrence.	Kastak *et al.*, 2008, Kastak *et al.*, 2005, Kastelein *et al.*, 2012a, Harris *et al.*, 2001, Blackwell *et al.*, 2004, Edrén *et al.*, 2010, Götz and Jannick, 2011, Southall *et al.*, 2000, Van Parijs et al, 2000, 2003a, Erbe *et al.*, 2016, Holt and Schusterman, 2007, Cunningham *et al.*, 2014	VU/LC	NEGLIGIBLE	Distribution data is available for the Southern Baltic harbour seal subpopulation, and haul-out data is available for both the Southern Baltic and Kalmarsund subpopulations	Dietz *et al.*, 2012; BALSAM, 2015
Baltic ringed seal (*Phoca hispida botnica*)	Range of best hearing sensitivity covering a wide frequency range (1-40 kHz)	Terhune and Ronald, 1975, Sills *et al.*, 2015	There are no studies for ringed seals alone, but knowledge from harbour seals and other pinnipeds can serve as a guide at this stage	Studies have described communication sounds in ringed seals, and critical ratios have been described for this species, making it possible to conservatively estimate masking occurrence	Sills *et al.*, 2015, Stirling, 1973	VU	NEGLIGIBLE	Distribution data is available for part of the ringed seal population in the Baltic	BALSAM, 2015
Grey seal (*Halichoerus grypus*)	Low frequency hearing sensitivity less than described for other seal species in the Baltic. Frequencies of best hearing (20-30 kHz), Underwater communication signals contain significant energy at lower frequencies; therefor further data on underwater hearing is needed, to ensure accurate description of the full hearing range..	Ridgway and Joyce, 1975	Startle and avoidance responses have been documented in grey seals to sounds with a high rise time, and a high degree of "roughness", but knowledge from harbour seals and other pinnipeds on other effects can also serve as a guide	Studies have described communication sounds in grey seals, and their underwater hearing has been investigated in a single study, making it possible to roughly estimate masking occurrence	Asselin *et al.*, 1993, Van Parijs et al, 2003b, Ridgway and Joyce, 1975	LC	NEGLIGIBLE	Distribution data is available for part of the grey seal population in the Baltic, haul-out data is available for the entire Baltic	Dietz *et al.*, 2012, BALSAM, 2015

Table 3: List of priority noise sensitive fish species based on the five criteria: 1) hearing sensitivity, 2) impact of noise, 3) threat status, critically endangered (CR), vulnerable (VU), near threatened (NT), and least concern (LC), 4) commercial value, and 5) data availability. Each criteria is ranked based on relevance according to available knowledge as: high (red), medium (yellow), low (green), negligible (grey) or unknown (white).

	Hearing sensitivity	References	Impact of impulsive noise	Impact of continuous noise	References	Threat status	Commercial value	Data availability	References
Cod (*Gadus morhua*)	Range of best hearing sensitivity covering low frequencies (below 300 Hz)	Chapman and Hawkins, 1973; Offut, 1974	PTS, TTS and injury in non-auditory tissue, has not been investigated in cod, but catch rates of cod went down after the use of an air-gun also, suggesting some behavioural reaction	The overlap between cod communication sounds anthropogenic noise could result in masking, but so far this has not been investigated	Rowe and Hutchings, 2004; Engås *et al.*, 1996; Wahlberg, 1999	VU	HIGH	Two major spawning areas for the Easter Baltic cod stock can be identified. Several spawning areas can also be identified for the Western Baltic and Kattegat stocks.	Warnar *et al.*, 2012; HELCOM, 2013, *Gadus morhua*
Herring (*Clupea harengus*)	Range of best hearing sensitivity covering low frequencies (below 1 kHz)	Enger, 1967	Herring in an area appeared to move to greater depth after the use of an air-gun	An overlap in frequency could result in masking of environmental cues by anthropogenic noise, but so far this has not been investigated	Slotte *et al.*, 2004	LC	HIGH	Spawning areas in the western part of the Baltic can be identified for herring	Warnar *et al.*, 2012
Sprat (*Sprattus sprattus*)	Based on close kinship and anatomical studies of the hearing apparatus hearing sensitivity is approximated by using the hearing sensitivity of herring	Allen *et al.*, 1976; Enger, 1967	Schools of sprat in an area appeared to disperse and move to greater depth after exposure to play-back mimicking an impulsive noise source (e.g. pile-driving or airgun)	An overlap in frequency could result in masking of environmental cues by anthropogenic noise, but so far this has not been investigated	Hawkins *et al.*, 2014	UNKNOWN	HIGH	Two major sprat spawning areas can be identified	Warnar *et al.*, 2012

Table 4: Periods of biological significance for each of the identified priority noise sensitive species. Periods not applicable (N.A.) to a species are marked in blue.

Species	Calving/Pupping period	Mating/spawning period	Nursing Period	Moulting period
Harbour porpoise (*Phocoena phocoena*)	June -September	June -September	July through the end of the year	N.A.
Harbour seal (*Phoca vitulina vitulina*)	June	July-August	June-July	August
Ringed seal (*Phoca hispida botnica*)	February-March	Thought to occur during the nursing period	February-April	April-May
Grey seal (*Halichoerus grypus*)	February-March	March-April	February-April	May - June
Cod (*Gadus morhua*)	N.A.	March-December	N.A.	N.A.
Herring (*Clupea harengus*)	N.A.	Spring	N.A.	N.A.
Sprat (*Sprattus sprattus*)	N.A.	March-August	N.A.	N.A.

5. Discussion and conclusions

The BalticBOOST project theme dedicated to underwater noise aims, among other issues, to identify spatial and temporal distribution of sound sensitive species and habitats in the Baltic Sea and to propose principles for defining sound levels that are compatible with GES for populations. Two HELCOM indicators are being developed to address the impact of anthropogenic noise in the Baltic Sea: an indicator for impulsive noise, and an indicator for continuous noise, aiming at setting levels for impulsive and continuous noise consistent with no adverse effects on marine animals. The continuous noise indicator is primarily to address masking of important signals, whereas the impulsive noise indicator is to mainly address aversive behaviour and immediate hearing loss or physical damages to non-acoustic tissues in marine animals.

The first step towards defining GES is to identify species that could potentially be impacted by noise. Based on the limited data available for the five criteria: hearing sensitivity, known or suspected impact of noise, threat status, commercial value, and distribution data availability, seven species were identified as priority noise sensitive species, with a high likelihood of being impacted by noise assessed by one or both of the HELCOM noise indicators. The proposed list of priority noise sensitivity species is summarized in Table 2 and Table 3. As knowledge and understanding of hearing sensitivity, noise impact and distribution of more species becomes available, more species could be added to the list. If possible identifying a kind of “canary” or “umbrella” species especially sensitive to noise could also occur at a later stage.

The likely effects of impulsive noise on harbour porpoise, harbour seal, ringed seal and grey seal are behavioural changes, cessation of normal ongoing behaviour (e.g. feeding or nursing), and temporary or permanent hearing loss. Impulsive noise may also disrupt migration or spawning behaviour in cod, sprat and herring. Close to the noise source fish with a gas-filled cavity may experience physical injury to non-auditory tissues, but this is only expected to occur at short ranges within 100 meters of most noise source (Continental, 2004, dos Santos *et al.*, 2010). Finally prolonged exposure to impulsive noise may result in increased levels of stress hormones, perhaps even at lover noise levels, with potential negative long-term effects for all species.

Continuous noise can likely affect harbour seals, ringed seals, grey seals, cod, sprat and herring due to masking of important communication signals especially during mating/spawning seasons, and for seals, cod, sprat, herring and European eel also through masking of important acoustic migratory cues, such as the low frequency noise naturally occurring in the underwater environment (Wilcock *et al.*, 2014), and conspecific communication. For harbour porpoises there may be some effects on sound production, as well as on behaviour, and masking of migratory cues may also occur, but the significance of the latter is still unknown. For all species prolonged exposure to continuous noise may also result in negative long-term effects due to increased levels of stress hormones.

Based on available distribution data, and information on biologically relevant areas for the different species, a preliminary map of biologically sensitive areas has been developed for the harbour porpoises, harbour seals, grey seals, ringed seals, cod, sprat and herring (Figure 28). More areas may be added at a later stage for the identified species as well as for new species, as data becomes available.

5.1. Next steps to identify sound sensitive areas and special and temporal calendars

With the high level of maritime activities in the Baltic Sea, it becomes increasingly important to develop ways of minimizing negative effects from underwater noise on marine life forms. The development of spatial and temporal calendars, for the different priority species identified above, is one way of reducing impact, and a tool developed for the Swedish navy and coast guard when planning sonar use and detonations could be used as inspiration for further development of such a calendar (S. Koschinski pers. comm.) A spatial and temporal calendar identifies areas that are of biological importance for a species at certain periods during the year such as spawning areas for cod during their spawning period, or areas where harbour porpoises are found with their calves during seasons of calving and nursing. Spatial mapping of the two noise indicators as sound maps of continuous noise and a spatial and temporal registry of impulsive noise events, is underway as another aim of the BalticBOOST theme four. Combining information from the spatial and temporal calendar of species with the spatial and temporal mapping of the two noise indicator will provide information on the likelihood of noise effects for the different species, as these are a result of the animal's proximity to the noise source.

Currently there is sufficient data to identify some areas of seasonal biological importance for some parts of the population for some species in the Baltic. Information related to possible effects of underwater noise is also often based on data from a few captive individuals, introducing a large degree of uncertainty to the evaluation of noise effects, as results from single individuals are extrapolated to cover all animals of the species and other life stages. As more information becomes available both in terms of hearing sensitivity, potential noise impact, species distribution and biologically important areas, new species may need to be added to the list of priority species and to a spatial and temporal calendar.

Currently investigations of underwater hearing in grey seal and also in cormorant are under way at the University of Southern Denmark's Marine Biological Research Centre in Kerteminde, Denmark (Magnus Wahlberg, pers. communication).

Efforts to provide new distribution data as well as data on spawning and nursing grounds are under way for main commercial species such as cod, herring and sprat (Lena Bergström, pers. communication), and new distribution maps are also being prepared as part of the HELCOM TAPAS project theme 2.

Information is also mostly based on a single sound type (e.g. pile-driving) or a narrow frequency band and extrapolating results to other sound sources or frequencies will introduce additional uncertainties. There are on-going efforts to investigate more sound types and frequencies, and as information on effects from the different noise sources becomes available further division of the HELCOM indicators into smaller entities may also be warranted.

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7. Glossary

Audiogram	A graphical depiction of the hearing sensitivity of a species as a function of frequency.
Band-pass filter	Acoustic filter that removes sound below a lower cut-off frequency and above an upper cut off frequency.
Barotrauma	Injuries caused by high pressure.
Cetaceans	Whales, dolphins and porpoises.
Critical ratio	Ratio between a sound signal and the noise level, where a sound is just discernible to an animal.
Decibel	Logarithmic unit used to describe sound magnitude.
Fitness	An individual’s reproductive success and contribution to the gene pool of the next generation.
Hearing sensitivity	Sound magnitude detectable at a given frequency.
Lombard effect	Increase in intensity of communication sounds in a noisy environment.
Pinniped	Seals, sea lions and walrus.
Power spectral density	Energy of an acoustic signal as a function of frequency.
Psychoacoustics	The study of sound perception.
Threshold	Lowest level of sound detectable to an animal, or lowest level of noise causing a specific effect.
Threshold shift	Decrease in sound sensitivity, compared to baseline threshold.
Ultrasound	Sound with frequencies above the human hearing limit (20 kHz).
Weberian ossicles	Three small bones connecting the swim bladder to the inner ear in otophysan fish species (e.g. goldfish).