Impact of high-order UXO detonation on harbour porpoise presence at the ScottishPower Renewables East Anglia ONE offshore windfarm

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Executive summary

A large amount of unexploded ordnance (UXOs) is present on the North Sea seabed. Uncontrolled explosions of these war relics could potentially cause severe impacts including death to people and marine life alike. With ongoing progression of offshore developments, the presence of these devices is a cause of concern, and consequently they are being cleared. Behavioural impacts of such clearing activities on sensitive marine species such as cetaceans are anticipated, but have historically been difficult to evaluate.

We investigated the impact of high-order UXO detonation in and around the East Anglia ONE windfarm (southern North Sea) on acoustic detections of harbour porpoises. This is the first study assessing behavioural impacts based on *in-situ* empirical data rather than using modelling.

A total of 81 UXO detonations took place in and around the windfarm in 2018 and 2019, mostly coinciding with pin-piling activities. Simultaneously, passive acoustic data on harbour porpoise presence were collected at multiple monitoring stations using C-PODs that detect porpoises echolocation click trains. Impacts were assessed for four UXOs for which there was sufficient pre-and post-detonation monitoring effort devoid of other coinciding UXO detonations as well as piling. These included a 1,000 lb, two 500 lb and a 110 lb airdrop, all of which were detonated without sound propagation mitigation (bubble curtains). Impacts (in terms of changes to porpoise vocalisation rates) were assessed on three temporal scales (6-, 12- and 24-hour periods) across the monitoring sites (located 3.1-35.6 km from the detonation sites).

Impacts were most obvious for the 1,000 lb bomb, where both porpoise occurrence and presence of buzzes indicative of foraging behaviour were substantially reduced post-detonation compared to the pre-explosion baseline, especially at shorter distances from the detonation site. In contrast, increased detection and buzz rates were found at larger distances when assessed over longer time-periods, suggesting displacement of individuals.

For the other three UXOs considered here, overall pre-detonation porpoise presence was already much lower, and detection rates were generally more comparable between baseline and post-detonation periods. Especially for the 110 lb UXO, low detection rates prevented in-depth assessment of foraging activity.

Although based on limited data, porpoise presence appeared to be negatively impacted by UXO detonations out to distances up to 15-20 km, which is less than the Effective Deterrence Range currently specified by JNCC, Natural England, and DAERA's advice on the assessment of significant disturbance in Special Areas of Conservation for porpoises in England, Wales and Northern Ireland (JNCC, 2020).

While impacts from the explosions could not be disentangled from related activities (increased vessel presence, and pre-detonation acoustic deterrent device activation and detonation of fish scaring charges), these results show that the overall UXO detonation process can have wide-spread impacts on porpoise presence and foraging activity.

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Abbreviations

ADD	Acoustic deterrent device
BEIS	UK Department for Business, Energy and Industrial Strategy
CT	Computed Tomography
DCS	Dutch continental shelf
EA1	East Anglia ONE
EDR	Effective Deterrence Range
EIA	Environmental Impact Assessment
GMM	Gaussian Mixed Modelling
HRA	Habitats Regulations Assessment
HO	High-order
ICI	Inter-click interval
JNCC	Joint Nature Conservation Committee
LO	Low-order
NEQ	Net explosive quantity
PPBM	Porpoise positive buzz minute
PTS	Permanent threshold shift
PPM	Porpoise positive minute
RAF	Royal Air Force
SAC	Special Area of Conservation
SEL	Sound Exposure Level
SPL	Sound Pressure Level
SPR	ScottishPower Renewables
TNT	Trinitrotoluene
TTS	Temporal threshold shift
UTC	Coordinated Universal Time
UXO	Unexploded Ordnance
VHF	Very High Frequency
%PPBM^{-hr}	Percentage of porpoise positive buzz minutes per hour
%PPM^{-hr}	Percentage of porpoise positive minutes per hour

1. Introduction

1.1 General background

A large amount of unexploded ordnance (UXOs) is present in the North Sea[1], including sea mines, torpedoes, depth charges, air-dropped charges, artillery projectiles, rockets, land mines, and land service ammunition (e.g. mortars and grenades) (UK Government, 2022). An estimated 500,000 UXOs were estimated to be present in the waters surrounding the UK in 2020[2]. These UXOs are not restricted to areas surrounding historic munition dump sites, but are widespread in some areas such as the Channel and southern North Sea[3] due to World Wars 1 & 2-era active enemy engagement, emergency dumping of unused ammunition by RAF planes returning to Britain, among others.

Uncontrolled explosions of these war relics have the potential to cause severe impacts, and in worst-case scenario may cause death to people and marine life alike (OSPAR Commission, 2009 & 2010). With ongoing progression of offshore developments, the presence of these devices is a cause of concern for human safety and potential damage to equipment and infrastructure (von Benda-Beckmann et al., 2015). Consequently, to reduce the risk of uncontrolled explosions, UXOs are being cleared, typically through high-order detonation (Lepper et al., 2024); at least in UK waters, this involves applying marine mammal mitigation or sound abatement options (cf. JNCC, 2010 & 2023). To date, such measures have included spatial and temporal restrictions, visual and passive acoustic monitoring (PAM), the use of acoustic deterrent devices (ADDs) and/or use of scare charges to drive animals away from the detonation site, soft-starts, bubble curtains and low-order deflagration (BEIS, 2020; Lepper et al., 2024).

The detonation of UXOs produce loud sound impulses, which have the potential to disturb and physically injure marine species (Richardson et al., 1995; Koschinski, 2011), including porpoises (Ketten, 2004; van Benda-Beckmann et al., 2015; Aarts et al., 2016). The porpoise is the most abundant marine mammal in the North Sea, and is a conservation priority species for which several Special Area of Conservation (SACs) have been designated in UK waters, including the Southern North Sea SAC (JNCC, 2019). The species has been demonstrated to be highly sensitive to underwater sound (Southall et al., 2021), making them potentially exceptionally vulnerable to noise associated with anthropogenic activities (van Benda-Beckmann et al., 2015, and references therein).

1.2. Project background

Following the successful ScottishPower Renewables (SPR) southern North Sea harbour porpoise population modelling validation project (van Geel et al., 2023 a-d; In prep) which investigated population-level impacts of pin-piling on harbour porpoises in the North Sea, the East Anglia ONE (EA1) C-POD dataset offered an additional, unique opportunity to investigate behavioural responses of porpoises to other activities related to windfarm construction.

The current study aimed to assess the impacts of controlled UXO detonations associated with the construction of the EA1 windfarm on the local spatial and temporal presence of harbour porpoises and their foraging activity (i.e. foraging buzzes), as derived from a 12-element C-POD porpoise click detector array within and surrounding the windfarm site. In particular, this research aimed to

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[1] http://ortek.com/mine-map/.

[2] https://committees.parliament.uk/writtenevidence/11064/pdf.

[3] https://www.ospar.org/work-areas/eiha/munitions.

quantitatively investigate potential impacts of detonation across distance on porpoise detection rates (hereafter also referred to as porpoise presence) and foraging behaviour, and to compare impact ranges against the recommended Effective Deterrence Range (EDR) for UXO detonations, used when assessing the significance of noise disturbance to harbour porpoise within protected areas such as the Southern North Sea SAC, and presently specified as 26 km based on the EDR for the piling of monopiles (JNCC, 2023). Finally, the study aimed to summarise studies presenting information on the effects of UXO detonation on harbour porpoises.

2. Methodology

2.1 Data collection

The spatio-temporal presence of porpoises within and around EA1 was monitored using a PAM array from 11 March 2018 to 21 June 2019, involving eight consecutive deployments. The array of 12 monitoring stations, each containing a C-POD automated porpoise click detector (Chelonia Ltd., UK), was deployed in and around the EA1 site to monitor porpoise echolocation activity (Figures 1 & 2). C-PODs were configured using default settings, except that devices were programmed to record at all angles relative to vertical.

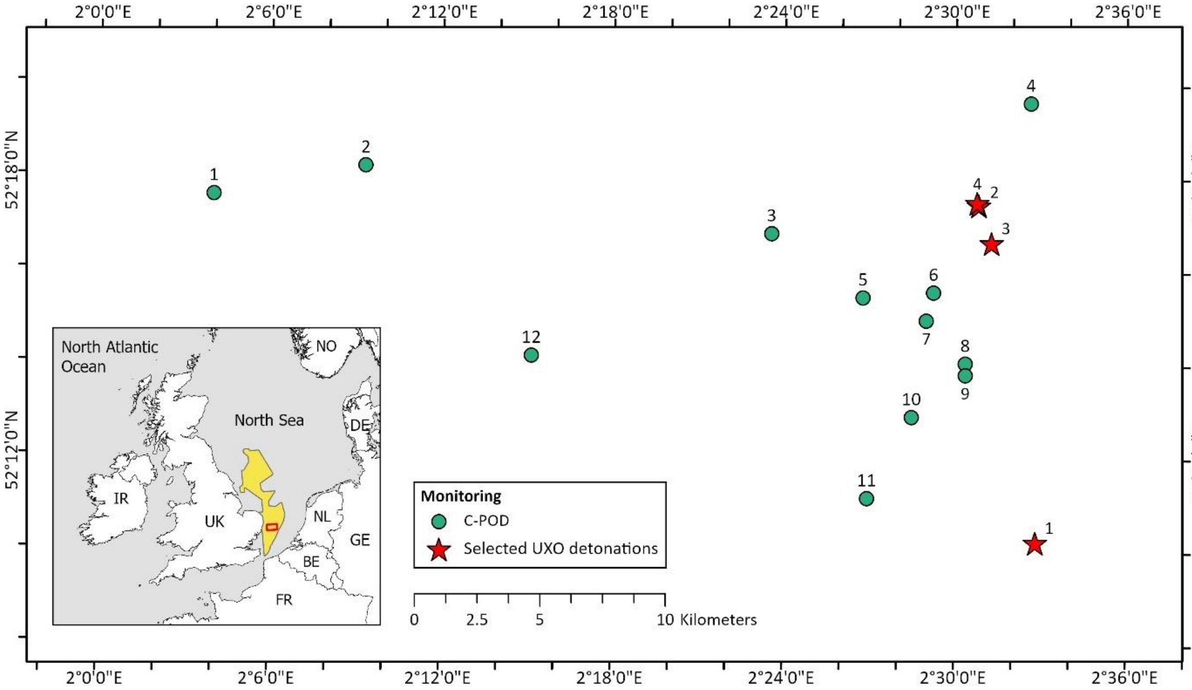

Figure 1. *Location of the ScottishPower Renewables East Anglia ONE offshore windfarm off south-east England (red rectangle in inset) located within the Southern North Sea Special Area of Conservation designation for the conservation of harbour porpoise (yellow area in inset), with positions of acoustic monitoring stations collecting C-POD porpoise echolocation data (green circles) and locations of selected unexploded ordnance (UXO) detonations (red stars). UK = United Kingdom, IR = Ireland, NO = Norway, DE = Denmark, NL = the Netherlands, BE = Belgium, GE = Germany, and FR = France. European country shapefile data were obtained from European Commission, Eurostat, GISCO @EuroGeographics and UN-FAO (https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries).*

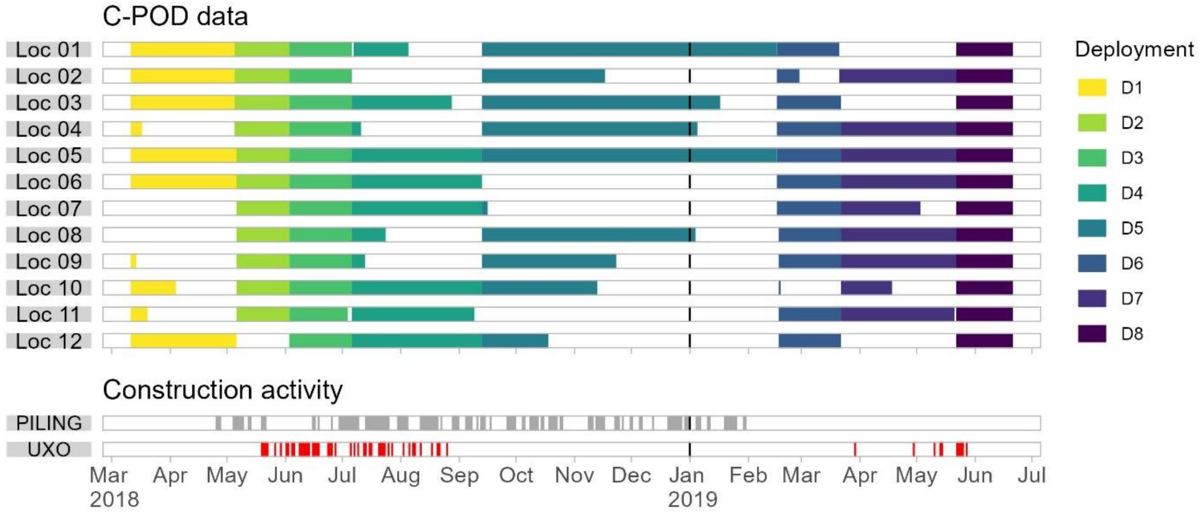

Figure 2. *Summary of East Anglia ONE unexploded ordnance (UXO) detonation and pin-piling activity in relation to C-POD harbour porpoise monitoring effort at deployment level for each monitoring location.*

Information on the UXO detonation activities was provided by SPR and included the 2018 and 2019 Marine Mammal Mitigation Reports covering UXO clearance operations. A total of 81 UXO detonations took place in and around the EA1 windfarm off southeastern England in 2018 and 2019, mostly coinciding with pin-piling activities (Figure 2). Detonations occurred between May-August 2018 (n=65), and March-July 2019 (n=16).

2.2 Data analysis

2.2.1 UXO selection

The selection of UXOs to be included in the current study was based on the presence of sufficient pre-detonation (specified as >60 hours) and post-detonation (minimal 30 hours) monitoring effort clear of other UXO detonations, as well as pin-piling activity.

2.2.2 Acoustic processing

2.2.2.1 Detecting porpoise presence

Analysis of the C-POD data for the presence of porpoise presence was undertaken in CPOD.exe (Version 2.048) through application of the KERNO classifier, and ‘High’ and ‘Moderate’ quality porpoise click train detections were subsequently exported on a 1-minute resolution. All minutes that were not monitored for the full 60 seconds were excluded, and remaining monitoring effort was assessed for each hour, taking the exact minute in which the UXO detonation occurred as the reference point. All hours with <50 minutes of effort were excluded from further analysis. Finally, for all remaining hourly periods, the hourly detection rate of ‘porpoise positive minutes’ (PPM) relative to the total monitoring effort per hour (%PPM^{-hr}) was calculated. It should be mentioned that a silent minute may represent the absence of porpoises, porpoises being quiet, or porpoises vocalising outwith the limited detection range of a few hundred meters from the C-POD.

Adapting the approach applied by Graham et al. (2019) to study responses of harbour porpoises to pile-driving, changes in porpoise presence were estimated for each monitoring location between a pre-detonation baseline period and a post-detonation assessment period. As there was no information available on the potential duration of the impact of UXO detonation activities on harbour porpoise, three different temporal scales during which impacts could occur were considered: a 6-, a 12-, and a 24-hour period. For each of these temporal scales, the assessment period from the end of detonation was equal to the compared baseline duration before the detonation event, but depending on the assessment scale, were specified to start at different timings prior to the detonation. Considering the diel and tidal variability in porpoise presence at the EA1 site (van Geel et al., 2023b), and in the wider North Sea (Williamson et al., 2017), the start of the 6- and 12-hour baseline was set at 24 hours before the detonation, to ensure that the pre-detonation baseline and post-detonation periods aligned with respect to time of day and tidal cycle (Figure 3). For the 24-hour assessment period, covering a full diel cycle and two semi-diurnal tidal cycles, the baseline was specified to commence 36 hours prior to detonation. For each of the assessment durations, at least 12 hours immediately before UXO detonation were specifically excluded to avoid baseline presence to be affected by detonation-associated activities, such as increased vessel presence, the activation of acoustic deterrence devices (ADDs) to deter porpoises (and other marine life) from the explosion site, and pre-detonation application of fish scaring charges.

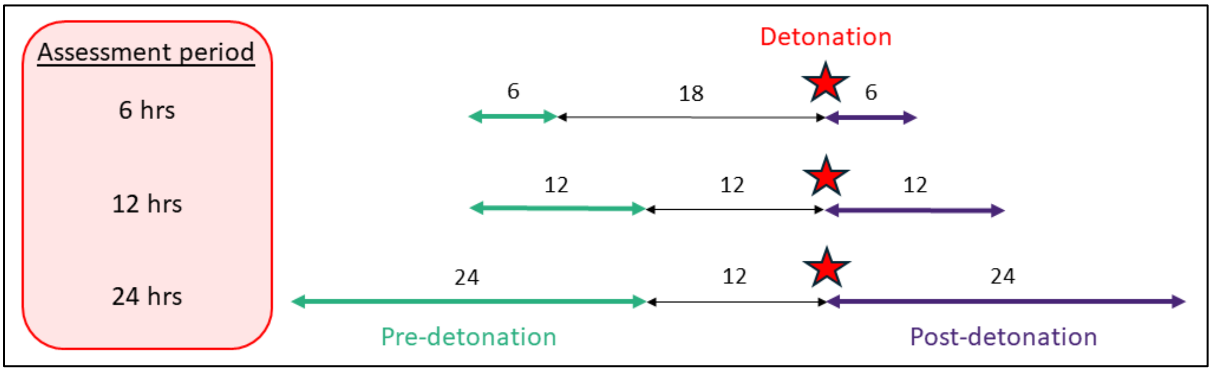

Figure 3. *Schematic overview of the start- and end times of the pre-detonation baseline and post-detonation periods for each of the three (6-, 12-, and 24-hour) assessment periods, relative to the time of UXO detonation (red starts).*

2.2.2.2 Porpoise foraging behaviour

To assess changes in foraging activity in response to UXO detonation, the KERNO classifier was applied in the C-POD complementary software to identify porpoise echolocation click trains, and the click characteristics of all 'High' and 'Moderate' quality trains were exported for every minute monitored. Following the approach described by Pirotta et al. (2014), inter-click intervals (ICIs) were calculated between successive clicks, and Gaussian Mixed Modelling (GMM) was undertaken to allocate clicks to one of three groups with ICIs representative of: 1) buzzes, 2) regular echolocation clicks, and 3) periods between click trains. The GMM was applied to for data from all C-PODs deployed during deployments

D2 (comprising of 596,452 clicks) and D7 separately (totalling 822,716 clicks), D2 covering the period at which the selected UXOs 1–3 were detonated, and D7 covering the clearance of UXO 4 (Figure 2; see also Results section). Finally, the porpoise foraging rates (percentage of ‘porpoise positive buzz minutes’ (PPBM) relative to the total number of PPM per hour; %PPBM^{-hr}) were calculated for the pre- and post-detonation periods on the three temporal assessment scales as described above.

It should be noted that porpoises are known to produce click trains with short ICIs, here referred to as buzzes, during both foraging and social activity (Clausen et al., 2010; Sørensen et al., 2018). As it is currently impossible to distinguish between the usage of click trains with short ICIs in these behavioural contexts, the approach used in this report assumed that all buzzes were indicative of foraging behaviour.

3. Results

3.1 UXO selection

Exclusion of UXO detonations that coincided with pin-piling activity reduced the original dataset of 81 UXOs to a limited number of detonations in 2018 and 2019 to further explore for inclusion in the current work. Application of the requirement for the complete pre-detonation baseline periods and post-detonation assessment periods to be free of other detonations or preparations in advance of the next detonation (i.e. no piling and/or UXO detonation at least 60 hours before, and 30 hours after detonation), resulted in 4 UXOs being taken forward for analysis. This included 1x 1,000 lb airdrop, 2x 500 lb airdrop and 1x 110 lb airdrop UXOs (Table 1), all of which were detonated without the use of bubble curtains to mitigate sound propagation. Their locations are indicated in Figure 1.

Table 1. *Overview of the date and time, as well as unexploded ordnance (UXO) class cleared using high-order detonation and included in the current assessment of impact on harbour porpoise.*

UXO	*Date & Time (UTC)*	*UXO Class*
1	01/06/2018 06:40	1,000 lb British airdrop
2	26/05/2018 09:03	500 lb British airdrop
3	29/05/2018 11:59	500 lb British airdrop
4	29/04/2019 14:08	110 lb German airdrop

During the original East Anglia ONE harbour porpoise monitoring project, C-PODs were deployed at 12 monitoring locations. However, data were not available for all sites for each of these UXO detonations, with an absence of data from monitoring location 12 for the selected detonations in 2018, and for monitoring locations 1, 3, 10 & 12 for the one selected in 2019.

3.2 Porpoise presence

3.2.1 UXO 1 – 1,000 lb airdrop

For the heaviest UXO, median, mean and maximum porpoise hourly acoustic detection rates were substantially reduced post-detonation, especially at shorter distances from the detonation location (Figure 4). Decreased detections nearer to the detonation site (roughly up to 15-20 km) was shown for all three assessment periods, but most obvious for the median and mean when assessed over the 6-hour assessment period, when pre-detonation detections were higher than porpoise presence across the 12- and 24-hour baseline periods.

While median and mean porpoise detection rates were relatively similar or slightly higher post-detonation compared to pre-detonation, maximum relative porpoise presence markedly increased at greater distances (also at approximately 15-20 km) from the detonation location, and this pattern was more prevalent when assessed over longer time periods (i.e. 12- and 24-hour periods).

It is worth noting that, since hours monitored for <50 full minutes were excluded, the sample size (i.e. the number of hours of effort) used to calculate porpoise detection rates fluctuated between pre- and post-detonation periods, for the 6-, 12-, and 24-hour assessment periods, as well as between monitoring locations (Table 2).

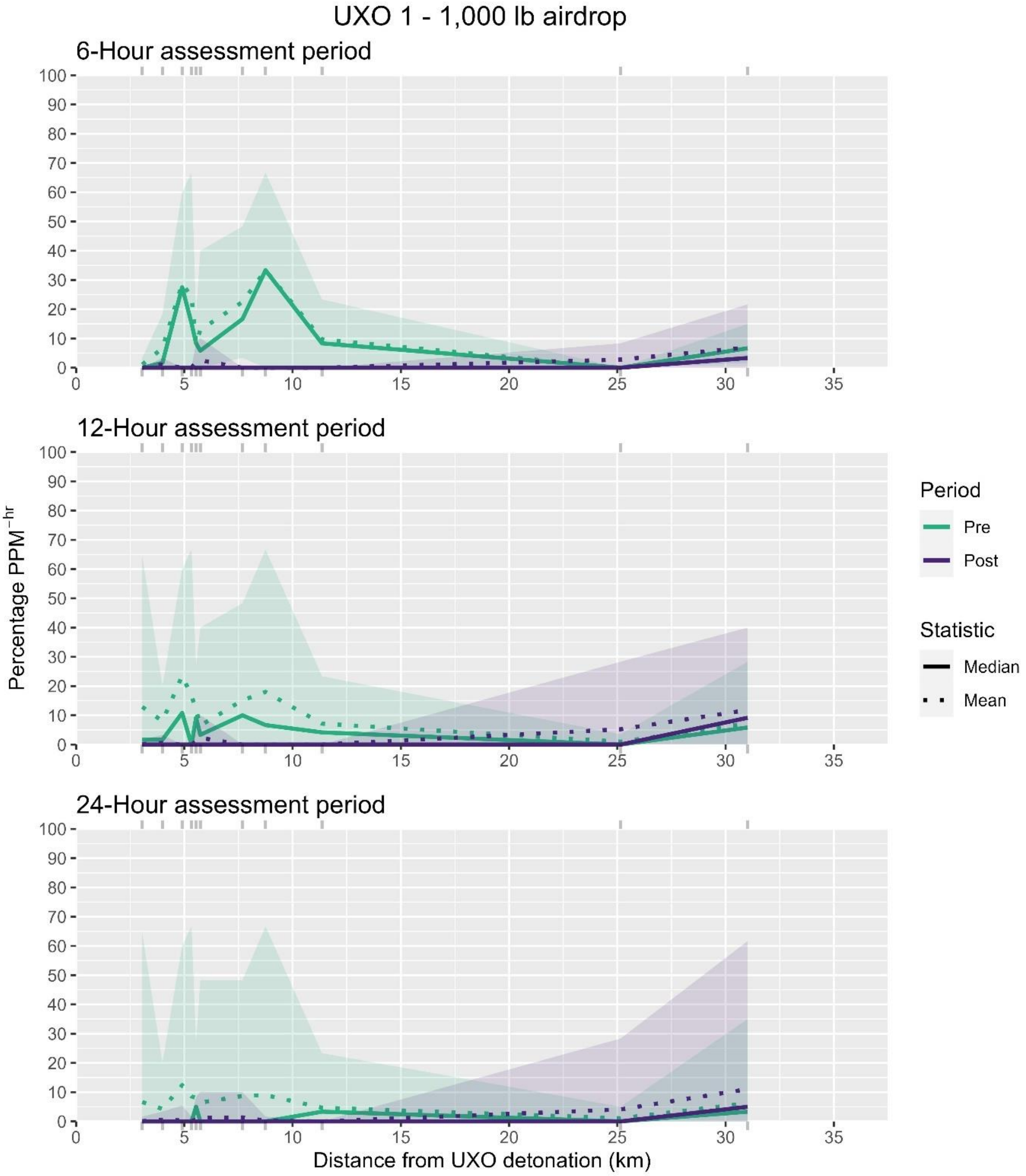

Figure 4. *Median (solid line) and mean (dotted line) porpoise presence (expressed as the percentage of porpoise positive minutes (PPM) per hour) during the pre-detonation (in green) and post-detonation periods (in purple), as determined across three assessment periods (6-, 12-, and 24-hours) in relation to the high-order detonation of UXO 1, a 1,000 lb airdrop. Minimum and maximum porpoise presence is represented by the shaded areas. Distances of monitoring locations relative to the UXO site is presented by the light grey rug ticks included above and below each plot. Note that as hours monitored for <50 full minutes were excluded, the number of hours of effort contributing to the calculations may fluctuate between pre- and post-detonation periods, for the different assessment periods, as well as between monitoring sites (see Table 2).*

Table 2. *Summary information of data underpinning the impact assessment for the detonation of UXO 1, a 1,000 lb airdrop.*

Monitoring location	***Distance to UXO (km)***	***Sample size 6-hour assessment***		***Sample size 12-hour assessment***		***Sample size 24-hour assessment***	
		Pre	***Post***	***Pre***	***Post***	***Pre***	***Post***
1	31.020	6	6	12	12	24	24
2	25.151	3	3	7	7	14	17
3	8.750	2	3	5	6	10	12
4	5.738	4	6	9	11	20	23
5	5.542	6	6	12	12	24	24
6	3.0553	3	4	9	10	19	21
7	3.988	3	3	5	6	11	12
8	4.899	4	6	8	9	16	20
9	5.331	4	5	9	10	18	20
10	7.686	6	6	12	12	24	24
11	11.359	6	6	10	11	21	14

3.2.2 UXOs 2 & 3 – 500 lb airdrop

Overall pre-detonation median, mean, and maximum porpoise detection rates were already much lower for the detonations of the two 500 lb UXOs, compared to the baseline rates ahead of detonation of the heavier 1,000 lb UXO presented above. Possibly related to the reduced baseline detection rate, median and mean porpoise detections during the baseline and post-detonation periods were comparable, although these were slightly higher post-detonation at larger distances when compared over the 12- and 24-hour assessment periods for UXO 2 (Figures 5 & 6). This transition, as well as a broad shift in maximum porpoise detection rate from higher relative presence during the baseline period at shorter distances to higher maximum rates post-detonation at larger distances, appeared to occur at approximately 15-20 km from the detonation location for UXO 2 (Figure 5). No comparable impact range was noted for UXO 3 (Figure 6).

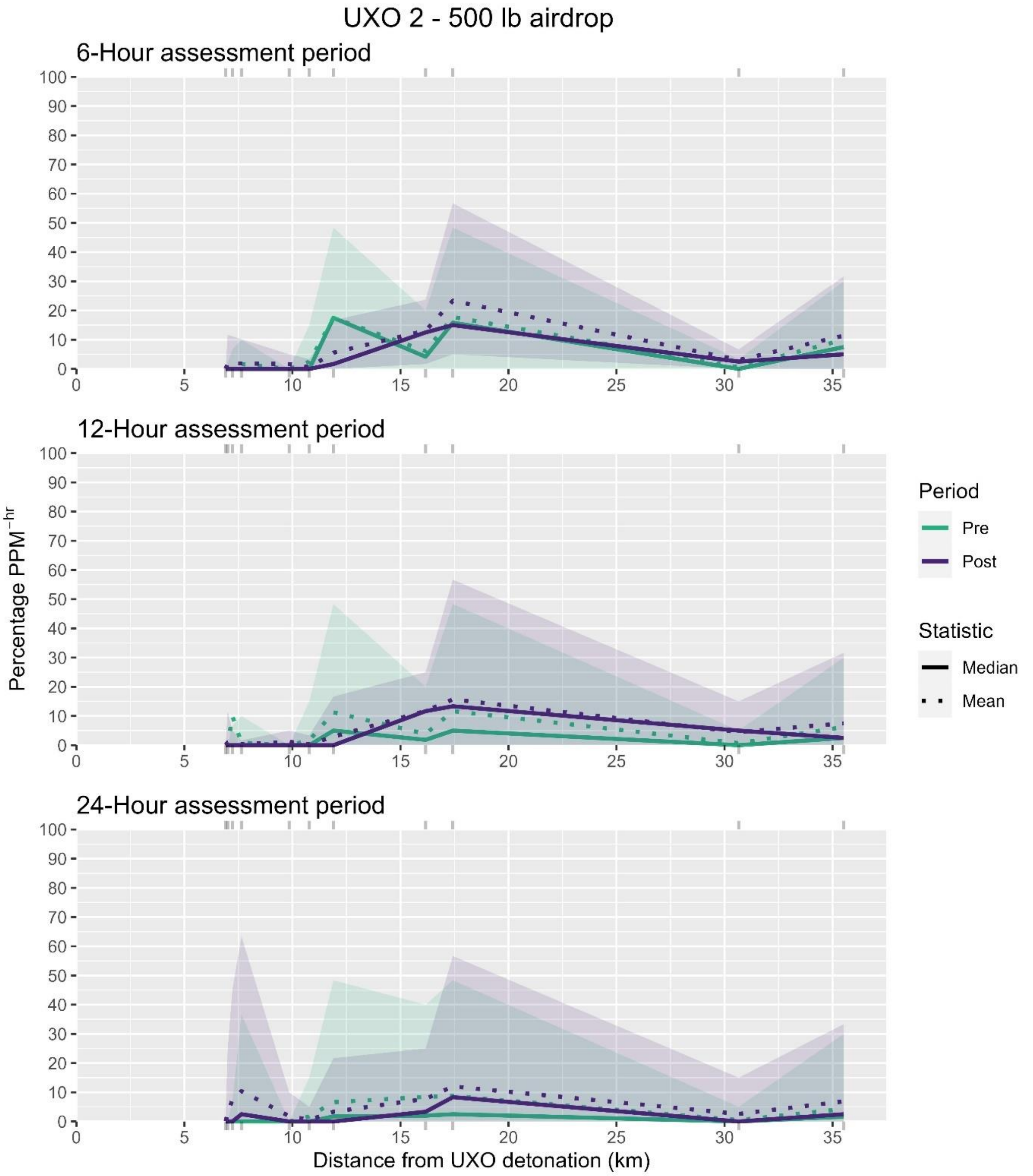

Figure 5. *Median (solid line) and mean (dotted line) porpoise presence (expressed as the percentage of porpoise positive minutes (PPM) per hour) during the pre-detonation (in green) and post-detonation periods (in purple), as determined across three assessment periods (6-, 12-, and 24-hours) in relation to the high-order detonation of UXO 2, a 500 lb airdrop. Minimum and maximum porpoise presence is represented by the shaded areas. Distances of monitoring locations relative to the UXO site is presented by the light grey rug ticks included above and below each plot. Note unequal monitoring efforts (see Table 3).*

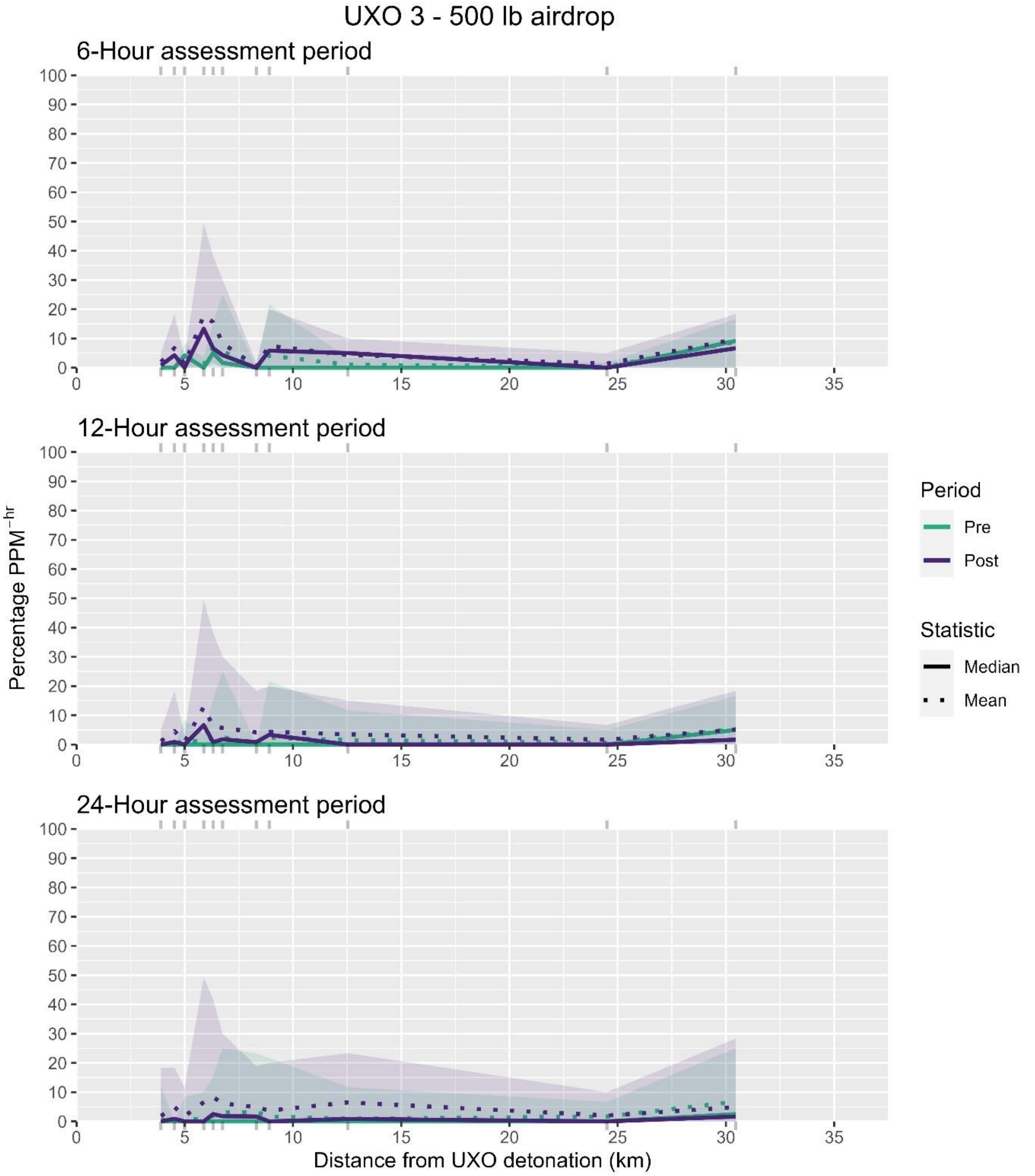

Figure 6. *Median (solid line) and mean (dotted line) porpoise presence (expressed as the percentage of porpoise positive minutes (PPM) per hour) during the pre-detonation (in green) and post-detonation periods (in purple), as determined across three assessment periods (6-, 12-, and 24-hours) in relation to the high-order detonation of UXO 3, a 500 lb airdrop. Minimum and maximum porpoise presence is represented by the shaded areas. Distances of monitoring locations relative to the UXO site is presented by the light grey rug ticks included above and below each plot. Note unequal monitoring efforts (see Table 4).*

Table 3. *Summary information of data underpinning the impact assessment for the detonation of UXO 2, a 500 lb airdrop.*

Monitoring location	***Distance to UXO (km)***	***Sample size 6-hour assessment***		***Sample size 12-hour assessment***		***Sample size 24-hour assessment***	
		Pre	***Post***	***Pre***	***Post***	***Pre***	***Post***
1	35.520	6	6	12	12	24	24
2	30.655	6	6	12	10	24	18
3	16.166	6	6	10	9	19	16
4	17.427	6	6	12	12	24	24
5	11.899	6	6	12	12	24	24
6	10.783	6	6	12	11	24	20
7	9.849	5	3	11	7	19	14
8	7.641	6	0	11	5	22	14
9	7.221	6	0	10	4	22	14
10	7.005	0	6	3	12	7	24
11	6.910	6	6	9	12	16	24

Table 4. *Summary information of data underpinning the impact assessment for the detonation of UXO 3, a 500 lb airdrop.*

Monitoring location	***Distance to UXO (km)***	***Sample size 6-hour assessment***		***Sample size 12-hour assessment***		***Sample size 24-hour assessment***	
		Pre	***Post***	***Pre***	***Post***	***Pre***	***Post***
1	30.454	6	6	12	12	24	24
2	24.500	5	6	10	10	16	18
3	8.306	4	4	6	6	11	11
4	4.522	6	6	12	12	22	22
5	5.877	6	6	12	12	24	24
6	3.902	6	6	9	10	19	19
7	4.993	2	3	5	7	11	12
8	6.308	3	3	8	8	16	16
9	6.750	5	6	11	10	18	18
10	8.899	6	6	12	11	24	23
11	12.535	5	5	12	11	23	20

3.2.3 UXO 4 – 110 lb airdrop

As for the 500 lb UXOs, median, mean, and maximum porpoise detection rates were already low prior to detonation of the 110 lb UXO (Figure 7). In general, median and mean relative porpoise presence was comparable before and after detonation for all three assessment periods, although maximum detection rates were equal to, or higher, during the baseline period, a pattern present across all distances from the detonation location, and for all three assessment periods (Figure 7).

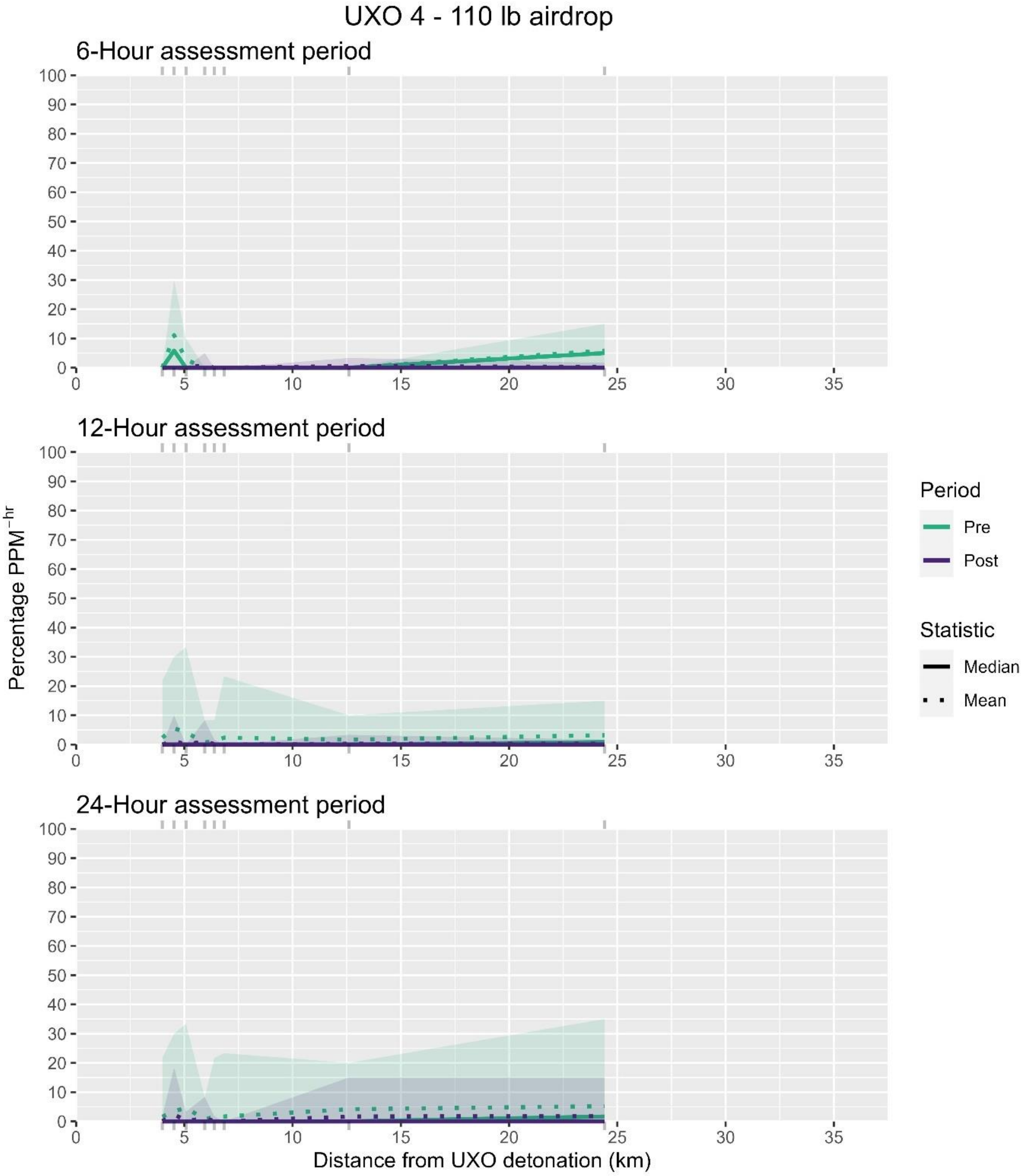

Figure 7. *Median (solid line) and mean (dotted line) porpoise presence (expressed as the percentage of porpoise positive minutes (PPM) per hour) during the pre-detonation (in green) and post-detonation periods (in purple), as determined across three assessment periods (6-, 12-, and 24-hours) in relation to the high-order detonation of UXO 1, a 110 lb airdrop. Minimum and maximum porpoise presence is represented by the shaded areas. Distances of monitoring locations relative to the UXO site is presented by the light grey rug ticks included above and below each plot. Note unequal monitoring efforts (see Table 5).*

Table 5. *Summary information of data underpinning the impact assessment for the detonation of UXO 4, a 110 lb airdrop.*

Monitoring location	***Distance to UXO (km)***	***Sample size 6-hour assessment***		***Sample size 12-hour assessment***		***Sample size 24-hour assessment***	
		Pre	***Post***	***Pre***	***Post***	***Pre***	***Post***
2	24.407	6	6	12	12	24	24
4	4.526	6	6	12	12	23	23
5	5.942	6	6	12	12	24	24
6	3.981	6	6	12	12	24	20
7	5.074	6	6	12	11	24	19
8	6.385	6	6	12	12	24	20
9	6.8340	6	6	12	12	24	23
11	12.607	6	6	12	12	24	24

3.3 Porpoise foraging

3.3.1 UXO 1 – 1,000 lb airdrop

As observed for general porpoise detection rates, assessment of impact of detonation of the heaviest UXO revealed that relative porpoise buzz presence, expressed as %PPBM^{-hr}, was generally reduced post-detonation at shorter distances from the detonation location, and increased at larger distances (Figure 8). This result was particularly notable when assessed over the two shortest assessment periods (i.e. 6- and 12-hour periods), with the transition distance at 5-10 km from the detonation location.

As relative occurrence of foraging activity was only assessed for those hours during which porpoises were detected, the sample size (i.e. total number of hours included in each pre- and post-detonation assessment period for individual monitoring locations) were reduced (Table 5) compared to the sample sizes included in the assessment for general porpoise presence (Table 2). Especially for the post-detonation period, available data were limited or completely absent for several of the monitoring sites.

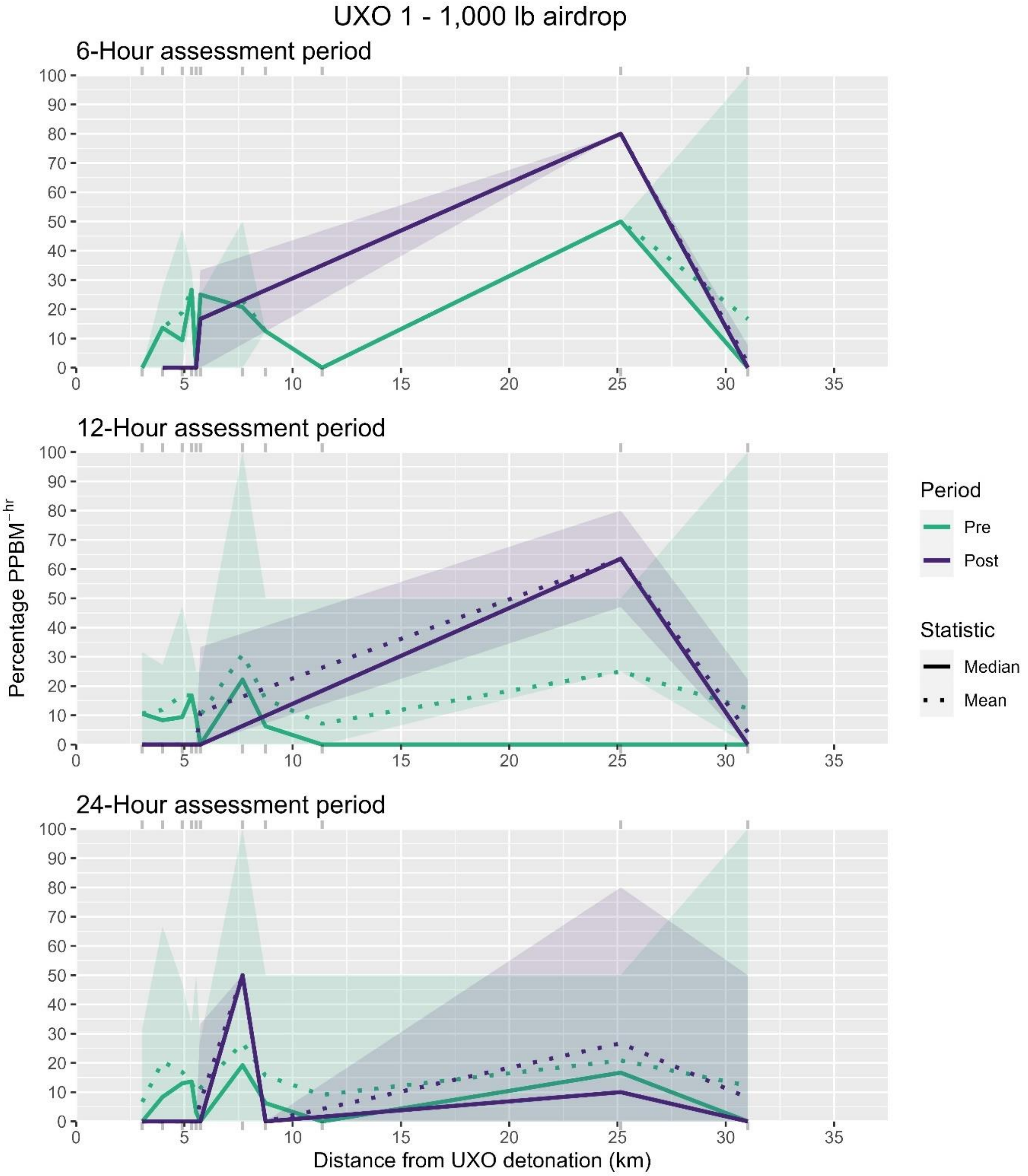

__Figure 8.__ Median (solid line) and mean (dotted line) porpoise foraging activity (expressed as the percentage of porpoise positive buzz minutes (PPBM) relative to the total number of porpoise positive minutes (PPM) per hour) during the pre-detonation (in green) and post-detonation periods (in purple), as determined across three assessment periods (6-, 12-, and 24-hours) in relation to the high-order detonation of UXO 1, a 1,000 lb airdrop. Minimum and maximum porpoise presence is represented by the shaded areas. Distances of monitoring locations relative to the UXO site is presented by the light grey rug ticks included above and below each plot. Note unequal monitoring efforts (see Table 6).

Table 6. *Summary information of data underpinning the impact assessment for the detonation of UXO 1, a 1,000 lb airdrop.*

Monitoring location	***Distance to UXO (km)***	***Sample size 6-hour assessment***		***Sample size 12-hour assessment***		***Sample size 24-hour assessment***	
		Pre	***Post***	***Pre***	***Post***	***Pre***	***Post***
1	31.020	6	5	10	11	17	18
2	25.151	1	1	2	2	4	7
3	8.750	1	0	4	0	4	2
4	5.738	3	2	5	3	9	5
5	5.542	5	2	10	3	16	4
6	3.0553	1	0	5	1	8	1
7	3.988	2	2	3	2	5	4
8	4.899	3	0	5	0	6	2
9	5.331	2	0	4	0	5	1
10	7.686	6	0	9	0	11	1
11	11.359	5	0	7	0	11	0

3.3.2 UXOs 2 & 3 – 500 lb airdrop

General porpoise detection rates were overall lower (compared to their rates at the 1,000 lb UXO), but comparable between before and after detonation across the various distances. Relative buzz presence, however, increased post-detonation at distances from about 10-15 km from the detonation location (Figures 9 & 10). The response in closer vicinity to the UXO detonation was less clear across assessment periods and both UXOs, and may reflect low data availability for these monitoring locations (Tables 7 & 8). For UXO 2, the results show a general reduction in porpoise foraging activity at closer distances, although data were limited or absent for some locations or assessment periods. In contrast, foraging activity post-detonation was more comparable, or even slightly higher for UXO 3 at locations closer to the detonation site.

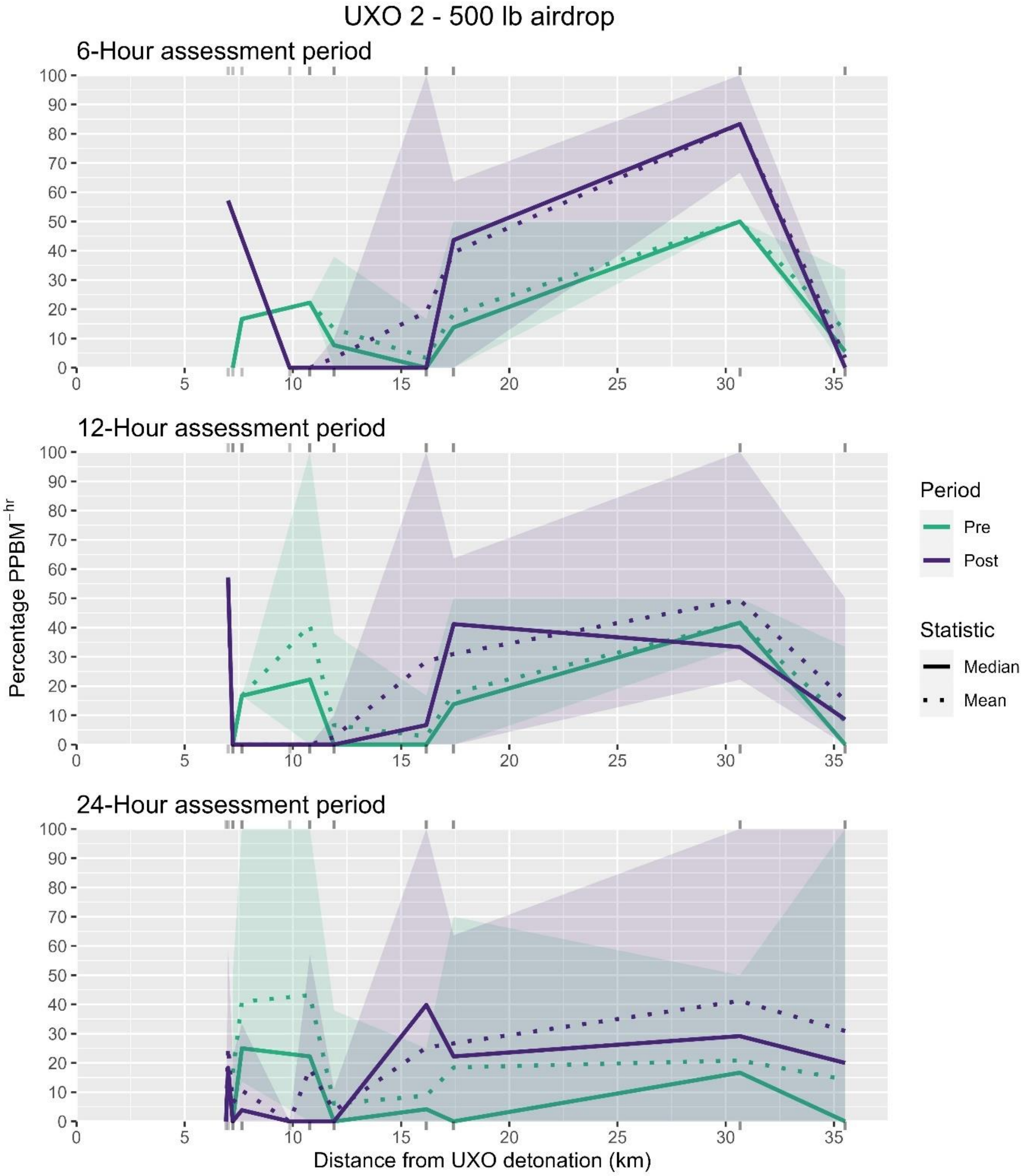

Figure 9. *Median (solid line) and mean (dotted line) porpoise foraging activity (expressed as the percentage of porpoise positive buzz minutes (PPBM) relative to the total number of porpoise positive minutes (PPM) per hour) during the pre-detonation (in green) and post-detonation periods (in purple), as determined across three assessment periods (6-, 12-, and 24-hours) in relation to the high-order detonation of UXO 2, a 500 lb airdrop. Minimum and maximum porpoise presence is represented by the shaded areas. Distances of monitoring locations relative to the UXO site is presented by the light grey rug ticks included above and below each plot. Note unequal monitoring efforts (see Table 7).*

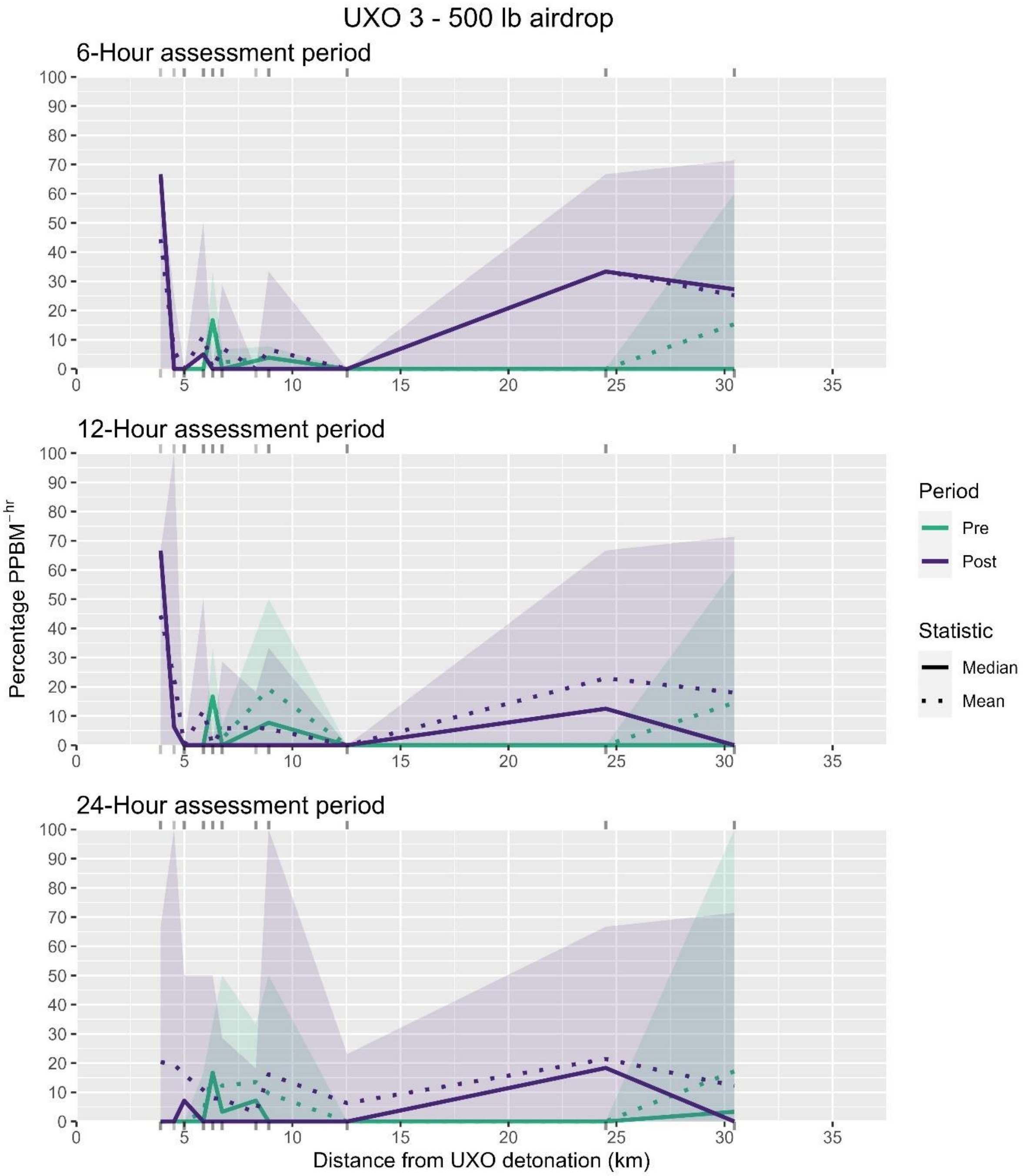

Figure 10. *Median (solid line) and mean (dotted line) porpoise foraging activity (expressed as the percentage of porpoise positive buzz minutes (PPBM) relative to the total number of porpoise positive minutes (PPM) per hour) during the pre-detonation (in green) and post-detonation periods (in purple), as determined across three assessment periods (6-, 12-, and 24-hours) in relation to the high-order detonation of UXO 3, a 500 lb airdrop. Minimum and maximum porpoise presence is represented by the shaded areas. Distances of monitoring locations relative to the UXO site is presented by the light grey rug ticks included above and below each plot. Note unequal monitoring efforts (see Table 8).*

Table 7. *Summary information of data underpinning the impact assessment for the detonation of UXO 2, a 500 lb airdrop.*

Monitoring location	***Distance to UXO (km)***	***Sample size 6-hour assessment***		***Sample size 12-hour assessment***		***Sample size 24-hour assessment***	
		Pre	***Post***	***Pre***	***Post***	***Pre***	***Post***
1	35.520	5	5	8	8	14	17
2	30.655	1	2	2	5	4	5
3	16.166	5	6	6	8	11	11
4	17.427	5	6	7	9	13	15
5	11.899	4	3	8	4	13	8
6	10.783	1	1	3	1	7	5
7	9.849	0	1	0	2	0	6
8	7.641	1	0	1	1	4	8
9	7.221	1	0	1	1	3	6
10	7.005	0	1	0	1	0	6
11	6.910	0	0	0	0	0	2

Table 8. *Summary information of data underpinning the impact assessment for the detonation of UXO 3, a 500 lb airdrop.*

Monitoring location	***Distance to UXO (km)***	***Sample size 6-hour assessment***		***Sample size 12-hour assessment***		***Sample size 24-hour assessment***	
		Pre	***Post***	***Pre***	***Post***	***Pre***	***Post***
1	30.454	5	5	7	7	11	14
2	24.500	1	2	2	4	7	6
3	8.306	0	1	0	3	3	6
4	4.522	0	4	0	6	0	11
5	5.877	2	5	3	10	5	11
6	3.902	0	3	0	3	2	7
7	4.993	1	1	1	2	1	4
8	6.308	2	4	2	5	3	11
9	6.750	3	4	3	5	6	9
10	8.899	2	5	3	6	6	11
11	12.535	3	3	4	5	5	10

3.3.3 UXO 4 – 110 lb airdrop

In contrast to previous UXOs revealing increasing relative buzz presence at larger distances, results for UXO 4 showed reduced foraging activity post-detonation at larger distances, while remaining more or less comparable over shorter distances (Figure 11). Results were based on very limited data for the impact assessments over the 6- and 12-hour timeframes, especially for the post-detonation period (Table 9).

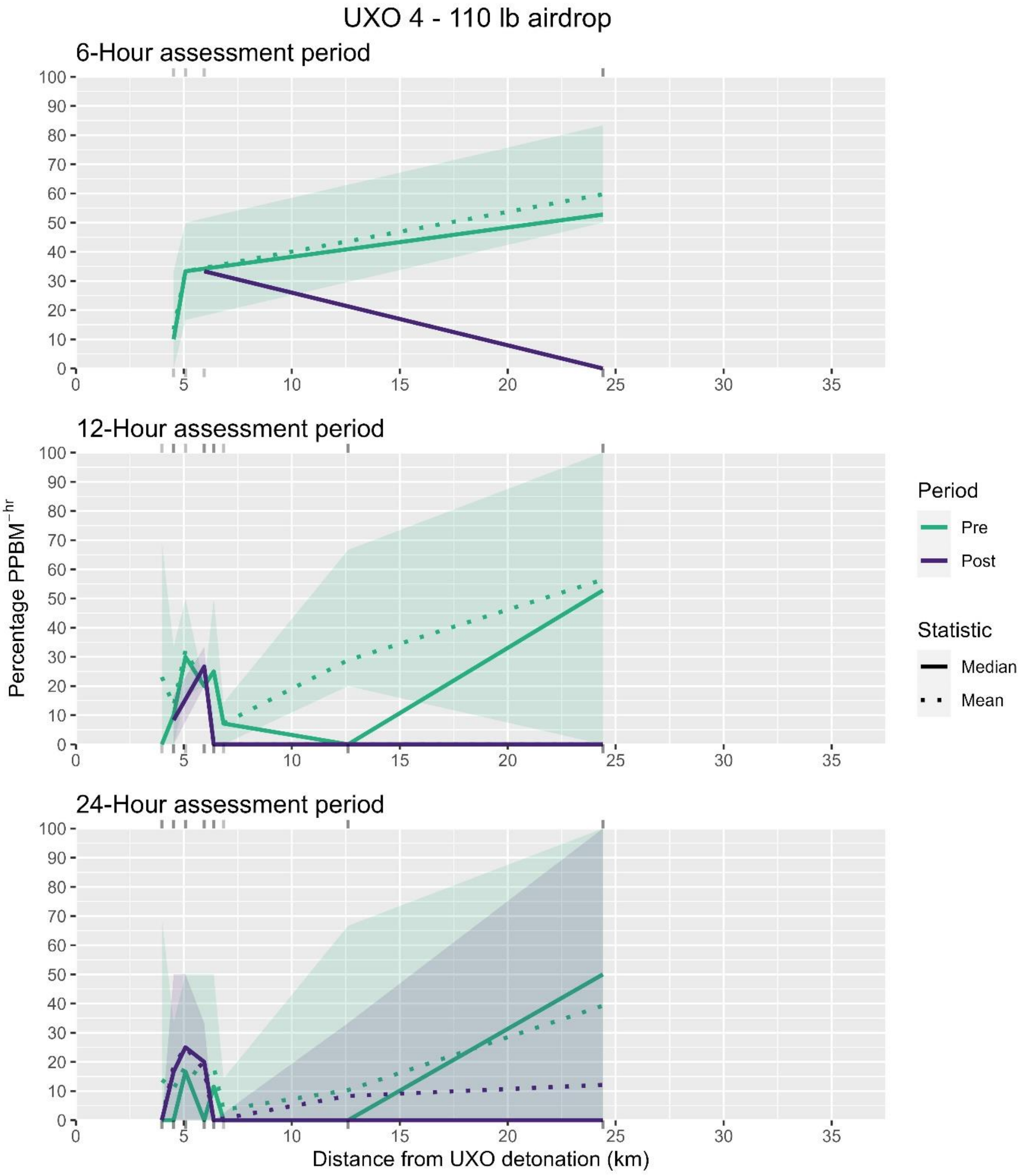

Figure 11. *Median (solid line) and mean (dotted line) porpoise foraging activity (expressed as the percentage of porpoise positive buzz minutes (PPBM) relative to the total number of porpoise positive minutes (PPM) per hour) during the pre-detonation (in green) and post-detonation periods (in purple), as determined across three assessment periods (6-, 12-, and 24-hours) in relation to the high-order detonation of UXO 4, a 110 lb airdrop. Minimum and maximum porpoise presence is represented by the shaded areas. Distances of monitoring locations relative to the UXO site is presented by the light grey rug ticks included above and below each plot. Note unequal monitoring efforts (see Table 9).*

Table 9. *Summary information of data underpinning the impact assessment for the detonation of UXO 4, a 110 lb airdrop.*

Monitoring location	***Distance to UXO (km)***	***Sample size 6-hour assessment***		***Sample size 12-hour assessment***		***Sample size 24-hour assessment***	
		Pre	***Post***	***Pre***	***Post***	***Pre***	***Post***
2	24.407	4	1	6	2	15	11
4	4.526	4	0	4	2	8	9
5	5.942	0	1	1	2	5	5
6	3.981	0	0	3	0	5	1
7	5.074	2	0	3	0	7	2
8	6.385	0	0	2	1	4	2
9	6.8340	0	0	2	0	4	0
11	12.607	0	0	3	1	10	7

4. Discussion and Conclusions

The potential impacts of UXO explosions on individual porpoises can be divided into three broad categories, namely: a) physical trauma or injury from the blast, causing immediate mortality or reducing an individuals' long-term fitness, b) auditory impairment resulting in temporary or permanent hearing loss, and c) behavioural change, including displacement, altered movement patterns and disturbance to important behaviour such as foraging, resting and reproduction (von Benda-Beckmann et al. (2015). Studies presenting information on UXO detonation impacts on porpoise auditory injury and trauma are discussed in Sections 4.3 and 4.4, respectively. The focus of the current study was on behavioural impacts, which will be discussed in the Sections 4.1 and 4.2.

4.1 Porpoise presence

The current study is the first to explore behavioural responses of porpoises to high-order UXO detonations. No empirical data were available on porpoise response to underwater explosions from UXO detonations prior to this work (Aarts et al., 2016).

The results indicate that short-term effects occur in relation to UXO clearance activities. For the heaviest UXO in particular, the impact was especially clear, with decreased median and mean detection rates after detonation, especially at shorter distances from the explosion location. In contrast, maximum detection rates substantially increased at greater distances, particularly when assessed over longer time periods. Combined, these two patterns may indicate that porpoises are deterred from nearer the explosion site with, over time, displacement movements to areas further away. Although a bigger short-distance impact could be expected for a heavier UXO, the baseline porpoise detection rate prior to detonation was also higher compared to the short-distance baseline presence for the other UXOs. For the 2018 UXOs, this may be related to fact that the time period between the cessation of piling (21st May 2018) and detonation of UXO 1 (1st June 2018) was the longest of the UXOs considered here.

Porpoise detection rates were, in general, lower both before and after the clearance of UXOs 2–4. Although more comparable porpoise detection rates were found between pre- and post-detonation periods, a post-detonation increase was also present for UXO 2, and was more obvious for the 12- and 24-hour assessment periods, while maximum relative porpoise presence also shifted from higher occurrence pre-detonation to higher presence post-detonation at shorter distances. No clear negative impact was observed for UXOs 3 and 4.

It is unclear what the consequences are to individual porpoises of the apparent localised avoidance and displacement behaviour. This will largely depend on the importance of the area they are leaving. For example, if these represent good foraging areas, avoidance may reduce the time and good habitat available for foraging. Additionally, there is the potential for increased energy expenditure when animals have to relocate to another area, and negative impacts may also occur if these are sub-optimal locations where there is reduced prey availability or increased inter- and intra-specific competition.

At present, the recommended impact range that should be applied when assessing the impacts of high-order UXO detonation on porpoises within English, Welsh and Northern Irish SAC boundaries, as stated in the Guidance for assessing the significance of noise disturbance against Conservation

Objectives of harbour porpoise SACs (England, Wales & Northern Ireland)' (JNCC, 2020), has been set as equal to the Effective Deterrence Range (EDR) of 26 km for piling of monopiles, which is based on the studies by Tougaard et al. (2013) and Dähne et al. (2013).

The results indicate that the various activities involved in high-order detonation of UXOs classed as 1,000 (UXO 1) and 500 lb (UXO 2), in absence of bubble curtains or other techniques mitigating noise propagation, may negatively impact porpoise detection rates, be it through a reduced actual presence or echolocation activity, within an area up to 15-20 km from the detonation site, irrespective of the impact assessment period. Although the results are based on relatively limited data, including for monitoring sites at distances >10 km from the explosions, this range is lower than the Effective Deterrence Range (EDR) of 26 km currently recommended, and results in a substantially smaller impact area (2,123.72 km^2 for a 26 km EDR *versus* 1,256.64 km^2 for a 20 km impact range).

Unfortunately, there were no coinciding broadband recordings of the UXO detonations incorporated in the current assessment. Consequently, the source levels of these explosions, as well as received noise levels or sound exposure level at the locations of the monitoring locations, were unknown and their potential for auditory injury could thus not be assessed from direct measurements. Although it would have been possible to explore this by applying similar approaches as used in some of the studies summarised in Section 4.3, this was considered beyond the scope of the present project. Nevertheless, according to BEIS (2020), a 500 and 1,000 lb bomb, are roughly equivalent to a 101 and 250 kg net explosive quantity (NEQ) UXO. Calculated using an unweighted peak sound pressure level (SPL) 202 dB re 1 µPa permanent threshold shift (PTS) onset threshold (Southall et al., 2019), the ranges within which PTS could be anticipated for UXOs of these charge sizes, as modelled for any location with the Southern North Sea SAC, were 7.16 and 9.71 km respectively (BEIS, 2020).

Finally, the current study was limited by the small amount of pre- and post-detonation times that were free of other UXO detonation or piling activities. It was therefore not possible to investigate impacts over longer assessment periods. Likewise, it was also not possible to fully explore impact duration of post-detonation occurrence or the times required for foraging activity to return to pre-detonation baseline levels.

4.2 Porpoise foraging

As mentioned in Section 4.1, relative porpoise presence was reduced post-detonation at shorter ranges and increased at greater distances. Of those minutes that porpoises were detected, the relative buzz presence was generally reduced post-detonation closer to the detonation, and increased at greater distances. The distance at which this transition occurred was at 5-10 km for UXO 1 (1,000 lb); for UXOs 2 & 3 (500 lb) there was no clear pattern in relative foraging activity at closer distances to the explosion, but buzz presence increased post-detonation from distances of approximately 10-15 km for both UXOs. It should be acknowledged, however, that data for several monitoring locations were absent or contained very low sample sizes for the pre- and/or post-detonation assessment periods, and especially for the 110 lb UXO, the limited data availability prevented full assessment of foraging activity.

The detection of foraging activity is based on the underlying assumption that buzzes are indicative of foraging. It is, however, known that click trains with very short ICIs are produced during both foraging and socialising activity (Clausen et al., 2010; Sørensen et al., 2018), but at present we cannot distinguish between these behavioural contexts. As a consequence, occasions that were designated as ‘foraging’ in this study likely also included non-foraging social activity, hereby over-estimating foraging occurrences by an unknown amount, which may also be variable through time (e.g. in relation to diurnal and tidal cycles) and in space.

Due to their small body size, high metabolic rate, and occurrence in cold-water habitats, porpoises require a high daily food intake relative to their body weight (Wisniewska et al., 2016; Rojano-Doñate et al., 2018). Porpoises showing avoidance movements from UXO detonations may need to compensate for this additional loss of energy, which may explain the post-detonation increases in foraging activity in areas at larger distances from the detonation activity to which they have (temporarily) relocated.

Although it is widely accepted that experiencing temporary threshold shift (TTS) and PTS may negatively impact porpoises’ foraging capability, no verified information exists on changes to foraging capability and success of porpoises suffering from temporary or permanent hearing loss. A study on a deaf captive common bottlenose dolphin (*Tursiops truncatus*), however, demonstrated decreased ability to acquire food due to slower reaction times and lower success rates (Wright, 2011). If foraging efficiency is compromised, this presumably will have a negative effect on an individual’s immediate fitness, and possible longer-term reproductive success, and survival.

4.3 UXO detonation impacts on porpoises – Summary of information from other studies

4.3.1 Impacts assessed through modelling

To a large extent, current knowledge on the impacts of UXO clearances on porpoises is based on source level measurements/back-calculations of specific detonations (or values derived for these using described scaling relationships), which are then modelled to propagate through local underwater environments, and ranges at which received levels reach certain thresholds computed to assess disturbance and/or auditory injury impact ranges. When combined with information on localised porpoise densities or in combination with individual-based modelling, the number of individuals impacted by these explosions can be inferred. The following section summarises several studies using such approaches.

Von Benda-Beckmann et al. (2015)

Von Benda-Beckmann et al. (2015) investigated the potential impacts from UXO detonation activities on porpoises in the Dutch continental shelf (DCS; the Dutch section of the North Sea). By integrating information on 88 cleared UXOs within a 1-year period (March 2010 – March 2011), and shallow water field measurements of detonations of six 1,000 lb and one 500 lb aerial bombs (with charge masses of 263 and 121 kg TNT equivalent, respectively; measurement of these larger UXO were lacking prior but required to complement existing data on small UXOs detonated in shallow waters) into a shallow-water propagation model, sound levels were estimated for explosions in shallow water and sound exposure maps produced for the entire DCS. The shallow-water modelling of sound levels across larger-distances was undertaken by combining an explosion model with a propagation model for shallow-water environments. When computing the unweighted sound exposure maps, broadband Sound Exposure Levels (SELs) were calculated for the near-surface layer (1 m from the surface) and the near-bottom layer (1 m from the bottom).

The generated exposure maps were subsequently compared to published temporary or permanent shift of the auditory threshold, known as TTS and PTS, respectively, as well as survey-based models of harbour porpoise seasonal distribution to obtain an estimate of the annual number of possible impact events (i.e. instances of a porpoise receiving sufficient sound exposure to cause hearing loss).

For TTS, an unweighted onset threshold level of 164 dB re 1 μPa^{2}s SEL was used, based on the results by Lucke et al. (2009) for porpoises exposed to single airgun sounds, as this sounds resembled UXO explosion sound better than the sounds porpoises were subjected to in other TTS studies available. An unweighted PTS onset threshold of 15 dB higher than the TTS onset was adopted, i.e. 179 dB re 1 μPa^{2}s SEL (following Southall et al., 2007). This level was considered as a limit below which PTS was deemed unlikely. As the risk of PTS increases with increasing SEL, an additional threshold was specified, presenting the threshold where the onset of PTS was very likely to occur. Based on post-mortem examination for porpoise hearing damage from blast injury (Ketten, 2004; see also Section 4.3.2), a higher PTS threshold of 190 dB re 1 μPa^{2}s SEL was also applied.

Measurements of the five 263 kg UXOs at different depths and distances up to 2 km from the detonations revealed that at the greatest distance, the SEL was 191 dB re 1 μPa^{2}s for the shallower recorder, and thus still 1 dB higher than the threshold, indicating that the impact range for the higher PTS onset is >2 km. Impact ranges across the total of 210 UXOs detonated in 2010 and 2011 (29 of which were outside the DCS), representing UXOs with charge masses between 10 to 1,000 kg (most at 125-250 kg; an assumed charge mass of 10 kg was applied for 62 UXOs for which the charge mass was unknown), revealed impact ranges of up to 11 km for TTS, up to 5 km for the lower PTS threshold, and up to 2 km for the higher PTS threshold.

Assuming that 50% of the porpoises were near the surface (between 0 and 2 m depth; Teilmann et al., 2013) and 50% were near the sea floor at the time of the explosion, the average number of porpoises impacted by a single detonation was 339 (‘TTS very likely’), 62 (‘PTS increasingly likely’; i.e. lower threshold), 15 (‘PTS very likely’; i.e. higher threshold), and 1 (blast wave ear trauma very likely; unweighted threshold of 203 dB re 1 μPa^{2}s SEL), respectively. Across the 88 explosions, the number of estimated impact events were 28,067, 5,451, 1,283, and 60 for the same impact classes respectively. Based on the average population size present in the DCS, the number of animals annually exposed to PTS represent 1.3 to up to 8.7% ‘Dutch population’.

Aarts et al., (2016)

Although the results from von Benda-Beckmann et al. (2015) revealed that underwater explosions likely resulted in hundreds to thousands of PTS events annually, the total number of individuals exposed could not be estimated. As such, building on the work by von Benda-Beckmann et al. (2015), Aarts et al. (2016) explored the number of individuals exposed to 88 UXO detonation activities on the Dutch continental shelf, and their frequency of exposure, under different animal movement scenarios (i.e. random dispersal *versus* site-fidelity).

Underpinned by empirical data of UXO detonation source levels, sound propagation modelling, application of noise threshold levels for TTS (164 dB re 1 µPa^{2}s SEL) and PTS (190 dB re 1 µPa^{2}s SEL), seasonal porpoise density maps, and agent-based modelling of porpoise movements, these authors estimated how different movement strategies affect the number of individual porpoises receiving temporary or permanent hearing loss due to UXO clearance. Results showed that 1,200 and 24,000 unique individuals would suffer PTS and TTS, respectively within a single year (respectively representing 0.50 and 10% of the estimated North Sea population of 230,000 individuals in 2005; Hammond et al., 2013). When porpoises were modelled to have high site-fidelity to a local area, it was estimated that fewer animals would be susceptible to PTS and TTS (1,100 (i.e. 0.47%) and 15,000 (i.e. 6.5%), respectively), but more individuals would be subjected to repeated exposures.

Based on the work by von Benda-Beckmann et al. (2015) and Aarts et al. (2016), the Dutch Ministry of Defence developed additional procedural guidance for clearances of UXOs, which included the compulsory usage of ADDs to mitigate the large number of animals potentially at risk of PTS (Ministry of Agriculture, Nature and Food Quality of the Netherlands, 2020). The requirement to consider using ADDs to mitigate UXO detonation within UK waters was already included in JNCC (2010), but has since become a compulsory element for detonations when predicted injury ranges are greater than 1 km from the detonation (JNCC, 2023).

BEIS, 2020

Modelling of behavioural disturbance, TTS and PTS impact ranges for six UXOs of different weights was undertaken by BEIS (2020), as part of their Habitats Regulations Assessment (HRA) to review whether consented offshore windfarms may cause a significant effect on the Southern North Sea SAC, hereby adversely affect the integrity of the SAC.

Noise modelling of UXO detonation (as well as other activities) was undertaken for three locations within the SAC and impact ranges for porpoises were assessed, while considering that animals were likely to swim away from the sound source rather than remaining stationary. The modelling scenarios incorporated UXOs of an explosive weight of 10–1,000 kg net explosive quantity (NEQ), corresponding to predicted peak SPL source levels ranging between 282–297 dB re 1 µPa at 1 m.

Potential impacts on porpoises were assessed using an unweighted peak SPL of 202 dB re 1 µPa and a porpoise frequency-weighted weighted SEL of 155 dB re 1 µPa^{2}s for permanent auditory injury (Southall et al., 2019) and an unweighted SEL of 145 dB re 1 µPa^{2}s for potential displacement. The latter was based on the study by Lucke et al. (2009) where a captive porpoise exposed to airgun noise showed consistent aversive behavioural reactions to sounds above this level.

Results from the noise modelling showed that noise levels from UXO clearance activities cause have the potential to cause permanent hearing injury to distances of 3.3–15.4 km, depending on the weight of the explosive.

When assessed for individual windfarms, taking into account local porpoise densities, the predicted number of individuals at risk of PTS from UXO detonation activities ranged from 25 to 1,657 porpoises, depending on the location of the windfarm and the weight of explosive charge, representing between 0.001% and 0.5% of the North Sea harbour porpoise Management Unit.

Salomons et al., 2021

Recently, acoustic measurements of the detonation of two UXOs with charge masses of 140 and 325 kg TNT equivalent were used to validate and improve the accuracy of model predictions of UXO detonation impacts on porpoises in the North Sea (Salomons et al., 2021). The resulting prediction model, extending the validation of the model used in the above-mentioned studies by von Benda-Beckmann et al. (2015) and Aarts et al. (2016) from 2 to 12 km from the explosion, was applied to determine PTS effect distances for porpoises.

To represent the hearing sensitivity of porpoises to noise-induced hearing loss, frequency-weighting for very high-frequency (VHF) cetaceans was applied (Southall et al., 2019). Both unweighted and frequency-weighted broadband SEL levels were computed and compared against several TTS and PTS onset thresholds specified in the literature. For unweighted SEL assessment, these were compared against levels were 'TTS is very likely', 'PTS is increasingly likely', and 'PTS is very likely' (164, 179 and 190 dB re 1 µPa^{2}s SEL, respectively; von Benda-Beckmann et al., 2015). For frequency-weighted levels, results were compared to VHF frequency-weighted TTS and PTS thresholds for exposure to impulsive noise (140 and 155 dB re 1 µPa^{2}s SEL, respectively; Southall et al., 2019).

Results indicated TTS effect distances of 10-20 km (unweighted) and 10-15 km (frequency-weighted) and revealed PTS ranges of 2-6 km (unweighted) and 2.5-4 km (weighted) for these detonations. When assessed as peak sound pressure level (peak SPL; rather than SEL) and compared to the unweighted peak SPL onset thresholds for TTS and PTS (196 and 202 dB re 1 µPa, respectively; Southall et al., 2019), the derived effect distance was comparable for PTS (4 km); the obtained range of 5-7 km for TTS, however, was considerable smaller.

Obviously, these results reflect the specific UXO charge mass and shallow-water propagation conditions considered in this study, and impact ranges may thus be different when assessing other scenarios. In any case, these authors conclude that "*porpoises are at risk of permanent hearing loss at distances of several kilometres from large explosives*" and thus recommend the application of noise mitigation or alternative detonation options resulting in reduced source levels (Salomons et al., 2021).

Robinson et al., 2022

Robinson et al. (2022) present the acoustic measurements of clearances of 54 UXOs using high-order detonation during pre-construction of the Moray East (17 UXOs) and the Naert na Gaoithe (37 UXOs) offshore windfarms off eastern Scotland, providing the largest dataset available to date. The average total charge masses of the UXO type plus donor charge varied between 2.5 and 295 kg TNT equivalent, with measurements made at distances ranging between 1.5–58 km for the detonation locations. Measurements of small scare charges (50–250 g) that are used as mitigation are also provided.

Received peak SPL and SEL were measured and presented as a function of distance from source, and compared to data from underwater propagation modelling using a source model and shallow-water propagation model. As in several of the other studies mentioned previously, these authors applied the unweighted peak SPL threshold of 202 dB re1 µPa and porpoise frequency-weighted SEL threshold of

155 dB re 1 µPa^{2}s (Southall et al., 2019) to assess PTS impact distances for UXO charge sizes ranging from 1.0 to 200 kg.

The results revealed PTS ranges of 1.6–7.1 km for peak SPL and 2.1–10.2 km for SEL assessments. Whilst also discussed in some of the other studies discussed here (e.g. von Benda-Beckmann et al., 2015; BEIS, 2020; Lepper et al., 2024), the study by Robinson et al. (2022) highlighted that uncertainty in effective charge size and in the propagation will increase the uncertainty on the exceedance ranges, and that modelling scenarios typically result in higher estimated received levels across distances compared to the actual measurements.

Sanderson et al. (2023)

The opportunistic study by Sandersons et al. (2023; including Supplementary Information Section 3) does not relate to controlled UXO detonations, but reports on the environmental impact of the explosion of the Nord Stream 1 and 2 pipelines in the Baltic Sea that were deliberately damaged on the 26th September 2022, using four coordinated explosions. Based on seismometer data, it was assumed that these explosions were caused by charge sizes of 500 kg TNT equivalent each. Based on the equations specified by Yelverton et al. (1973), estimates were calculated of the acoustic energy (in kPa·ms) as a function of the charge size and distance from the explosion for the surface layer as well as near the seabed (70 m depth).

These estimates were compared against various thresholds, including a ‘safe level’ (acoustic impulse of 30 kPa·ms) corresponding to a 10% risk of injury to lungs or intestines by human divers, and a 50% fatality rate (300 kPa·ms) (Lance et al., 2015), as well as VHF frequency-weighted TTS and PTS SEL thresholds (Southall et al., 2019). As actual sound measurements of the shock wave and hydrographical conditions were lacking, ranges to TTS and PTS thresholds for porpoises presented in Robinson et al. (2022) were extrapolated to a charge weight of 500 kg.

Depending on animal depth, the distance for the ‘safe level’ was 4 km (at the sea surface) to 18 km (at 70 m depth) from the explosion site, whilst fatal injuries were considered likely for individuals present within 1–4 km from the blast site. PTS impact ranges of up to 12 km were derived from the extrapolation, while temporary impact on hearing was predicted to occur up to 50 km away.

The authors acknowledge the uncertainty in the exact knowledge of the charge sizes and the exact locations of the charges, as well as substantial different environmental conditions (e.g. water depth, stratification), and therefore the obtained distances are considered associated with great uncertainty.

Lepper et al., 2024

Finally, Lepper et al. (2024) investigated the impact ranges of a 430 kg TNT equivalent Amatol British Mk 4-6 mine detonated using low-order (LO) deflagration and a 170 kg TNT equivalent Amatol (estimated 50-60% of original 340 kg) British Mk 1-4 mine cleared using traditional high-order (HO) detonation.

Back-calculated measurements of these detonations revealed source levels of 225.0 dB re 1 µPa^{2}s SEL and peak SPL of 241.8 dB re 1 µPa for LO UXO, and 245.9 dB re 1 µPa^{2}s SEL and peak SPL of 263.3 for the HO UXO, respectively. Measured received sound level data were combined with both SEL and peak SPL propagation loss profiles (i.e. propagation loss *versus* range), to estimate received porpoise frequency-weighted (i.e. adjusted for the VHF cetacean hearing group; Southall et al., 2019) SEL and unweighted peak SPL *versus* range for both these UXOs. The TTS and PTS thresholds for impulsive noise for the VHF group (Southall et al., 2019) was then applied to derive corresponding TTS and PTS impact ranges.

The estimated TTS ranges were 1.77 (LO) and 6.3 km (HO) for the unweighted peak SPL impact criteria, and 3.9 (LO) and 13.1 km (HO) for the frequency-weighted SEL impact criteria. Corresponding PTS impact ranges were 1.16 (LO) and 4.0 km (HO) for the unweighted peak SPL impact criteria, and 1.03 (LO) and 4.7 km (HO) for the unweighted peak SPL impact criteria.

Other assessments and reports

In addition to the studies summarised above, offshore wind developers have had assessments undertaken on their behalf to determine detonation impacts of the UXOs identified or expected in their respective development sites. Likewise, developers need to obtain a Marine License and a European Protected Species License before UXO clearance can commence. These require an assessment of the impacts of detonation activities and specification of mitigation measures to reduce potential impacts. Additionally, underwater noise measurements of pre-construction UXO clearances may also be required as part of the licensing conditions. As work in relation to these assessments is typically based on comparable literature, and/or presents similar modelling scenarios compared to the studies described above, these studies are not further discussed here. Nevertheless, there will be project-specific differences relating to UXO charges and corresponding source levels, choice and parameterisation of acoustic propagation models, applied TTS/PTS onset thresholds, and local environmental conditions to take into account.

4.3.2 Impacts derived from empirical data

The number of studies reporting on physical injury from UXO explosions on porpoises is limited. As previously mentioned, underwater explosions produce broadband sounds with very high peak source level and rapid rise times. The high amplitude underwater shock wave and the initial fast rise time in pressure can cause blast injuries when transmitted through the body, causing damage to tissue and gas filled cavities (Koschinski, 2011). In shallow waters, formation of gas bubbles within soft tissues may cause physical injury or death (BEIS, 2020). Evidence of blast trauma can be identified during post-mortems.

Ketten, 2004

Although not assessing the physical impacts of UXO detonation specifically, the study by Ketten (2004) "*addressed a critical US Navy need for explicit data to assign mitigation zones for ship shock and other underwater high velocity explosive tests and procedures*". To determine the onset for damage from blast trauma, 11 freshly dead porpoise specimens (as well as carcasses from other species; all live stranded and euthanised for medical reasons) were exposed to underwater blast pressures of 0-300 psi (Ketten, 2004). The individuals were subsequently subjected to a post-mortem examination, and their post-exposure CT scans compared to those made before exposure.

Overall, the results from this study revealed that the severity and type of impact depend on the mass of the individual as well as on received psi. In general, smaller individual demonstrated more severe blast trauma compared to larger animals when exposed to the same pressure, and there was a positive correlation between the severity of damage to multiple tissues and received pressure. Pressure-induced damage to the mid- and inner-ears were reported for porpoises, as well as all other tissue/organs assessed (bone, blubber, intestine, liver, kidney, brain, melon, lung, larynx, and jaw fat). Serious injuries were sustained by all specimens at high psi (100-300 psi), included liver disruption and haemorrhage, classic blast lung, laryngeal haemorrhage, segmental gut haemorrhages, cerebral ventricular inflation, intra-orbital haemorrhages, middle ear ossicular fractures, and inner and middle ear haemorrhage. The majority of these traumas were profound and considered to be likely mortal for exposures over 100 psi.

While some of the reported trauma can also be identified post-mortem in carcasses not exposed to blasting, the results of this study suggest that certain organs unique to cetaceans (e.g. blubber, jaw fats, and melon) show distinct damage patterns that may provide diagnostic markers in suspected exposure to pressure blast waves.

Based on the conducted experiments, while acknowledging that effect of various issues remained unclear (e.g. near-field vs far-field loading effect, exponential vs sinusoidal burst, and synergistic effects of rate of pressure increase, peak pressure, waveform and duration), the author concluded that for the smallest species (i.e. the harbour porpoise), safe margins are in the 10-12 psi received pressure range.

Siebert et al., 2020 & 2022

Recently, Siebert et al. (2020 & 2022) reported on post-mortem investigation of porpoises stranded along the German coast following a NATO ammunition clearance operation. During a period of four days, 42 British ground mines (type Mk 1-7) were cleared by means of blasting within a Marine Protected Area (a Nature Conservation Area designated for the conservation of porpoises, as well as other protected species and features[4]) in the Baltic Sea off Germany. In the following four months, 24 porpoises were found dead and examined for direct and indirect evidence of blast injury. In addition to immediate lethal damage, blast injury can also lead to sublethal changes, which can lead to reduced foraging and disorientation of porpoises, in turn increasing the risk of developing sickness, and being at risk of collisions with vessels or of bycatch.

Results suggested blast injury for eight of these individuals, evidenced by detected microfractures of the malleus, dislocation of middle ear bones, bleeding, and haemorrhages in the melon, lower jaw and peribullar acoustic fat. In addition, signs of blast injury were also found in one bycaught porpoise, as well as one individual with blunt force trauma. The causes of death of the remaining 16 individuals varied (14x) or were unclear (2x).

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[4] The Fehmarn Belt Nature Conservation Area. https://www.bfn.de/en/fehmarn-belt-nature-conservation-area.

Finally, these authors stated that, whilst regulation exists in Germany to mitigate piling noise impacts during the construction of windfarms, whereby the maximum threshold of 160 dB re 1 µPa^{2}s SEL at a distance of 750 m cannot be exceeded, no legal obligatory UXO noise mitigation currently exists despite the presence of evidence for hearing impairment and blast effects that are more severe than for pile-driving.

Overall, limited information is available on the impacts of controlled high-order detonation of UXO on harbour porpoise (*Phocoena phocoena*). However, in general, modelled auditory impacts and observed pathological noise-induced trauma range in severity, depending on a variety of factors including:

- distance of the animals from the detonation,
- the UXO charge,
- the frequency of repeated UXO detonations, and
- environmental conditions influencing underwater sound propagation (e.g. water depth, sediment substrate).

4.4 Future direction

Numerous further UXO detonation campaigns are expected to occur in future offshore windfarm development sites throughout UK waters, including within SACs, as well as the wider North Sea. From the recent UK Government statement and JNCC guidelines (UK Government, 2022; JNCC, 2023; developed with other UK Statutory Nature Conservation Bodies), it is clear that there is increased focus on low noise alternatives (e.g. deflagration, or other low-order detonations) for future UXO clearance. Deflagration is considered to lead to reduced environmental impact from noise, such as reduced risk of injury or death to marine mammals and other fauna. Results from deflagration test trials in a flooded quarry revealed reductions in peak SPL and SEL by about 20 dB, with higher reductions feasible for large UXO sizes (Robinson et al., 2020). The latter was demonstrated in a study measuring high- and low-order detonations of six historic mines in Danish waters. Despite a larger charge mass for the mines cleared using deflagration, peak SPL and SEL were also roughly 20 dB lower than for the high-order explosions (Lepper et al., 2024). For deflagration, the acoustic output appeared predominantly related to the deflagration charge with little or no contribution from the historic UXO detonation or deflagration combustion process. Although low-order detonation alternatives revealed substantial reduced noise outputs compared to high-order clearances, the acoustic levels of deflagration still represent a significant noise source, with levels comparable to that of piling activities (Lepper et al., 2024 and references therein).

The crude impact range derived in the current study is smaller than the specified EDR of 26 km, which is based on piling operations (JNCC, 2020). Future studies may provide additional insights in the spatio-temporal presence and foraging activity of porpoises in relation to high-order UXO detonation campaigns. Additionally, it can be anticipated that behavioural impact ranges will decline due to reduced source levels from deflagration. Information on behaviour impact ranges in response to deflagration is currently lacking but can be assessed using ongoing and future UXO clearance and porpoise monitoring programmes.

4.5 Conclusions

In preparation of ScottishPower Renewables’ (SPR) East Anglia ONE (EA1) construction, a total of 81 identified UXOs were cleared using-high order detonation. The current study is the first to provide quantitative data on the behavioural response of harbour porpoises to high-order UXO detonation activities for four of these UXOs, a 1,000 lb, two 500 lb, and a 110 lb airdrop.

Whilst based on a limited number of UXOs, detonated in-between other activities (e.g. pin-piling, shipping), negative impacts (i.e. reduced porpoise detection rates and foraging activity) were observed up to distances of 15-20 km. Increased detection and buzz rates were detected at distances beyond this range, especially when assessed over longer time periods, suggesting displacement of individuals post-detonation.

While impacts from the explosions could not be disentangled from UXO-related activities (increased vessel presence, and pre-detonation acoustic deterrent device activation and detonation of fish scaring charges), these results show that impacts of the detonation activities as a whole can have wide-spread impacts on porpoise presence and foraging activity.

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