Impulsive Sound and Offshore Wind

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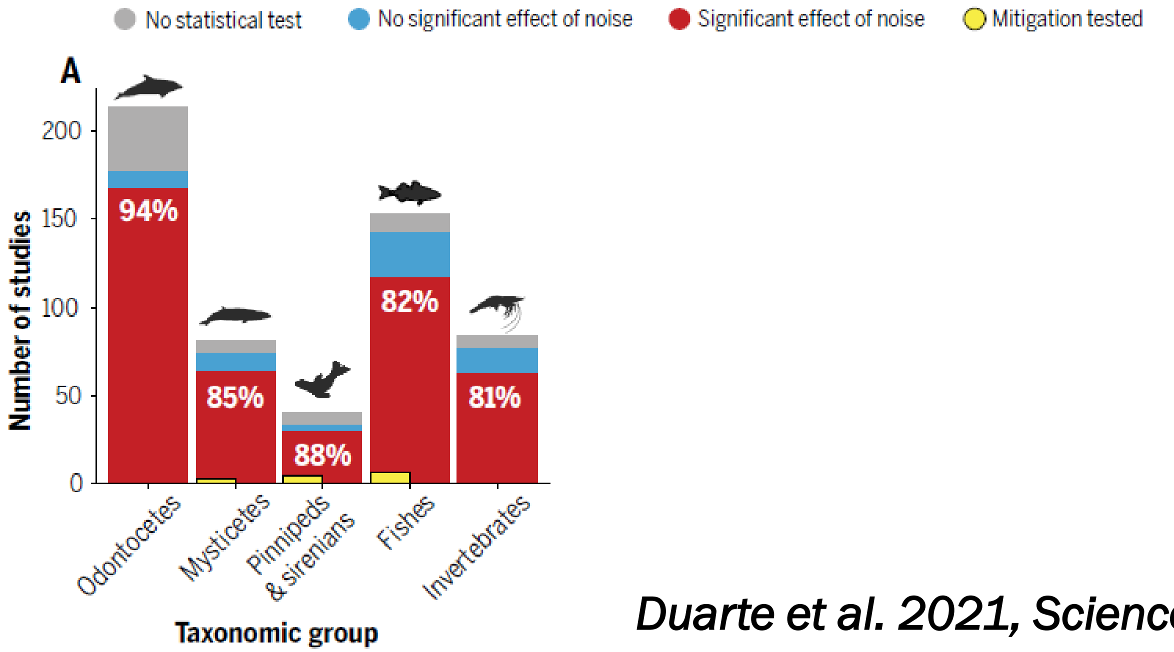
OUTLINE

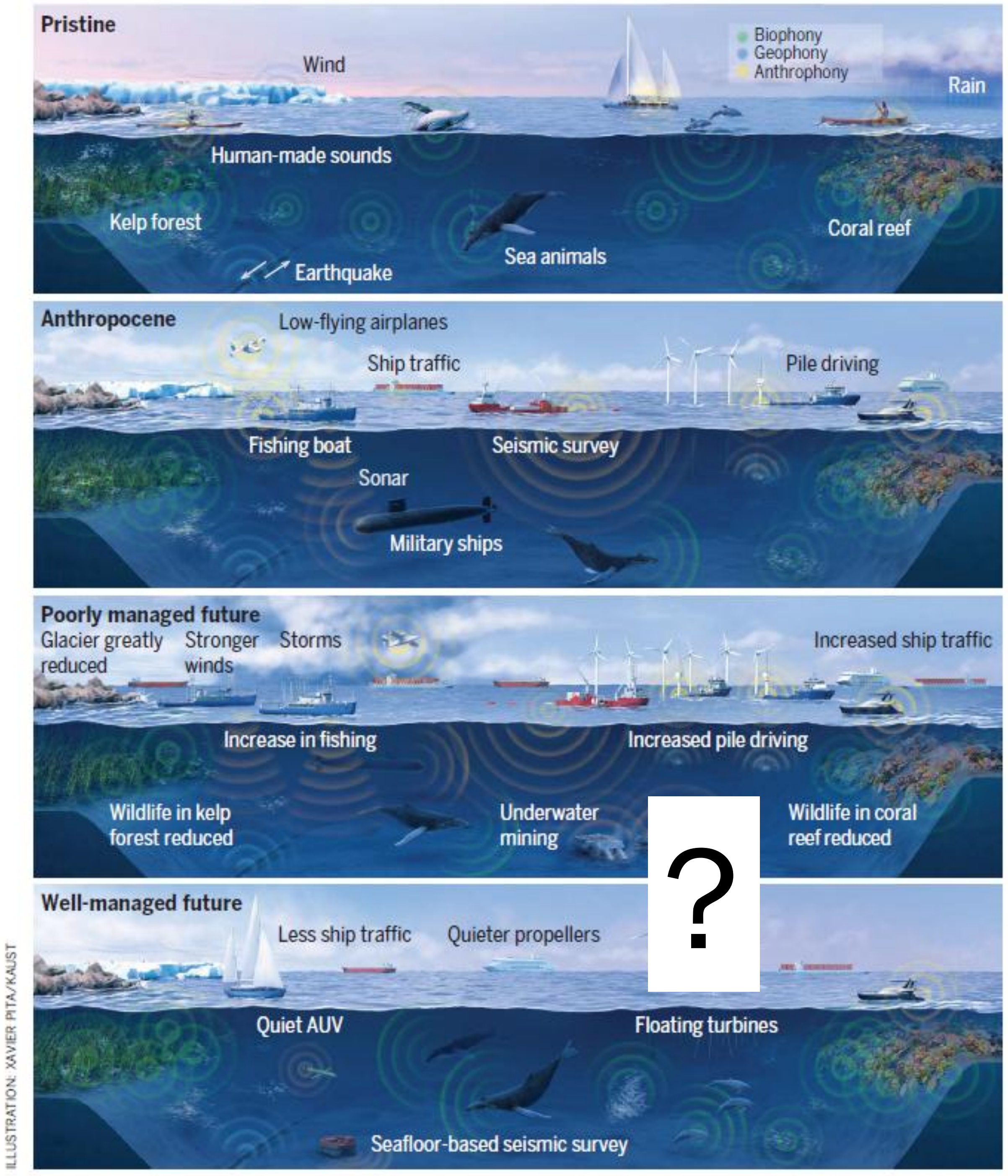
- Underwater noise, what are we worried about?
- Introduction on offshore wind development
- What is impulsive sound and why does it matter?
- Investigating the impact of offshore wind on marine life – experiences in Europe from the North Sea
  - Understanding effects of impulsive noise on hearing
  - Effects and consequences of impulsive sound on behaviour
  - Development of noise guidelines in the EU

UNDERWATER NOISE

- Sound in water is important for animals to communicate, orientate, and find food
- Almost all species can perceive sound underwater



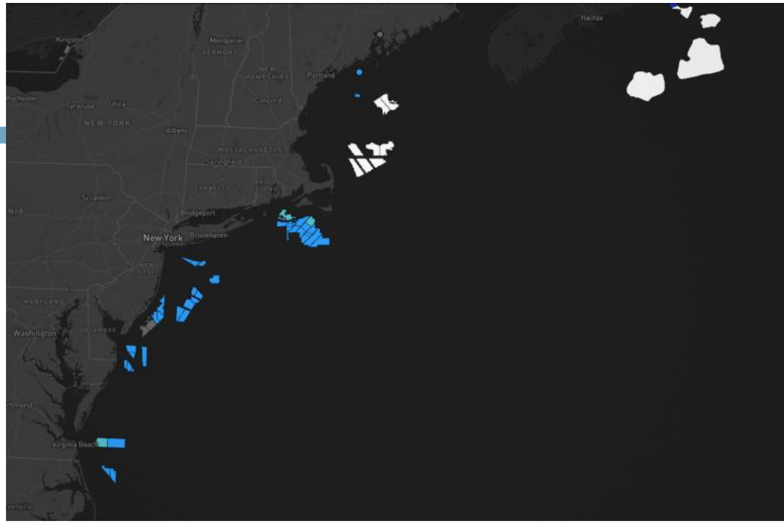
Duarte et al. 2021, Science



WHAT ARE WE WORRIED ABOUT?

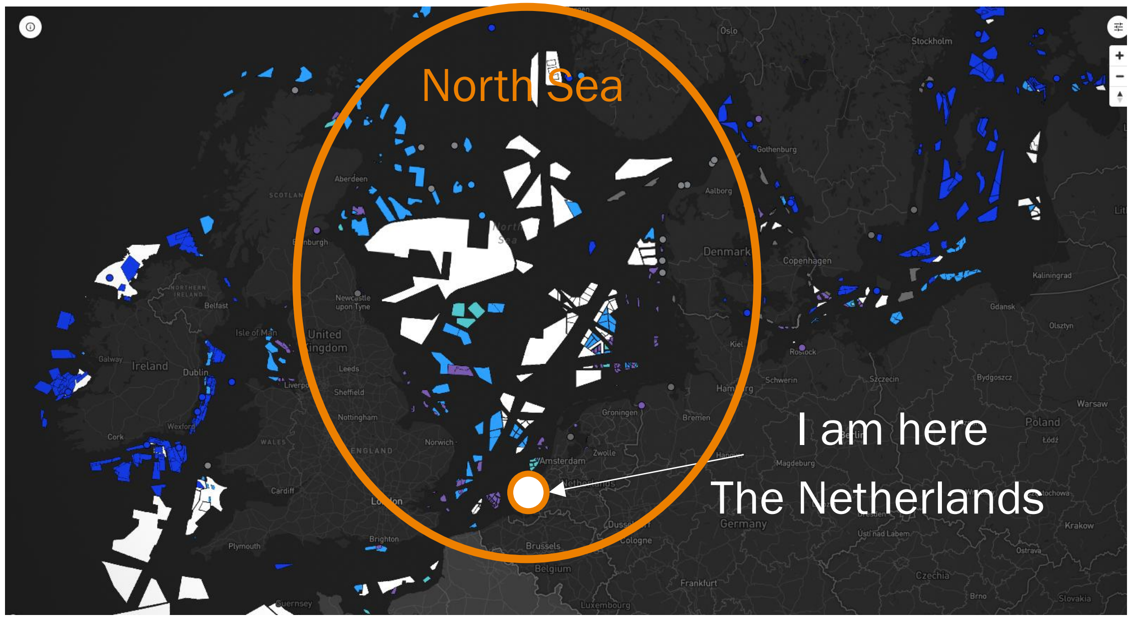
- Underwater sound may cause
  - Hearing damage, or temporarily reduce hearing sensitivity
  - Behavioural disturbance
  - Other effects … masking, stress?
- Effects on vital behaviour (feeding, migration, breeding, parental care, avoidance of habitats, vital rates, …)
- Regulations/guidelines being developed to manage noise pollution

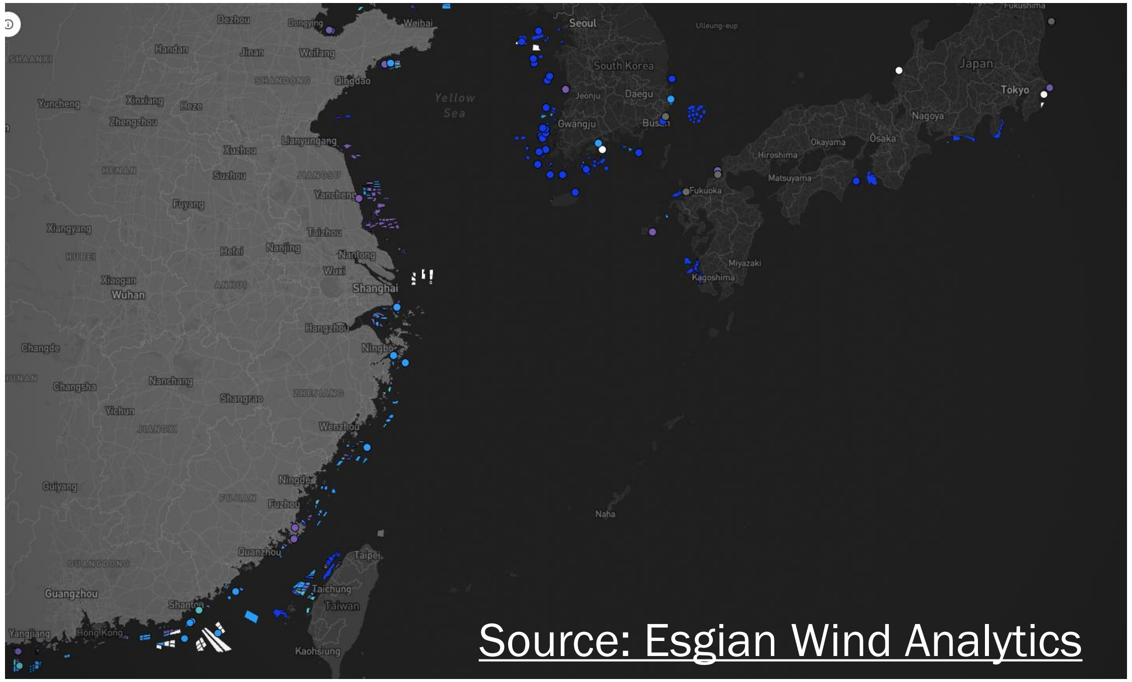
OFFSHORE WIND – GLOBAL DEVELOPMENT



According to Global Offshore Wind Council (GWEC):

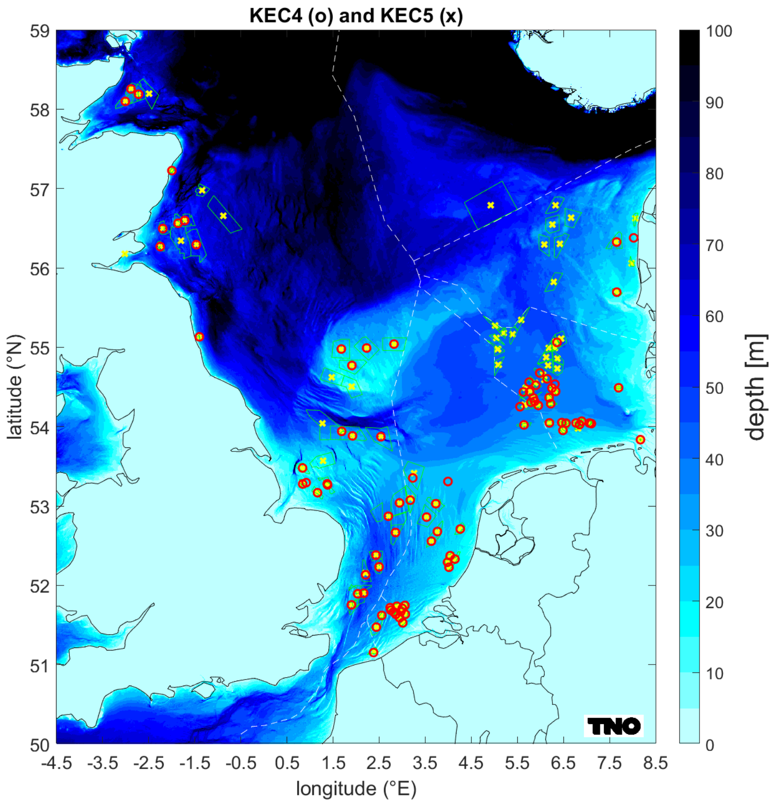
- A total of 75 GW of global offshore wind capacity was in operation by the end of 2023.
- GWEC's rolling ten year outlook to 2033 shows that, with the right frameworks in place, the world can be on course to deploy 410 GW by 2033

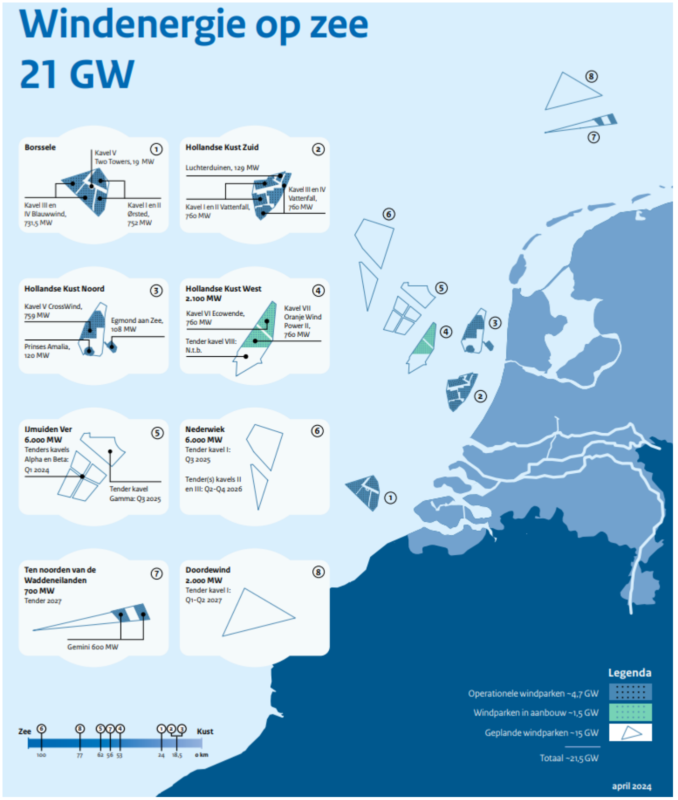




AMBITIONS OFFSHORE WIND IN THE NORTH SEA

- Current ambition ~ 123 GW until 2030 in the North Sea



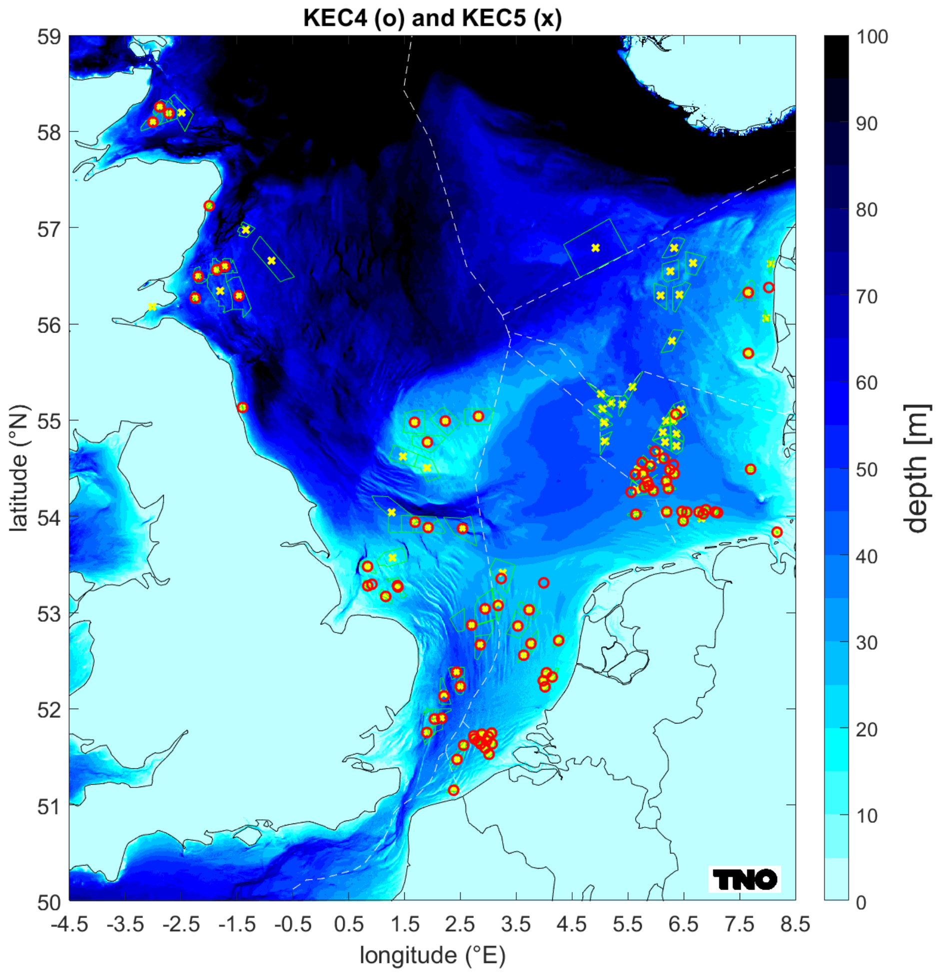


AMBITIONS OFFSHORE WIND IN THE NORTH SEA

- Trends in the North Sea:
  - Increasing number of countries have imposed noise restrictions
  - Increasing pile diameters
  - Larger water depths
  - Challenging to meet noise criteria
  - Increasing attention on operation phase

    how does habitat change, do animals avoid, or perhaps increase use in habitat?
  - Alternative construction techniques

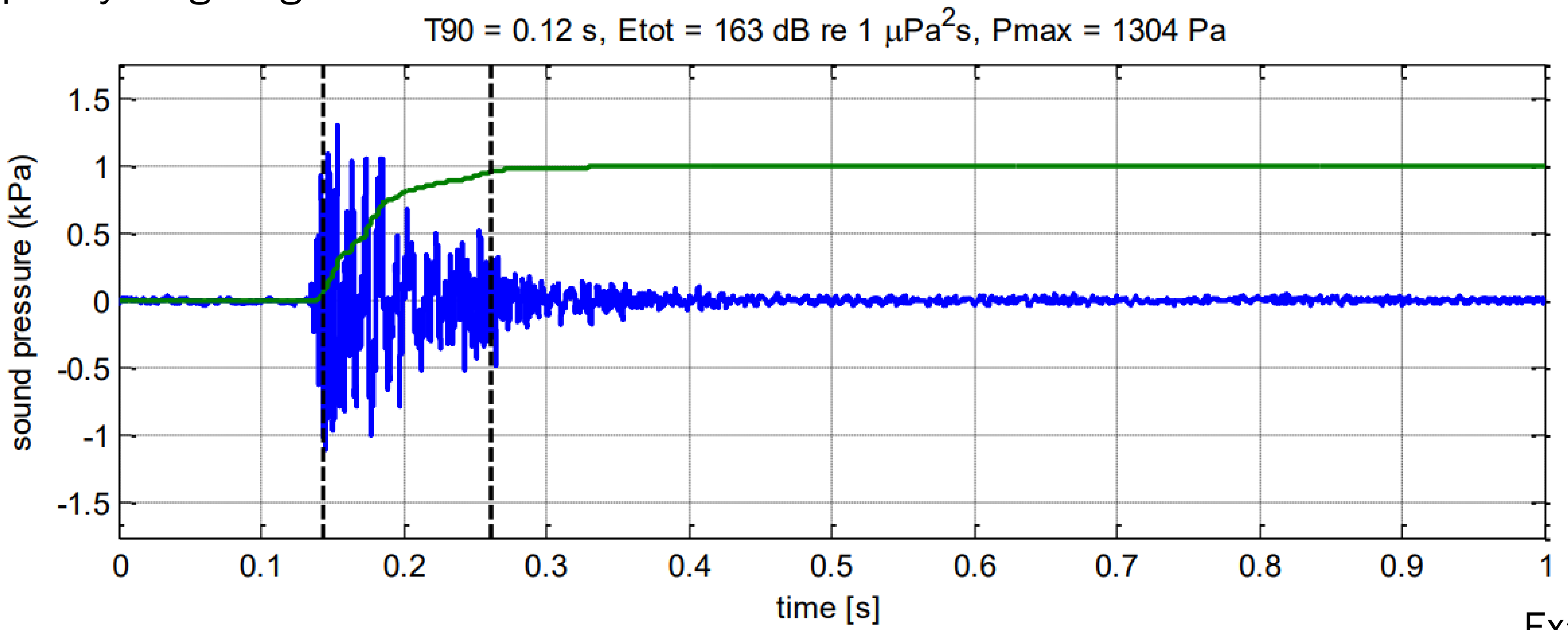
    Vibratory piling/ jetting, floating wind, …



NOISE SOURCES – BIG FIVE

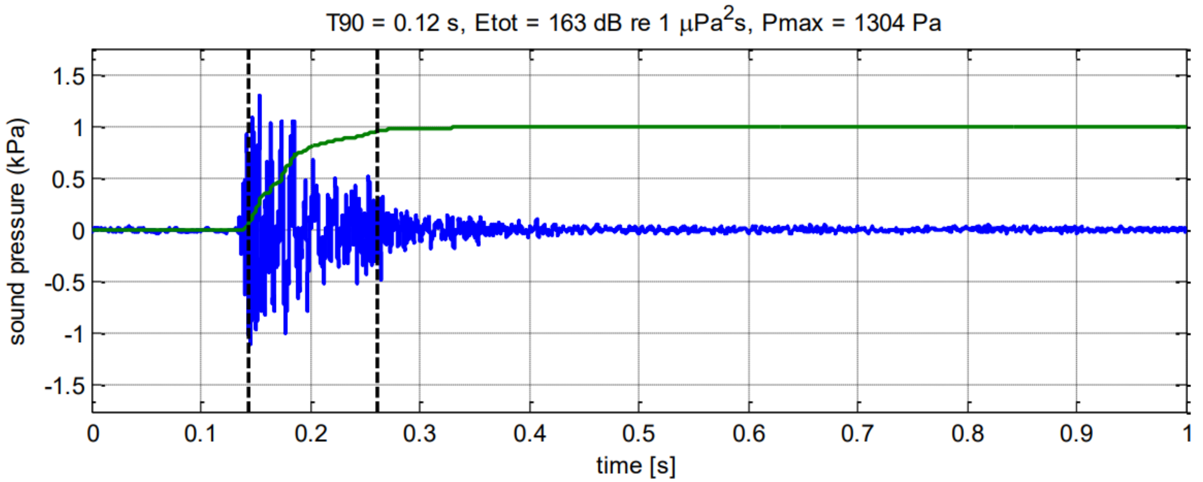
IMPULSIVE SOUND

- Different characteristics to describe sounds
  - Peak sound pressure, sound exposure level, (rms) sound pressure level, kurtosis, rise-time, pulse duration...
  - Frequency weighting?



Example pile driving sound

IMPULSIVE SOUND



- Different definitions in use for 'impulsive' sounds
- Southall et al. (2007; 2019) noise impact criteria for effects of sounds on marine mammal hearing
  - Pulsed sound: brief, broadband, atonal, transients
  - Non-pulse: can be transient signals of short duration but without the essential properties of pulses (e.g., rapid rise-time)
  - Impact thresholds for hearing damage differ ~ 16-18 dB between (im)pulse- and non-pulse sounds
- EU Impulse Noise Register also includes sonar sounds, which are considered non-pulse in US
- For behaviour no commonly accepted effect criteria (SEL, frequency weighting?, SPL, peak SPL, $L_{p,fast}$, ...)
- Lots of discussion how impulsive sound changes into non-impulsive as it propagates in water and what criteria to apply

ENVIRONMENTAL IMPACT UNDERWATER EXPLOSIONS

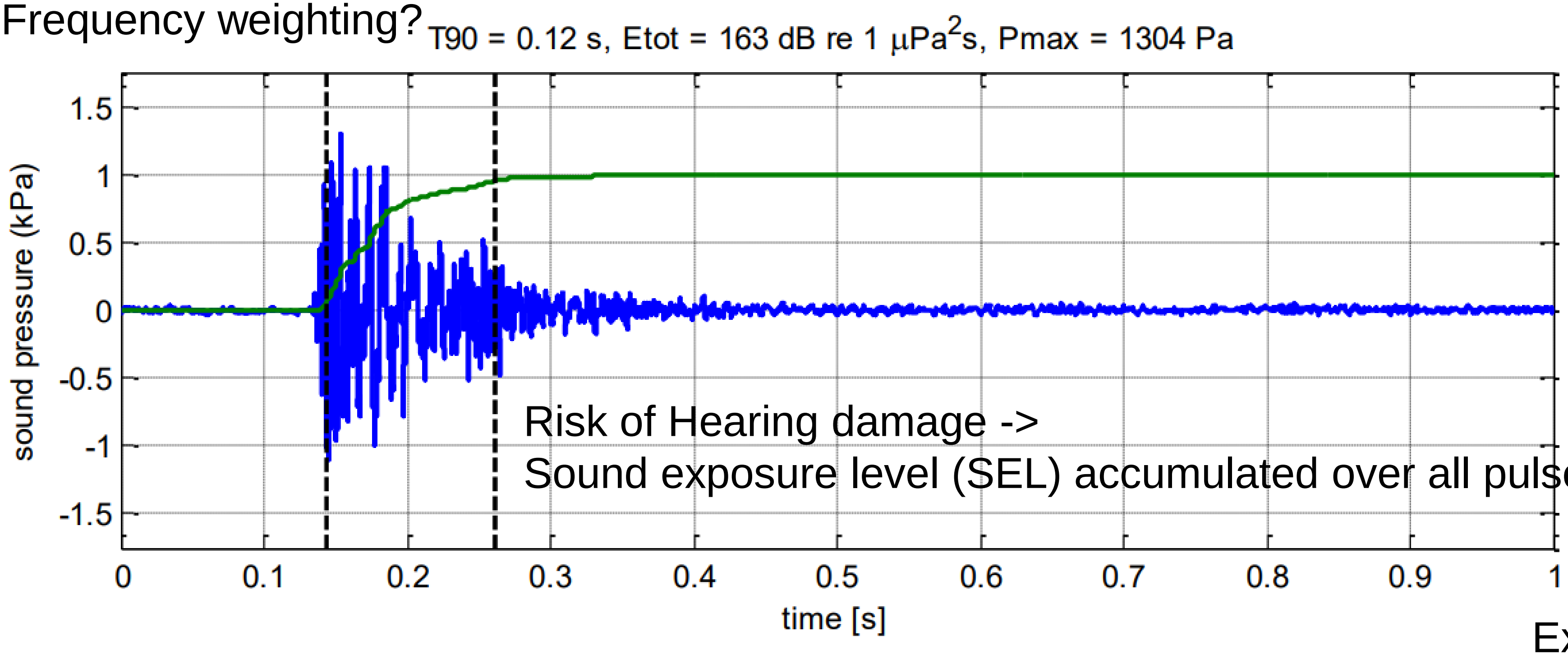
- Special concern for impact of noise on harbour porpoise
- Considered very sensitive to underwater sound
- Most abundant marine mammal species in North Sea (North Sea ~ 1 animal /km^2) with habitat overlapping with planned offshore wind areas

PREDICTING RISK OF HEARING DAMAGE FOR IMPULSIVE AND INTERMITTENT SOUNDS

17 March 2022

IMPULSIVE SOUND

- Different characteristics to describe sounds
  - Peak sound pressure, sound exposure level, (rms) sound pressure level, kurtosis, rise-time, pulse duration…
  - Frequency weighting?

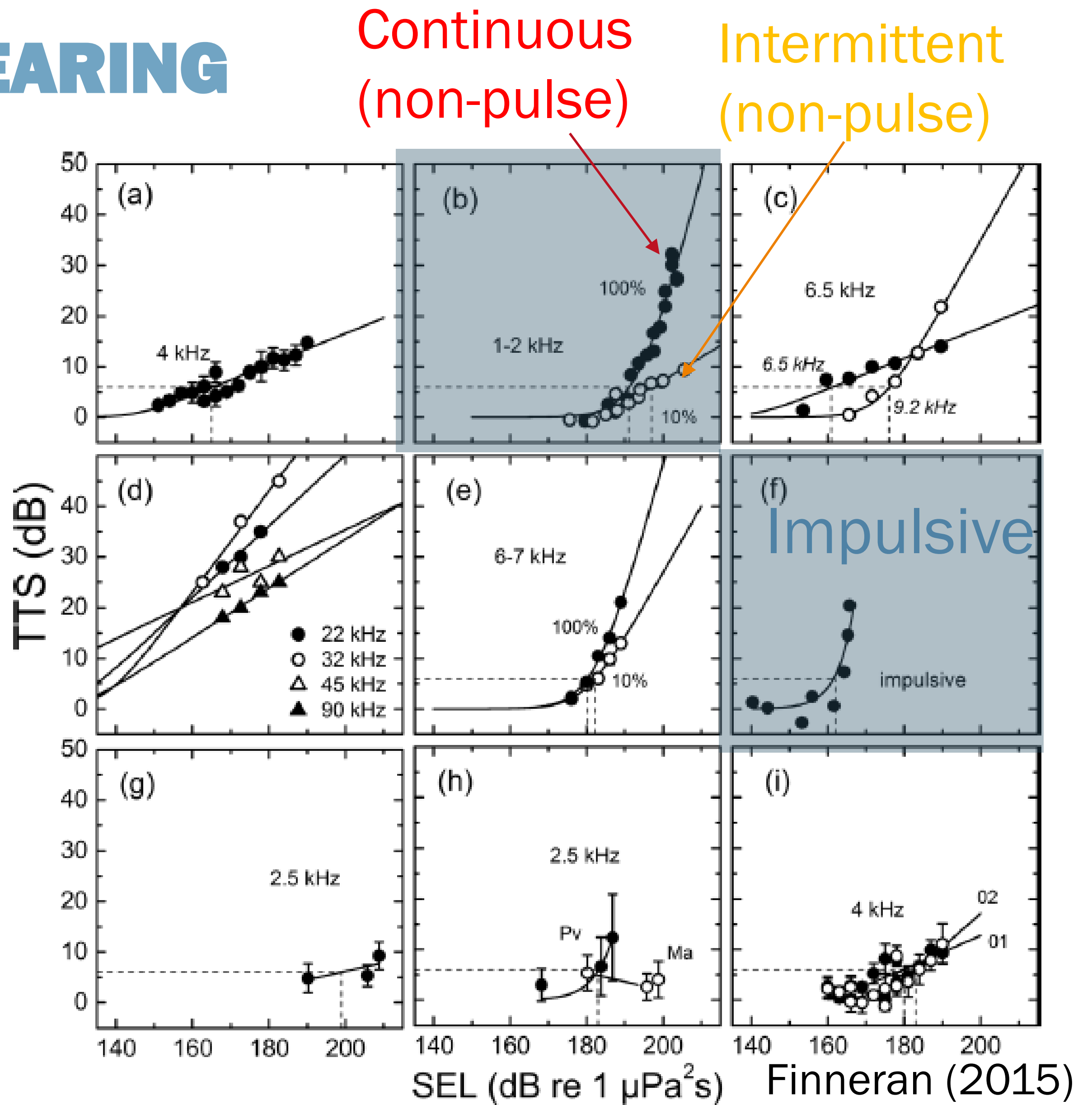


Risk of Hearing damage ->
Sound exposure level (SEL) accumulated over all pulses

Example pile driving sound

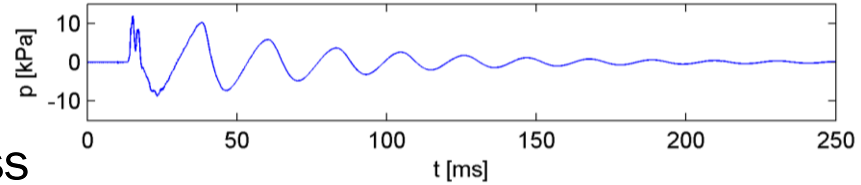
SUSCEPTIBILITY OF PORPOISE HEARING TO INTERMITTENT SOUND

- TTS = temporary threshold shift
  - Recoverable reduction in hearing sensitivity
- Used to set limits for hearing effects in marine mammals
  - Equal sound exposure level = equal risk
  - Account for frequency sensitivity
- Empirical fit to measured TTS growth
  - Fit depends on exposure conditions intermittent lower risk than continuous noise exposures
  - Different threshold for impulse and non-impulse noise

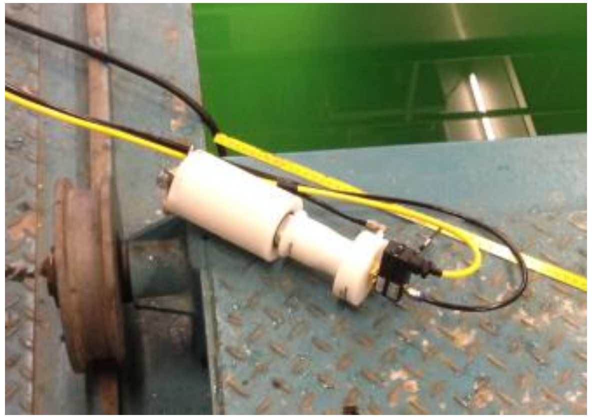


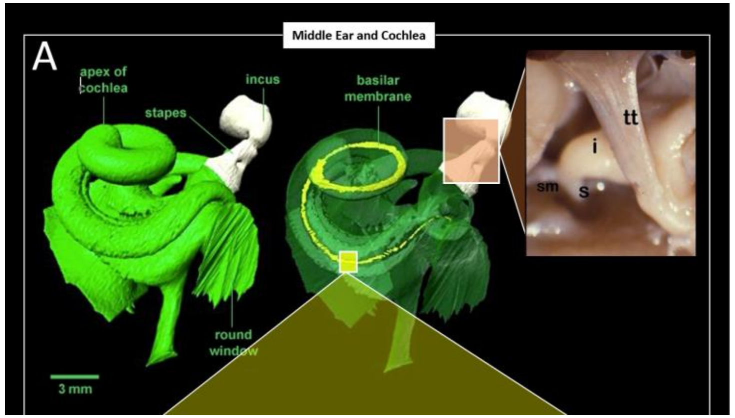
Finneran (2015)

TTS GROWTH IN HARBOUR PORPOISES EXPOSED TO AIRGUNS



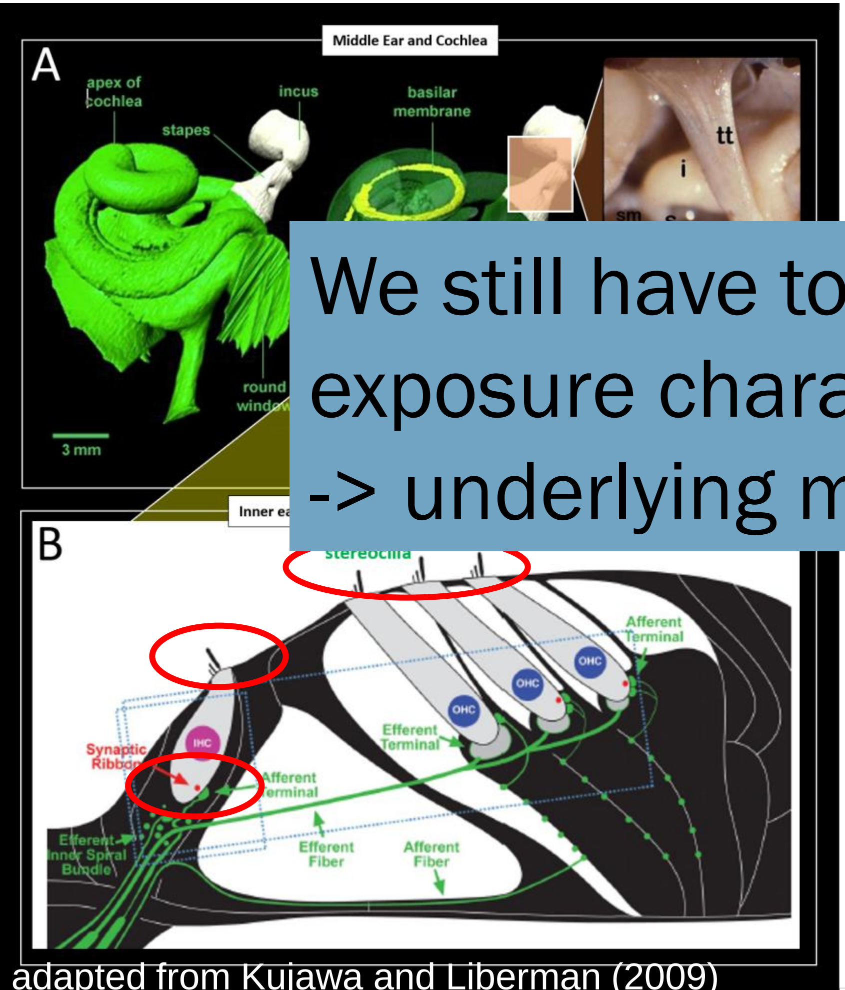
- Can we develop TTS growth models that account for impulsiveness of sound?
- Can we develop models that predicts TTS growth for intermittent sounds?
- Focus on harbour porpoise (collaboration with Ron Kastelein and Darlene Ketten)



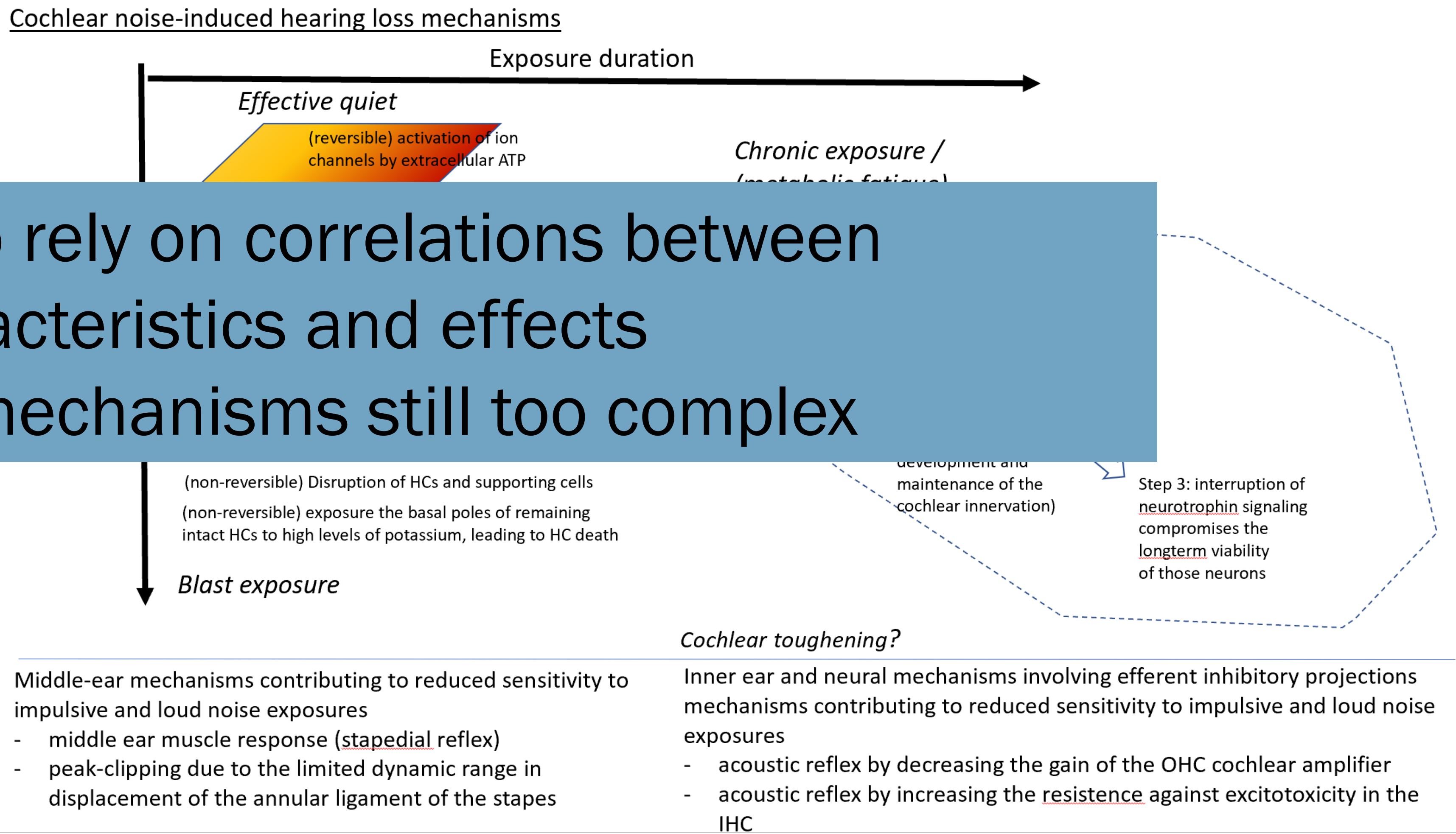


PORPOISE HEARING SYSTEM AND DAMAGE MECHANISMS

Von Benda-Beckmann et al. (2024)



adapted from Kujawa and Liberman (2009)



We still have to rely on correlations between exposure characteristics and effects

-> underlying mechanisms still too complex

IMPULSIVE SOUND : KURTOSIS-ADJUSTED SOUND EXPOSURE LEVEL

- Kurtosis = statistical measure of peakedness of signal

$$\beta = \frac{\frac{1}{t_2 - t_1}\int_{t_0}^{t_1} (p(t) - \bar{p})^4 \, \mathrm{d}t}{\left(\frac{1}{t_2 - t_1}\int_{t_0}^{t_1} (p(t) - \bar{p})^2 \, \mathrm{d}t\right)^2},$$

- Impulse and intermittent sounds have higher kurtosis than longer continuous noise exposures (Müller et al. 2020)

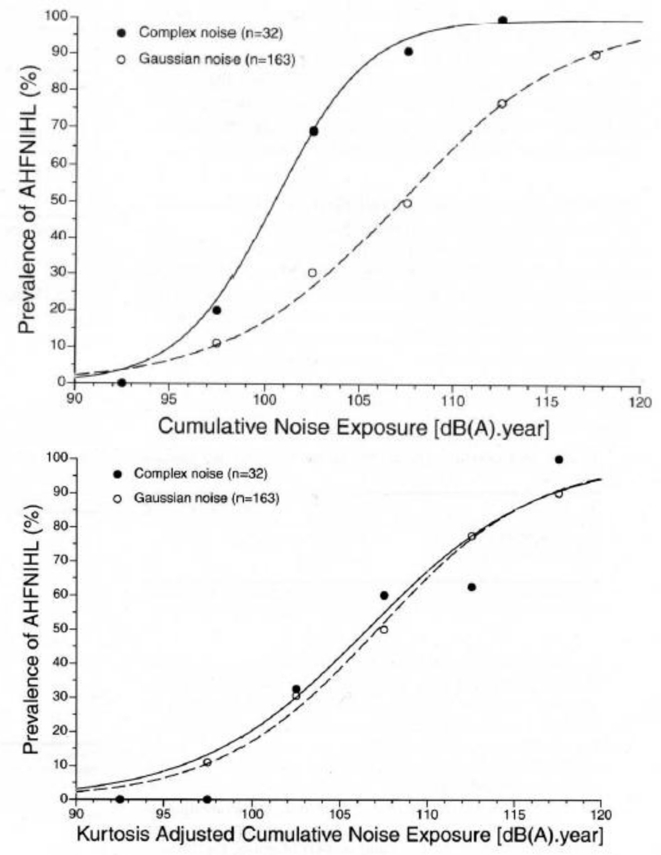
$$L_{E,A,\beta} = L_{p,A,eq} + K(\beta)\cdot\frac{\log_{10}\left(\frac{T}{1\,\mathrm{yr}}\right)}{\log_{10}(2)}\,\mathrm{dB}$$

Zhao et al. (2010)

~4 for chinchilla's/humans

$$L_{E,A,\beta} = L_{E,A} + \lambda \log_{10}\left(\frac{\beta}{\beta_G}\right)\,\mathrm{dB}$$

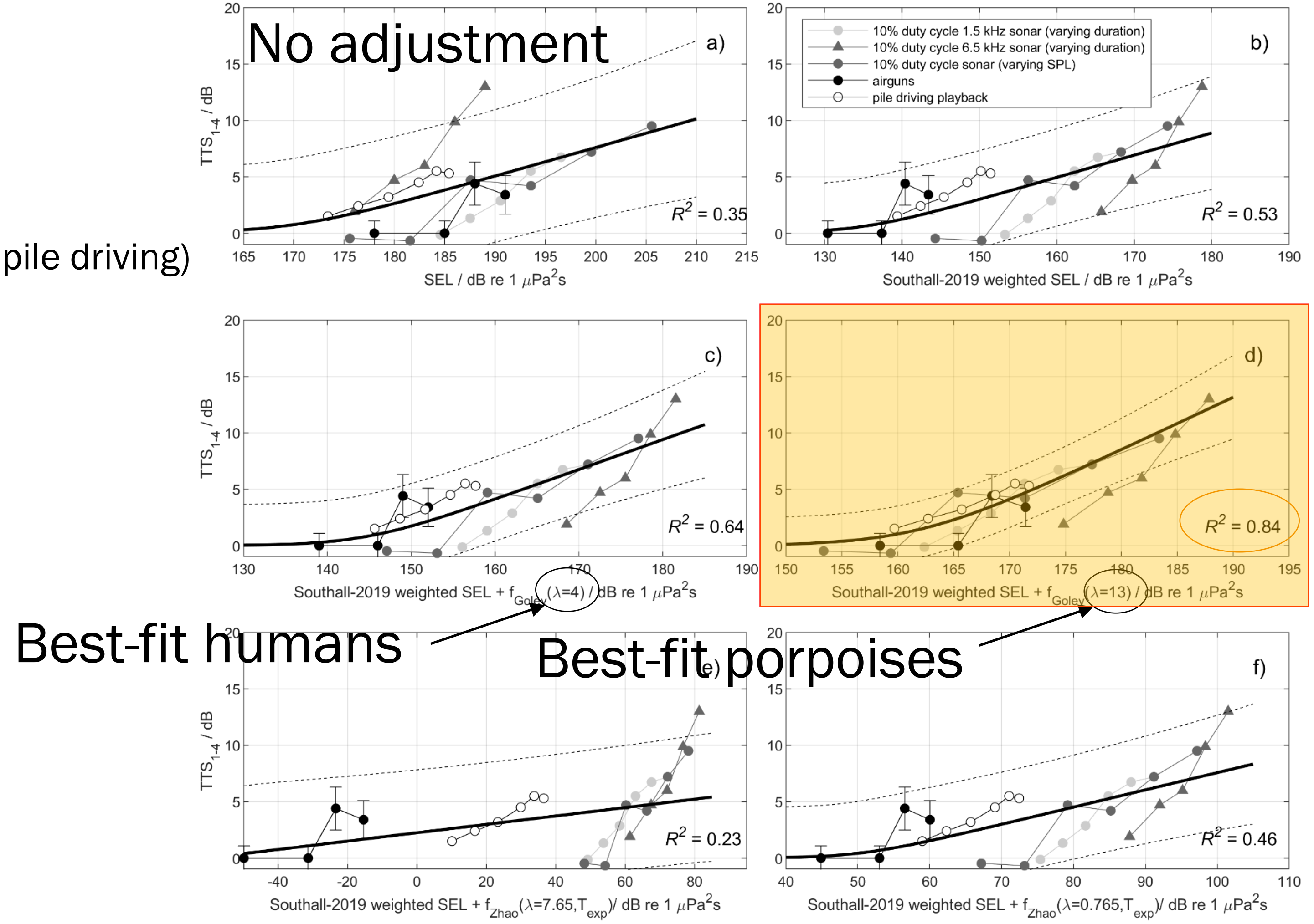
Goley et al. (2011)



Zhao et al. (2010)

KURTOSIS CORRECTION FOR HARBOUR PORPOISES

- Kurtosis-corrected SEL better explains TTS growth for wide range of intermittent exposures with different kurtosis/impulsiveness (sonar, airguns, pile driving)
- Goley et al. (2011) model provided better fit than Zhao et al. (2010) to porpoise TTS data
- Requires fitting parameters different from human fit
- Some differences to human exposure studies
  - Here low level TTS growth vs PTS
  - Short duration exposure vs long duration
  - Porpoise high-frequency echolocating species
  - Intermittent vs continuous
- <u>Still limited dataset (few animals and replications)!</u>



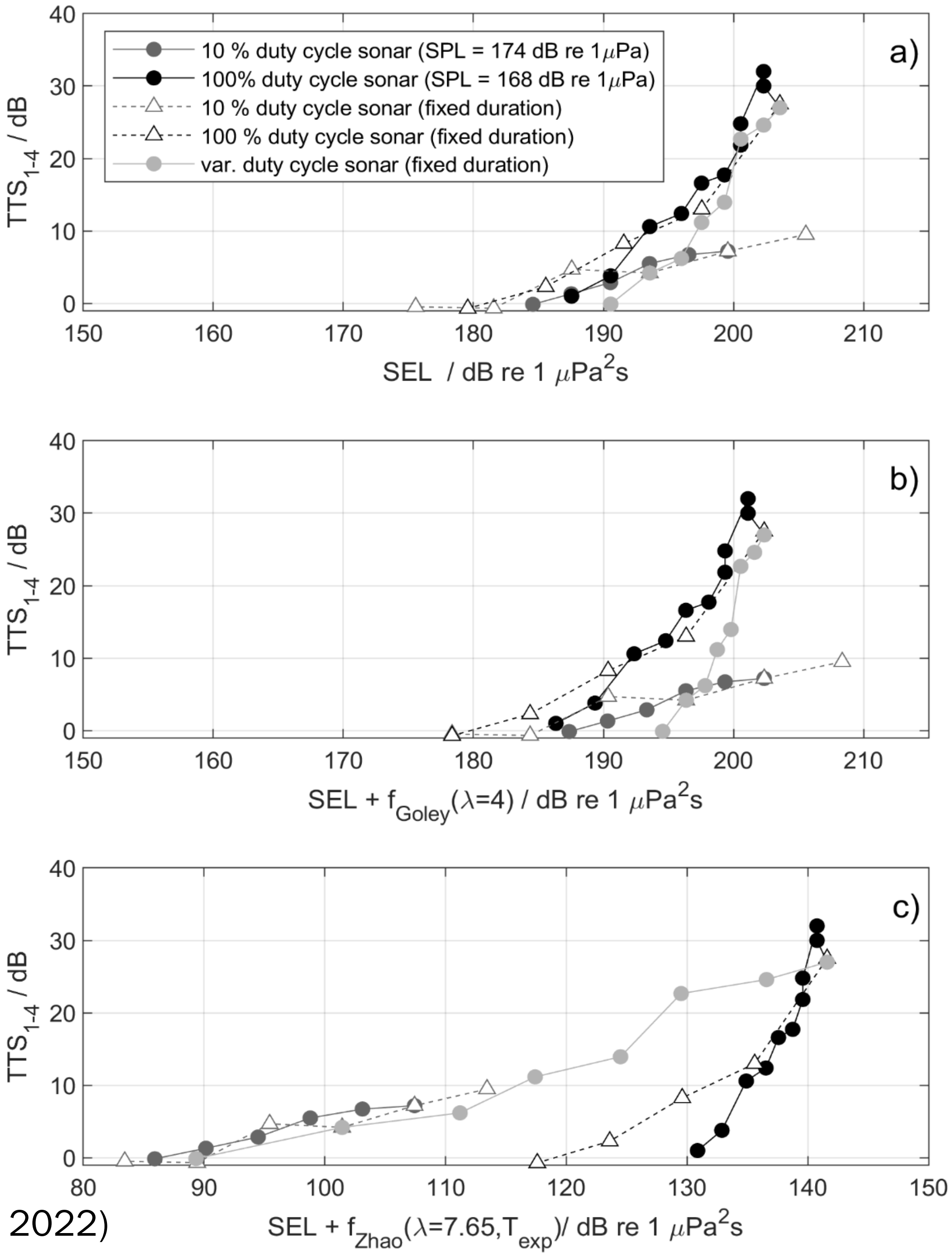
von Benda-Beckmann et al. (JASA, 2022)

KURTOSIS CORRECTION FOR HARBOUR PORPOISES

- Intermittent sonar: β = 15 (10% duty cycle)
- Continuous sonar: β = 1.5 (100% duty cycle)

- Important caveat:
  Kurtosis does not explain growth of intermittent vs continuous noise exposure!

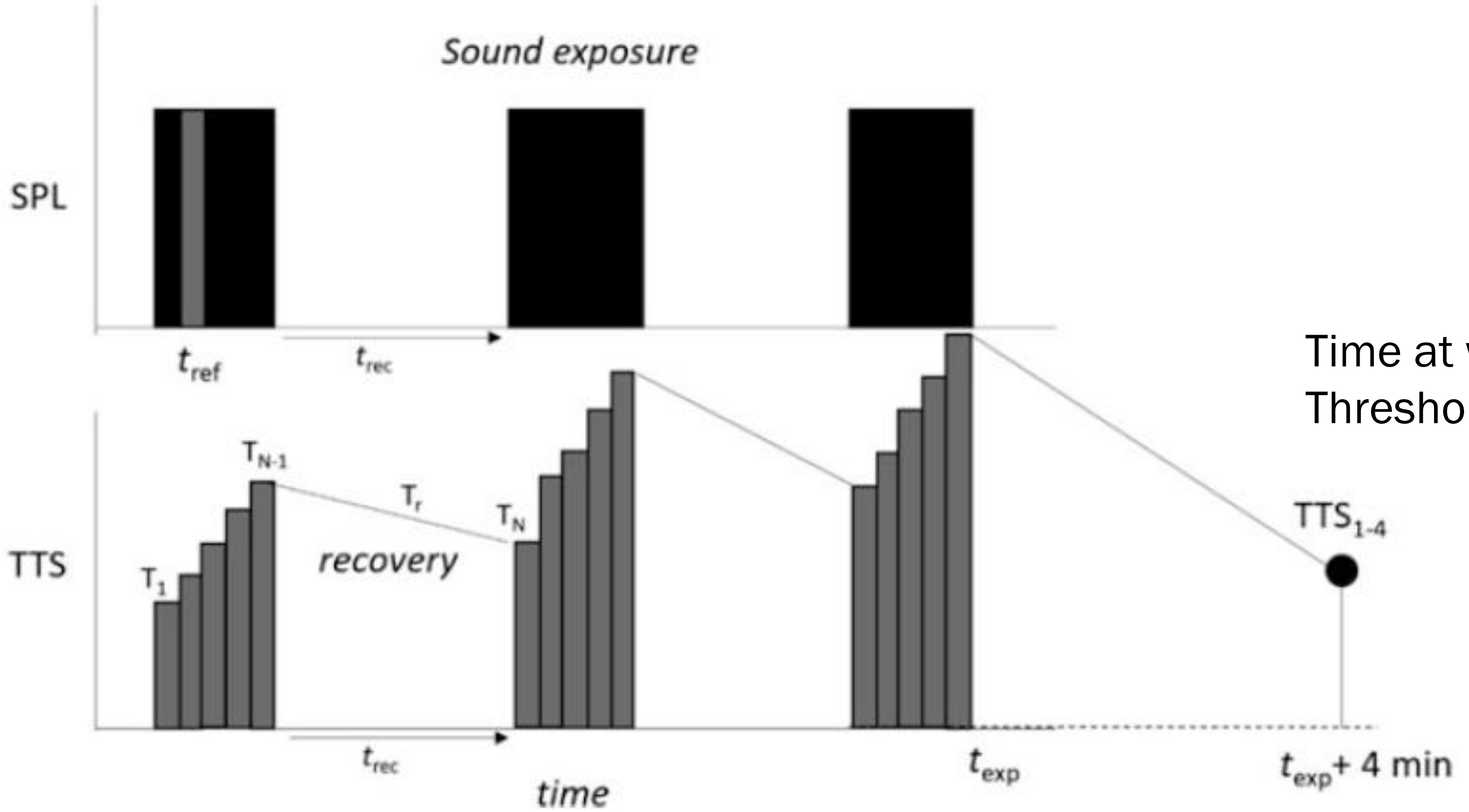
- Likely cause is hearing recovery during silence periods



von Benda-Beckmann et al. (JASA, 2022)

INTERMITTENT EXPOSURES AND RECOVERY

- Reason for slower TTS growth for intermittent signals likely due to recovery in during silent periods



Time at which Temporary Threshold Shift (TTS) is measured

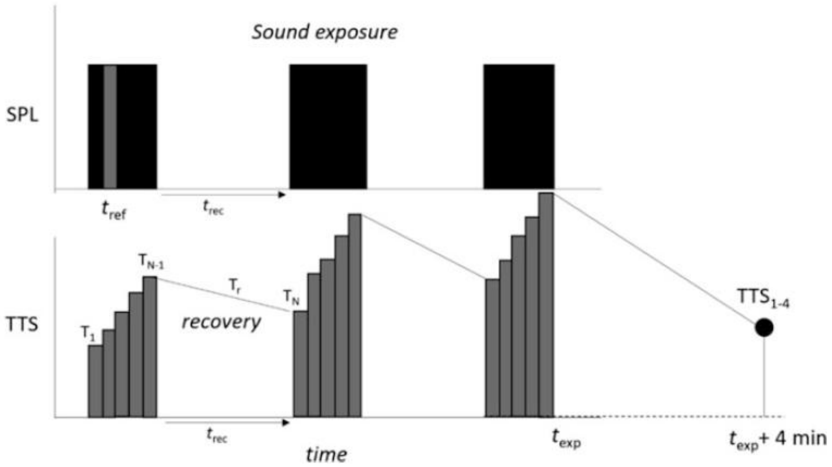
MODELS OF TTS GROWTH FOR INTERMITTENT SOUND EXPOSURES

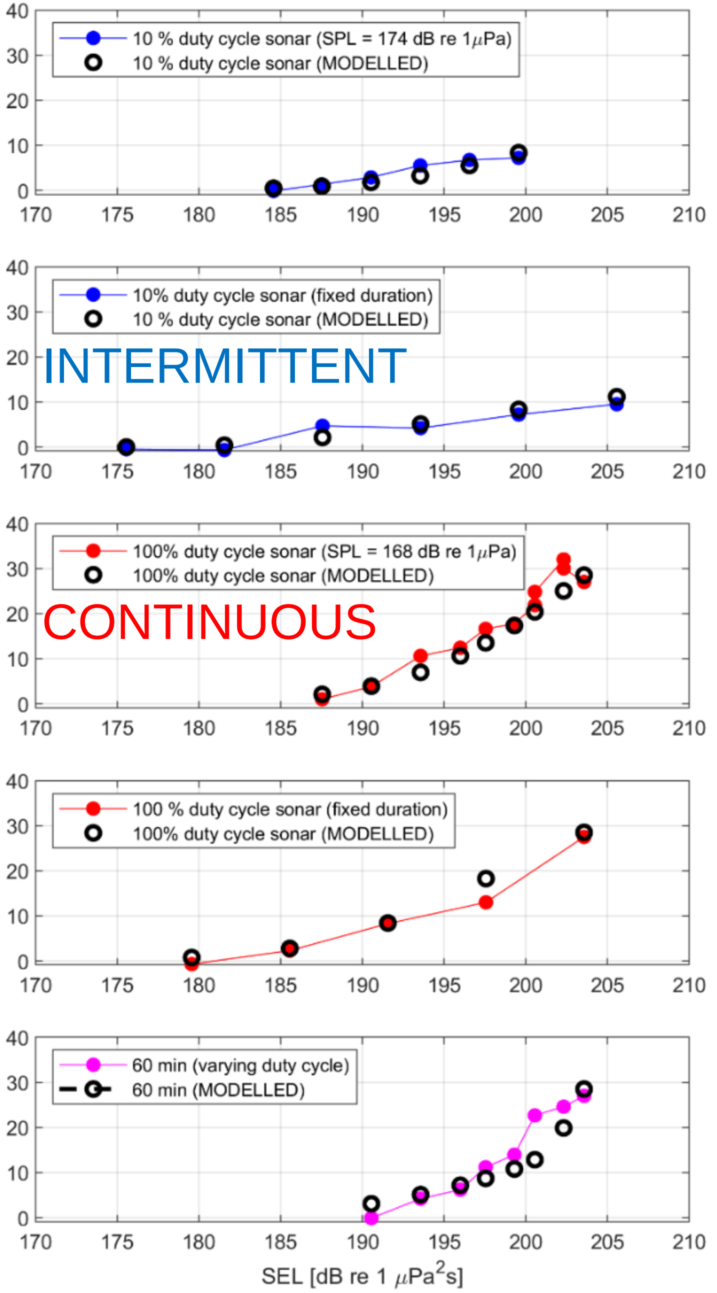
- Modified power law model

The modified power law model proposed by Humes et al. (1998) is of the form

$$\left(10^{\frac{T_N}{10}}\right)^P = \left[\left(10^{\frac{T_1}{10}}\right)^P + \left(10^{\frac{(T_{N-1}-T_r)}{10}}\right)^P - 1\right],$$

- Includes effect of recovery between pulses
- Can fit observed TTS growth for porpoise for intermittent and continuous sonar sounds
- Still challenging to match growth at other frequencies, and for impulse sounds





Von Benda-Beckmann et al. (2024)

SUMMARY – PREDICTING HEARING EFFECTS

- Models are being explored to better predict effect of impulsiveness on TTS growth
  - Kurtosis-correction appears useful to predict TTS growth in a wide range of intermittent sound types
  - We caution against using this until replicated on more individuals and other species
- Include effect of recovery
  - Modified power-law methods useful framework to predict TTS growth-
  - Predicts TTS growth for intermittent and continuous noise with one model
  - Provides predictions that can be tested empirically
  - Need to test wider range of recovery function for short intervals

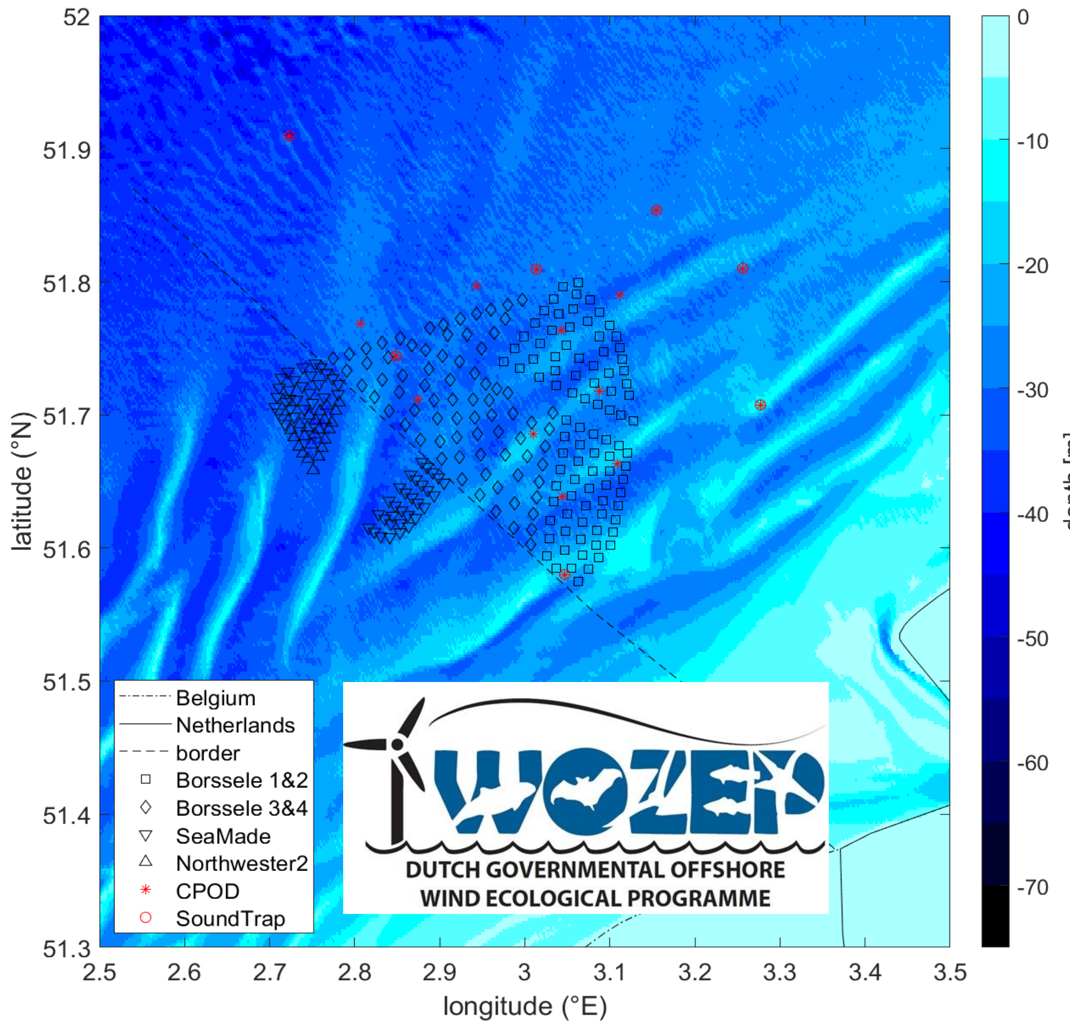
BEHAVIOURAL DISTURBANCE AND OFFSHORE WIND

BEHAVIOURAL DISTURBANCE FROM PILE DRIVING

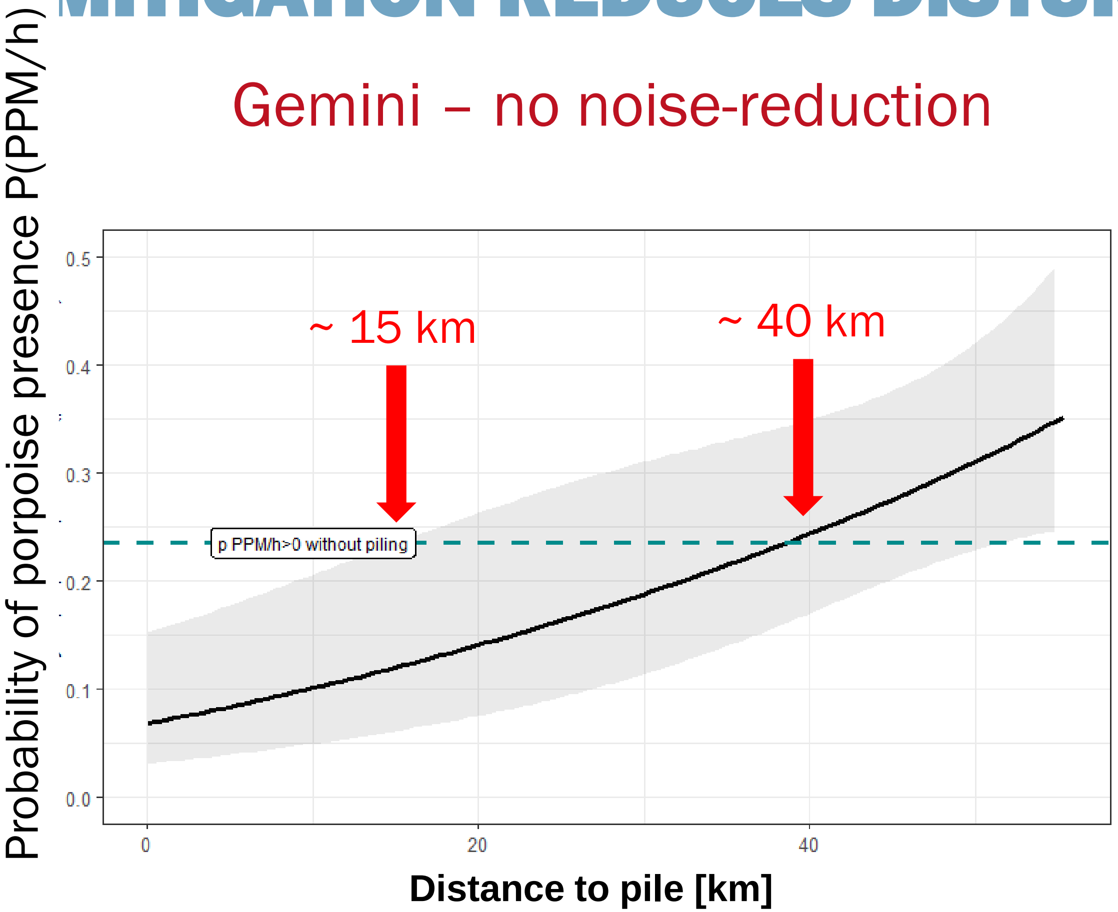
- Several studies have shown that harbour porpoises can be disturbed to large distances due to pile driving
  - Avoidance/ reduction of echolocation clicks (feeding)
- Likely hard to completely avoid disturbance
- How to deal with behavioural disturbance?

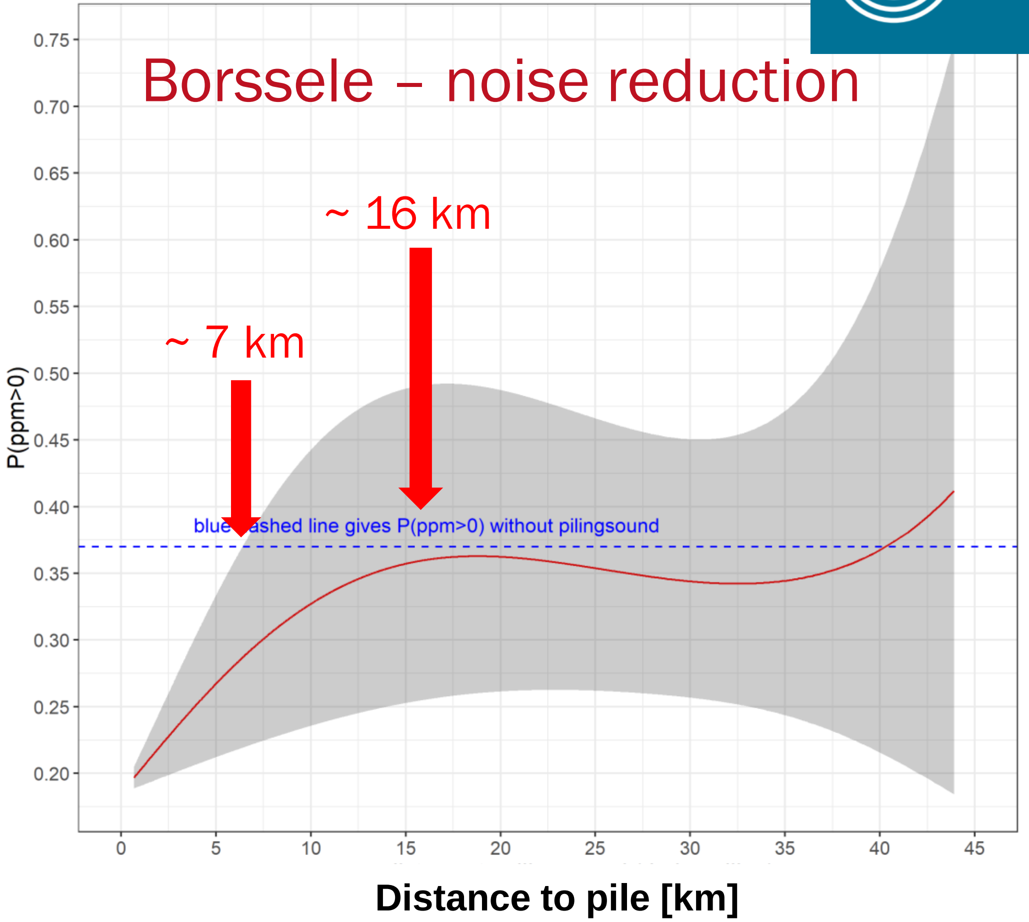
RESPONSES OF PORPOISES TO PILING SOUND

- Measure sound generated by piling with noise reduction methods
- Measure presence of porpoises using passive acoustic monitoring (PAM)
  - Ultrasonic echolocation clicks indicate presence and foraging of harbour porpoises
  - Reduction of number of clicks detected indicates avoidance, and/or cessation of echolocation
  - Estimate how many animals are disturbed, and for how long.



MITIGATION REDUCES DISTURBANCE DISTANCE

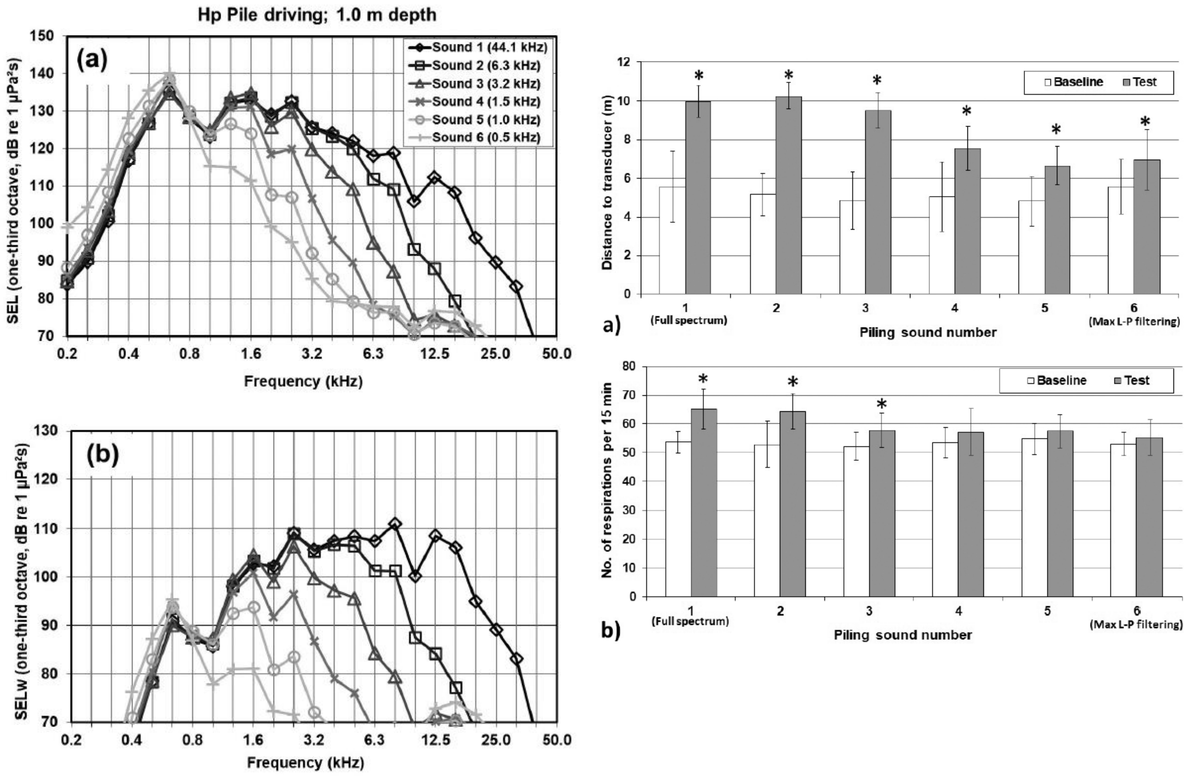




De Jong et al. (2022)

FREQUENCY WEIGHTING?

- Spectrum strongly affected by mitigation and propagation
- Active discussion how noise criteria should consider spectrum of the sound
- Studies with captive porpoises suggest that high-frequency content affects potential for disturbance
  (Tougaard et al. 2015; Kastelein et al. 2019; Kastelein et al. 2022).
- Analysis of responses to mitigated vs unmitigated pile driving remained inconclusive
  (de Jong et al. 2022)



Response of captive porpoise to pile driving playbacks with different frequency content (Kastelein et al. 2022).

INTERNATIONAL HARMONIZATION

- Approaches on how to establish noise thresholds vary by nation
  - Based on avoiding hearing injury, and/or behavioural disturbance
- Various studies find different sizes of disturbed areas
  - Methods to quantify disturbance still need to be harmonized/standardized
  - Possible that disturbance differs per site, other effects than acoustics are likely to matter
  - Shows importance of continuing to monitor!
- But ...
  - Noise reduction works in reducing behavioural disturbance
  - Noise reduction also reduces impacts on other species

CONTINUOUS VS INTERMITTENT SOUND

Mitigated impact pile driving

Heerema Marine Contractors

Airgun array


www.sercel.com/products/ggun-2.aspx

Pulsed Active Sonar

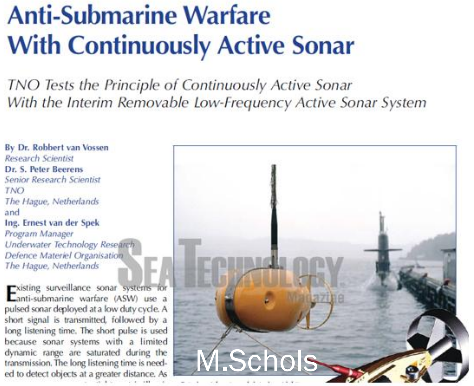
Vibratory piling

Vibroseis

Teyssandier & Sallas (2019)

Figure 1. (a) CGG's MV elements (LF and HF), called twin transducers, with their respective piston diameters. (b) Validation and verification testing phase.

Continuous Active Sonar


Anti-Submarine Warfare With Continuously Active Sonar

TNO Tests the Principle of Continuously Active Sonar With the Interim Removable Low-Frequency Active Sonar System

By Dr. Robbert van Vossen
Research Scientist
Dr. S. Peter Beerens
Senior Research Scientist
TNO
The Hague, Netherlands
and
Ing. Ernest van der Spek
Program Manager
Underwater Technology Research
Defence Materiel Organisation
The Hague, Netherlands

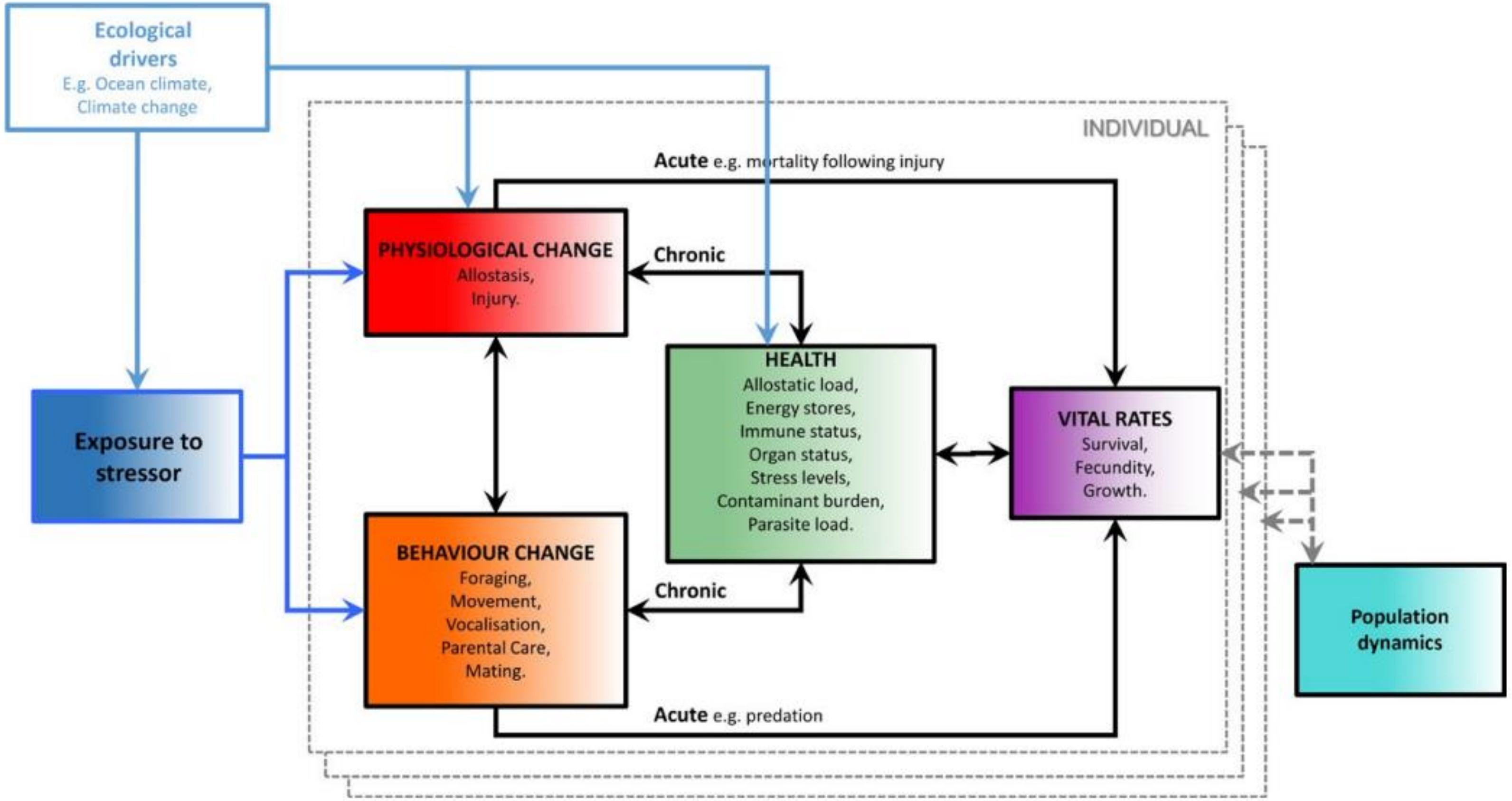
Existing surveillance sonar systems for anti-submarine warfare (ASW) use a pulsed sonar deployed at a low duty cycle. A short signal is transmitted, followed by a long listening time. The short pulse is used because sonar systems with a limited dynamic range are saturated during the transmission. The long listening time is needed to detect objects at a greater distance. As

Sea Technology, 2011.

On the environmental impact of continuous active sonar
van Vossen et al (UASP 2013; IEEE workshop on CAS)

CONSEQUENCE OF DISTURBANCE

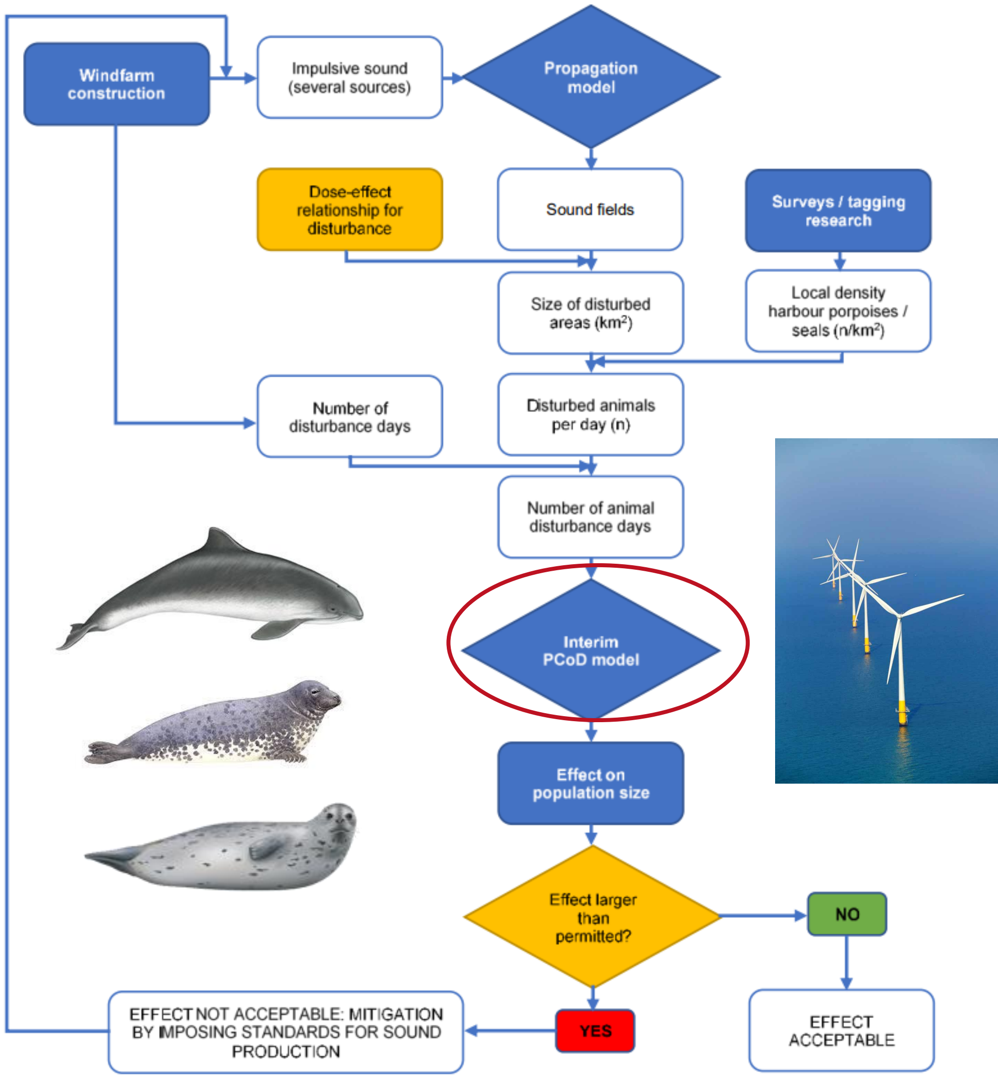
POPULATION CONSEQUENCES OF DISTURBANCE (PCOD)



Pirotta et al. (2018) – Population Consequence of Disturbance (PCoD)

KEC – DUTCH APPROACH FOR ASSESSING CUMULATIVE IMPACT OF OFFSHORE WIND CONSTRUCTION

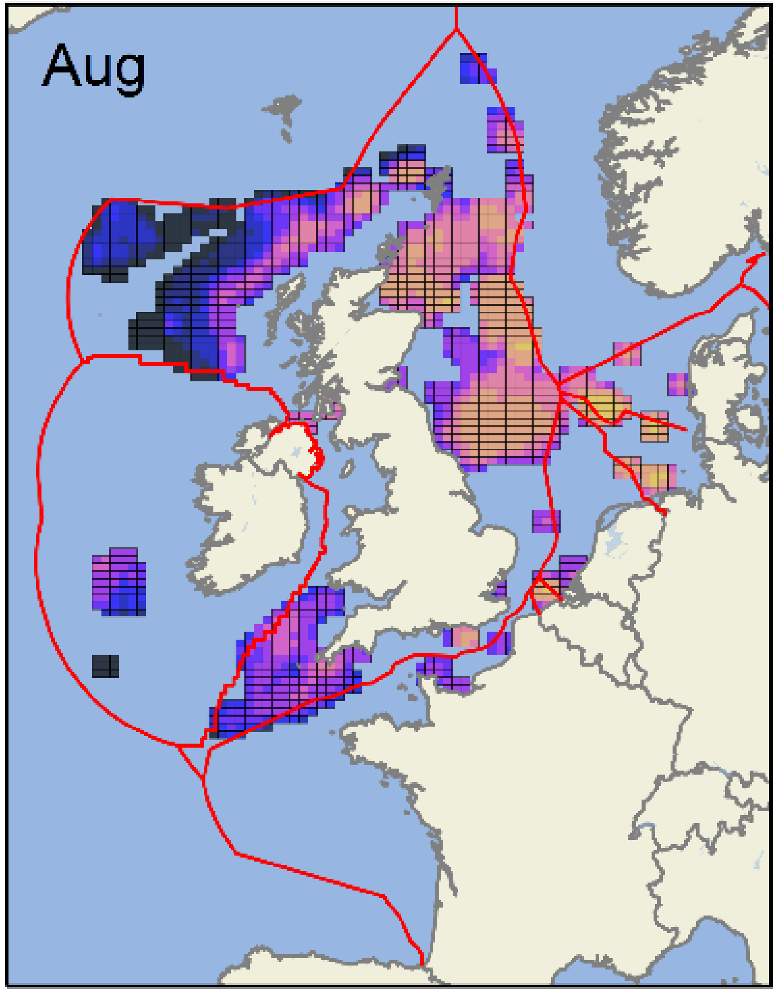
- Framework for assessing impact of offshore wind construction
- Accumulates effects of disturbance over large timescale (2030)
- Computes potential for population reduction using *Interim PCoD model* (iCPoD) (King et al. 2015; Booth et al. 2018)
- Translate risk of population decline predicted by iPCoD model into noise thresholds for pile driving



Heinis et al. (2022)

WOZEP
DUTCH GOVERNMENTAL OFFSHORE WIND ECOLOGICAL PROGRAMME

EU IMPULSIVE UNDERWATER NOISE



OSPAR ICG Noise - EIHA 2020

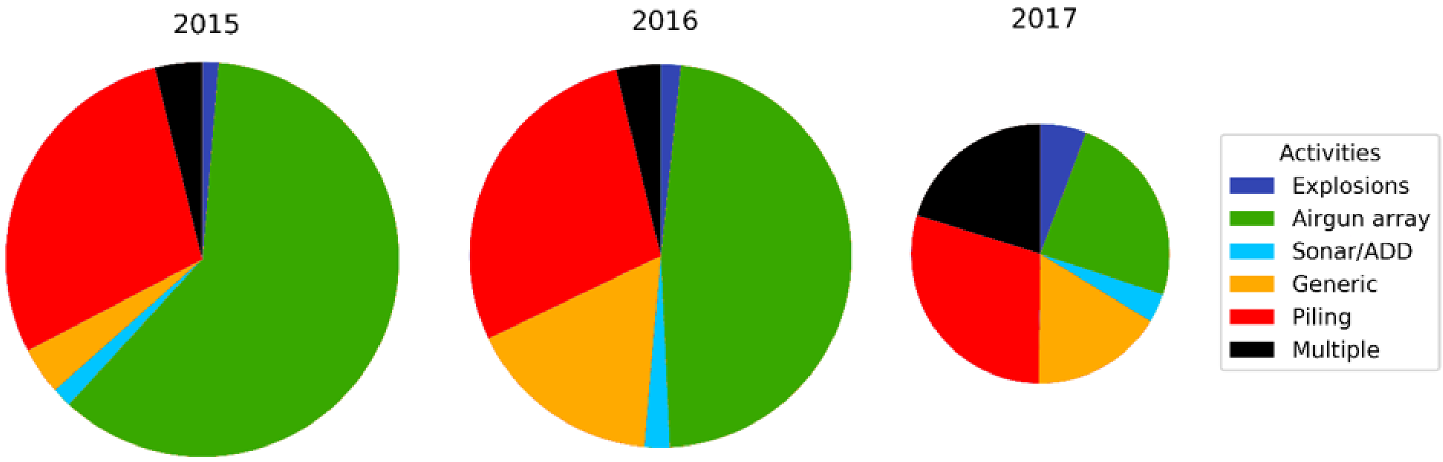


Fig. IX. Proportion of harbour porpoise noise exposure attributable to each source type. Size of pie proportional to total exposure reported for that year.

DEVELOPMENT OF CRITERIA FOR IMPULSE NOISE

- EU Technical Group Underwater Noise (2023) advice:
  - **For short-term exposure (1 day, i.e., daily exposure)**, the maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than LOBE, over 1 day, is 20% or lower (≤ 20%).
  - **For long-term exposure (1 year)**, the average exposure is calculated. The maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than LOBE, over 1 year on average, is 10% or lower (≤ 10%).
- The Level of Onset of adverse Biological Effects (LOBE):
  - is a sound level above which an adverse biological effect on an indicator species is expected to occur, i.e., an effect that may affect the comfort, survival, and vital functions of individual animals
  - Area/species specific

INTERNATIONAL HARMONIZATION

- Currently looking at cumulative impact of all sound producing activities
- First step to understand how much disturbing activity is present (Noise Registers)
- Still challenging to translate disturbance into population level effects
  - PCoD models are being developed for some species/locations
  - PCoD models contain many assumptions/ require a lot of data
  - Nations differ in how/when to incorporate PCoD models into regulatory frameworks

EFFECTS OF WIND FARMS ON MARINE LIFE

- Development of offshore wind moving fast
  - large ambitions, due to need for transition to alternative energy sources
- Current focus on few (sensitive) species.
  - How to extrapolate to new areas, species, construction type?
- North Sea is a busy area – also other noise sources to consider
- Extensive monitoring required as developments happen
  - Adaptive management strategies are key to implement new insights!

THANK YOU FOR YOUR ATTENTION