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Dredging displaces bottlenose dolphins from an urbanised foraging patch

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ABSTRACT

The exponential growth of the human population and its increasing industrial development often involve large scale modifications of the environment. In the marine context, coastal urbanisation and harbour expansion to accommodate the rising levels of shipping and offshore energy exploitation require dredging to modify the shoreline and sea floor. While the consequences of dredging on invertebrates and fish are relatively well documented, no study has robustly tested the effects on large marine vertebrates. We monitored the attendance of common bottlenose dolphins (*Tursiops truncatus*) to a recently established urbanised foraging patch, Aberdeen harbour (Scotland), and modelled the effect of dredging operations on site usage. We found that higher intensities of dredging caused the dolphins to spend less time in the harbour, despite high baseline levels of disturbance and the importance of the area as a foraging patch.

1. Introduction

The exponential growth of the human population and the increasing development of industrial activities worldwide often involve large scale modifications of the environment, with associated construction periods (McKinney, 2002; Magle et al., 2012). In the marine environment, the installation of renewable energy devices (Inger et al., 2009) together with more classic forms of offshore energy exploitation (e.g. seismic exploration, or trenching for oil and gas pipelines) (de Groot, 1982; Wardle et al., 2001) has recently raised a lot of attention. However, coastal areas have a longer history of urbanisation activities, such as land reclamation and harbour construction or enlargement (Davenport and Davenport, 2006; Jefferson et al., 2009).

The effects of construction activities on wildlife populations are largely unknown. The potential concerns range from the noise introduced into the environment (Popper et al., 2003; Weilgart, 2007) to the release of toxic compounds (Blus et al., 1993; Hedge et al., 2009) and, in general, the modification of the natural state of the habitat (Johnson et al., 2005). Animals have been observed to leave areas subject to intense construction activity (Frid and Dill, 2002; Brandt et al., 2011), and even modify their habitat use on the long-term as a result of industrial development (McLellan and Shackleton, 1988; Sawyer et al., 2006). However, the relevance of these responses for the management and conservation of populations is unknown. The disruption of animal behaviour might compromise an individual's energy balance and, consequently, its vital rates (e.g. its ability to reproduce). When repeated across most individuals in a population, this can translate into a change in the population dynamics (National Research Council, 2005; New et al., 2013). Long-term population effects are therefore likely to depend on the overall ecological landscape that individual animals experience (Gill et al., 2001; Frid and Dill, 2002; Bejder et al., 2009). The importance of the disturbed area for the population, the duration and characteristics of the disturbance source, and the trade-off between the perceived risk and the alternative habitat patches available will all contribute to determine the biological significance of any impact. For instance, we expect healthy individuals in a rich environment to avoid an area they perceive as risky. On the other hand, animals might be forced to use a disturbed patch if food is limited, the area is especially important, or their physical condition is poor (Gill et al., 2001; Frid and Dill, 2002; Beale and Monaghan, 2004b; Bejder et al., 2006).

With a total of 1481 vessels operating worldwide, the capacity of the dredging industry has increased by up to 75% since 2000 (International Association of Dredging Companies (IADC), 2011). This rapid expansion was mainly driven by the needs imposed by trade, demography, climate changes, energy, defence, and tourism (International Association of Dredging Companies (IADC), 2011).

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The construction of new harbours and the maintenance or enlargement of existing ones is topical given the increasing size and number of vessels using the oceans, and the growing needs of the offshore energy industry (Hildebrand, 2009).

Previous studies have focused on the effects of dredging on marine invertebrates and, to a lesser extent, on fish (Wilber and Clarke, 2001). The mobilisation of toxic compounds (Sturve et al., 2005; Hedge et al., 2009), the alteration of substrate composition and dynamics (Guerra-Garcia et al., 2003; Cooper et al., 2011), and the suspension of large quantities of sediments (Lewis et al., 2001) have all been documented to lead to changes in the nearby ecological communities. However, little is known about the potential effects on large marine predators. It is expected that marine predators may respond behaviourally to the elevated noise levels generated during dredging operations. Dredging noise is concentrated predominantly at low frequencies (<1 kHz), with sound pressure levels potentially greater than 180 dB re 1 μPa at 1 m (Thomsen, 2009). Detection is predicted at distances up to 6 km, depending on local conditions (Thomsen, 2009). While low-frequency noise is unlikely to mask the echolocation signals of odontocetes, it has the potential to affect cetacean communication (Weilgart, 2007) and to be perceived as a risk, thus eliciting avoidance responses (Pirotta et al., 2012). Animals' behaviour may also be affected by the increased level of shipping movements, the use of side-scan sonar and the reduced visibility associated with sediment suspension (Morris et al., 1985). Finally, predator habitat use may change as a result of the responses of prey to both noise and water turbidity (Wilber and Clarke, 2001; Popper et al., 2003). In their controlled exposure study, Richardson et al. (1990) observed bowhead whales changing their behaviour when exposed to simulated construction noise, although responses were variable. The ten year-long abandonment of Guerrero Negro Lagoon (Mexico) in the 1960s by grey whales was also linked to the shipping and dredging resulting from an evaporative salt works project (Bryant et al., 1984). In all studies, however, boat traffic and dredging activities have been confounding factors. In the absence of any conclusive evidence on the response of large predators to dredging, a precautionary approach has been generally adopted and mitigation measures put into place to minimise risks (Jefferson et al., 2009).

Here we assess the response of common bottlenose dolphins, *Tursiops truncatus*, (hereafter 'dolphins') to harbour dredging in a recently established foraging patch on the east coast of Scotland by looking at the patterns of attendance to the area over subsequent years of visual sampling. For the first time, the effect of dredging activities was tested as an added factor to normal harbour activities.

2. Materials and methods

2.1. Study system

Our study focused on the population of approximately 227 (95% highest posterior density interval: 162–384) bottlenose dolphins that range over the north-eastern coast of Scotland (Cheney et al., 2013). While in the past these dolphins tended to primarily use the inner portion of the Moray Firth (Fig. 1), a range expansion has been documented in recent years (Wilson et al., 2004), and since c. 1992 Aberdeen harbour has progressively become a stable foraging patch (Wilson et al., 2004; Stockin et al., 2006). In this area, dolphins tend to occur between the two outer piers of the harbour (Fig. 1), where they appear to feed close to the surface, in association with the tidal front created by the freshwater flow of the Dee River. The animals might use the front to aid in prey capture as they do at other locations in north-east Scotland (Mendes et al., 2002; Bailey and Thompson, 2010). Some temporal and tidal patterns of usage of the harbour have been observed in the past (Sini et al., 2005; Stockin et al., 2006), but their stability over time has yet to be demonstrated.

Aberdeen harbour is one of Europe's most active ports, due to its role as a supporting centre for the oil and gas industry in the North Sea. The harbour also sustains high levels of trade, fishing, transport and tourism, with 7784 vessel arrivals in 2011 (Aberdeen Harbour Board, 2012). 70% of this traffic is associated with the offshore oil industry and therefore involves large ships (Aberdeen Harbour Board, 2012). Most of the remaining traffic is also represented by large ships, although smaller sized boats (e.g. tugboats) are regularly present in the area. Boats transit through the channel throughout the day (e.g. http://www.aberdeen-harbour.co.uk/shipping/arrivals.jsp?type = arrivals). The importance of Aberdeen harbour is predicted to increase in the near future with the development of renewable energy on- and offshore (Aberdeen Harbour Board, 2012). This expansion will require large investments in infrastructure and consecutive intense construction operations, some of which are already being carried out. The current depth of the seabed in the area varies between less than 1 m near the shore to a maximum of 10 m in the middle of the channel.

2.2. Data collection

Land-based observations were conducted in April–June 2008, May–June 2009, and June–September 2012 from an elevated location on the shoreline (57.140°N, 2.058°W; Fig. 1). Data were collected by trained observers doing one or two three-hour shifts per day (limiting observations to good weather conditions, i.e. good visibility and Beaufort <3). Each observer only carried out one shift per day, in order to reduce the risk of fatigue. Visual scan sampling every 15 min was used to record the presence of dolphins (Altman, 1974), and covered a radius <1 km around the observation point. Given the small size of the study area (Fig. 1), it was assumed that dolphins were not missed when they were in the harbour. If dolphins were sighted, additional 5-min scans were performed. During these scans, the number of dolphins present and the number and type of boats were recorded. Moreover, the presence or absence of active dredging operations in the harbour during each scan was noted. The dredgers were only present in the channel when they were operating, and on these occasions they were visibly active. Dredging activities took place in the end of May-first half of June 2008 and 2009 to maintain the navigation channel, while in mid July-mid September 2012 the channel underwent more substantial widening and deepening as part of the planned harbour expansion.

2.3. Statistical analysis at a day level

We first focused on the day-level occurrence of the dolphins, measured as the proportion of minutes the observers detected dolphins in the harbour over the total number of minutes spent scanning the site per day. This proportion was modelled as a function of explanatory variables using a binomial Generalised Linear Model (GLM) with logit link. The explanatory variables included the proportion of scans during which dredging activity was recorded, the median, maximum and minimum number of other non-dredging related boats per scan during each day, the median and maximum size of the dolphin groups, the median tide level (obtained for Aberdeen harbour from the UK Tide Gauge Network site of the British Oceanographic Data Centre; http://www.bodc.ac.uk/data/online_delivery/ntslf/processed/) and the mode tidal state. The latter was defined as a categorical variable with four three-hour long states (low, rising, high, and falling tide) determined as 1.5 h on either side of high (high) and low (low) tide, with the remaining

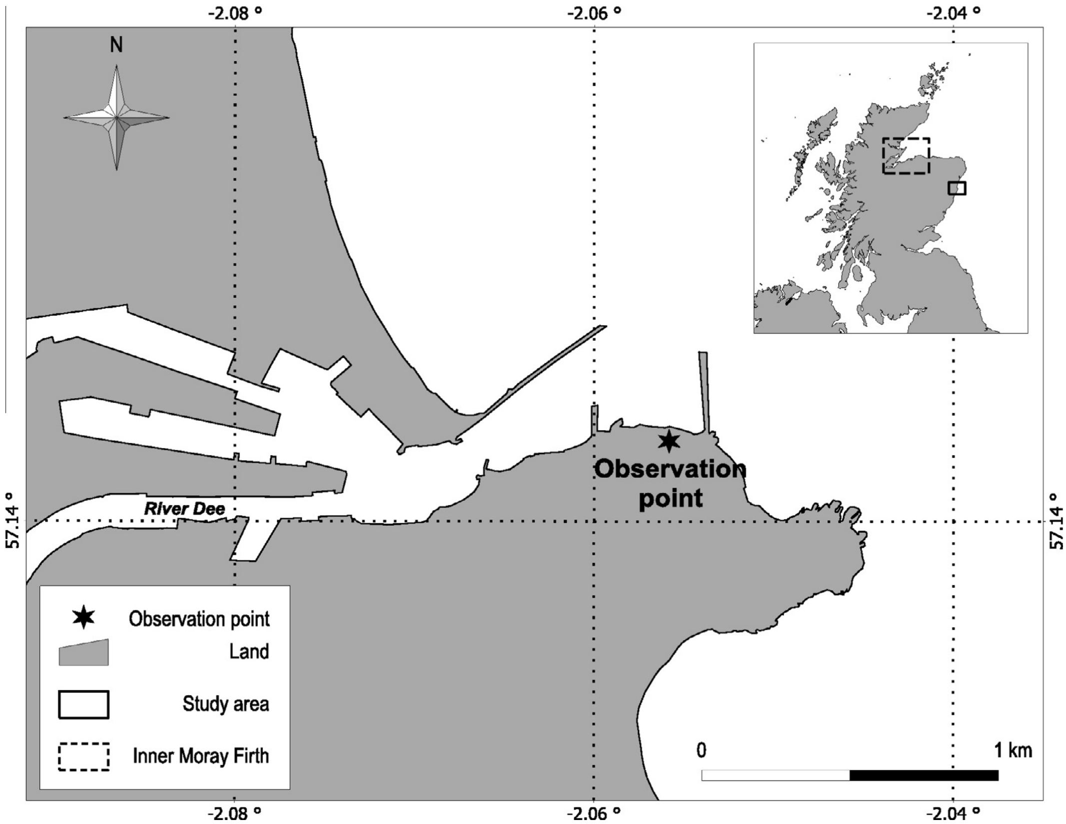

Fig. 1. Map of Scotland showing the location of Aberdeen harbour and the observation point.

time from low to high tide categorised as rising tide and from high to low tide as falling tide. The year was also included, together with its interaction with the proportion of dredging, in order to allow the effect of dredging to vary between years. An alternative model included the presence/absence of dredging as a categorical variable instead of the proportion of dredging time. The absence of multicollinearity between the explanatory variables was verified using the variance inflation factor (VIF). The models were quasi-likelihood estimated to account for any overdispersion in the residuals. As a result, the QAIC model selection criterion was used to identify the most parsimonious subset of predictors, following a stepwise procedure (Burnham and Anderson, 2002). Likelihood ratio Chi-square tests were finally used to assess the significance of the retained predictors.

2.4. Statistical analysis at a scan level

In addition to the day-level analysis, we carried out a scan-level investigation by looking at the presence/absence of the dolphins in each scan sample. A Generalised Estimating Equation (GEE) approach was used to fit a binary GLM and account for any temporal autocorrelation in the model residuals (Liang and Zeger, 1986). We used the date of sampling to define clusters of data points within which residuals were allowed to be autocorrelated (Liang and Zeger, 1986; Hardin and Hilbe, 2003). This relaxed the assumption of independence between scan-level presences and absences within each sampling occasion. The quasi-likelihood under the independence model criterion (QIC; Pan, 2001) was then used to select the most appropriate correlation structure for the residuals. Specifically, we compared an autoregressive (AR1) structure (the correlation declines as the lag between residuals increases), an exchangeable structure (the correlation is uniform within the cluster), and a working independence model (Liang and Zeger, 1986; Pan, 2001). In the latter, the correlation matrix is an identity matrix, but realistic standard errors are calculated using a robust sandwich variance estimator to account for the observed degree of autocorrelation in the data (Hardin and Hilbe, 2003). The presence/absence of dredging activity, the number of other boats, the hour of the day, the tide level, the categorical tidal state, and the interactions between year and dredging, tide level and tidal state were included as initial explanatory variables. The QICu model selection criterion was then used in a stepwise procedure to select the smallest subset of relevant predictors (Pan, 2001), whose significance was assessed with repeated Wald's tests (Hardin and Hilbe, 2003). The goodness-of-fit of the final model was evaluated using a confusion matrix, in which the binary predictions from the model were compared to the observed dolphin presence/absence, and expressed as the proportion of presences and absences correctly classified by the fitted model. The cut-off above which a predicted probability was classified as a presence was selected using a Receiver Operating Characteristic (ROC) curve (Zweig and Campbell, 1993). The area under the ROC curve (AUC) was also calculated as an additional measure of model performance (Zweig and Campbell, 1993). Finally, we tested whether the presence of dredging operations and the number of other boats transiting in the harbour affected the size of the observed dolphin groups. To this purpose, we only considered those scans when dolphins were present in the harbour and modelled the recorded group size as a function of the anthropogenic covariates in a Poisson GEE-GLM. The same model selection procedure used for the binary analysis was then repeated. All statistical analysis were carried out using the software R (R Development Core Team, 2012). The library geepack was used for the GEE analysis (Yan, 2010).

3. Results

Sampling effort covered 146 days across the three years (63 in 2008, 27 in 2009 and 56 in 2012), which corresponded to a total of 6223 scans. The temporal dynamics of dredging operations and dolphin attendance at the harbour in the three years of sampling are summarised in Fig. 2. While the first phase of the dredging activity in 2012 coincided with the dolphins leaving the harbour for approximately five weeks, the animals reappeared (although for a lower proportion of time) towards the end of the operations, when the dredging intensity was lower. In previous years, dolphins also seemed to spend less time in the area during dredging operations for harbour maintenance.

Model selection with QAIC for the day-level analysis retained the proportion of time dredgers were operating and the median number of boats per sample as relevant predictors of the proportion of time the dolphins spent in the area over the effort. Both covariates had a negative relationship with the response (Fig. 3). This model performed better than the model with dredging as a binary variable (ΔQAIC = 9). The two retained variables were also found to be significant under the likelihood-ratio Chi-square test (proportion of dredging: Chi-square = 5.9; degrees of freedom (df) = 1, $p = 0.01$. Median number of boats: Chi-square = 16.0; df = 1; $p < 0.0001$). Model residuals were overdispersed and the dispersion parameter was estimated to be 119. The VIF did not identify any issue with multicollinearity (all VIF values <5).

For the binary GEE-GLM analysis at the scan-level, a working independence model was preferred over the AR1 (ΔQIC = 517) and the exchangeable (ΔQIC = 529) correlation structures. The QICu model selection confirmed the day-level results and retained the presence of dredging and the number of other boats as negatively affecting the dolphins' probability of occurrence (Fig. 4a and b). The interaction between year, tidal state and tide level was also found to be a relevant predictor. The tidal states appeared to have a different relevance to the dolphins in different tide level conditions, i.e. as a function of the spring/neap tide cycle, and these relationships changed between years (Fig. 4c–e). The Wald's tests confirmed that dredging presence (Chi-square = 21.8; df = 1; $p < 0.0001$), the number of boats (Chi-square = 41.0; df = 1; $p < 0.0001$) and the interaction between tidal state, level and year (Chi-square = 16; df = 6; $p = 0.01$) were all significantly associated with dolphin probability of occurrence. The final model correctly classified 65.3% of the observations, and the AUC value was 0.705, suggesting a satisfactory fit of the model to the data. Finally, the QICu model selection procedure applied to the Poisson GEE-GLM did not retain either the presence of dredging activity or the number of other boats as affecting the size of the observed dolphin groups.

4. Discussion

Our results document a clear avoidance response of a marine predator to dredging activity in a highly urbanised foraging patch. Aberdeen harbour is one of the busiest ports in Europe, with boats transiting through the entrance channel throughout the day (Aberdeen Harbour Board, 2012). Given that boats have always been present since dolphins started using the harbour on a regular basis, individual animals are expected to show high levels of tolerance towards disturbance at this site (Bejder et al., 2009). The high food availability is also likely to outweigh any perceived cost of the disturbances associated with regular harbour activities. Nevertheless, we found dredging activity to affect dolphins' patterns of attendance. Specifically, dolphins spent proportionally less time in the harbour as the intensity of dredging activity (expressed as the proportion of time operations were carried out) increased. The effect was consistent across years, and the larger effect size estimated during the first phase of operations in 2012 (with dolphins leaving the harbour completely for approximately five weeks) can be ascribed to a higher intensity of dredging in this period (the proportion of dredging time repeatedly reached the value of 1, versus a maximum value of 0.6 in 2008 and 2009). Dolphin response was also detectable at a smaller temporal scale, i.e. at the scan-level

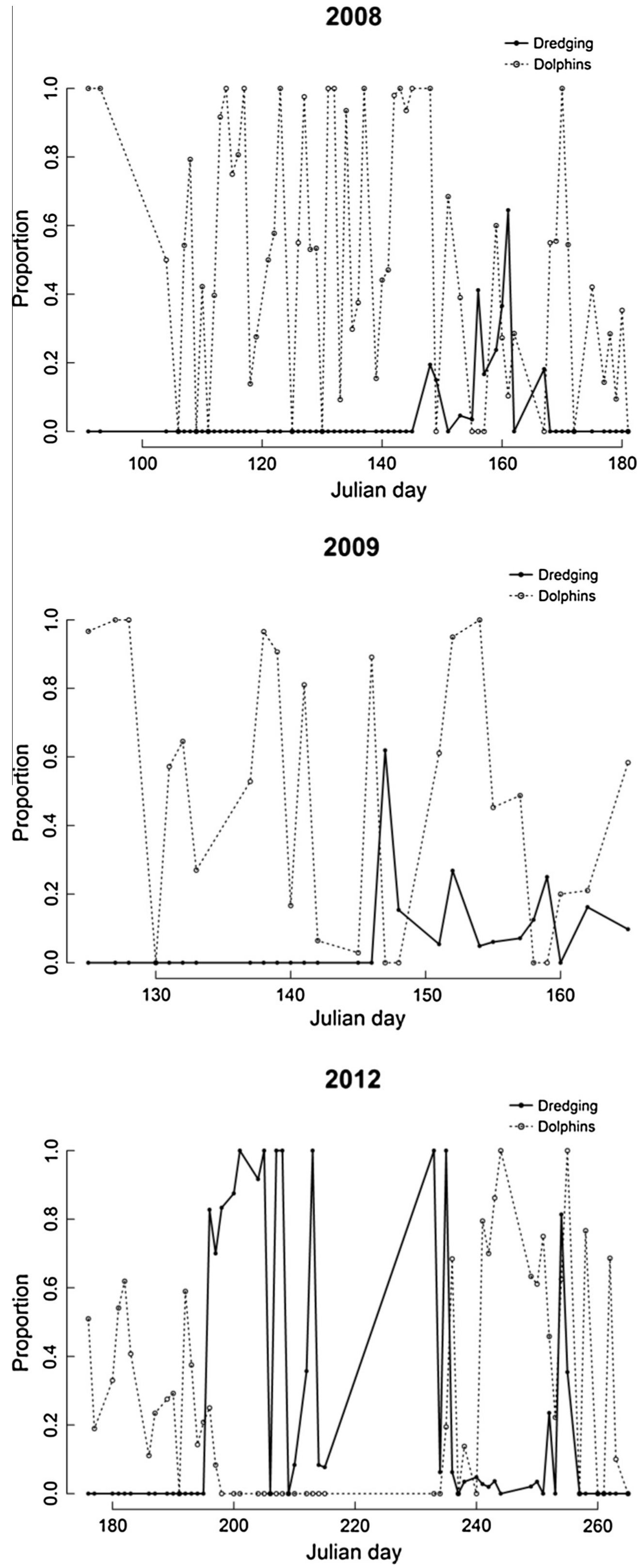

Fig. 2. Proportion of time during which the dolphins and the dredging boats were observed in Aberdeen harbour across each year.

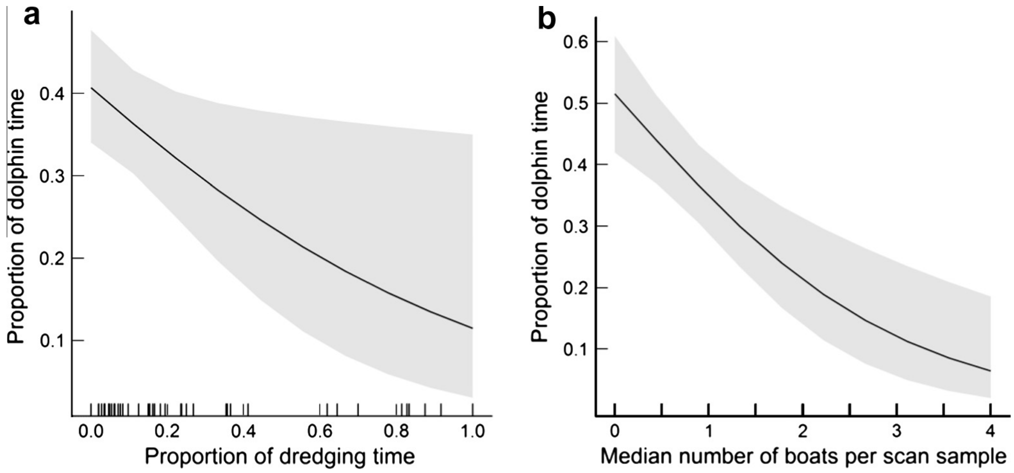

Fig. 3. Results of the binomial GLM for the proportion of time dolphins were observed in the harbour during each sampling occasion. (a) Estimated relationship between the response variable and the proportion of time that dredgers were operating. (b) Estimated relationship with the median number of boats per scan sample during each sampling occasion. The shaded areas represent the 95% confidence intervals around the estimated relationships, and the rug plot shows the actual data values.

there was a lower probability of dolphins being present when dredging boats were operating. The number of other boats present was included in the models, so the recorded effect was disentangled from the disturbance by regular traffic. The absence of multicollinearity between the two variables also confirmed that the effects were not confounded. Conversely, the size of the observed groups was not affected by the presence of dredgers, suggesting that all individuals in a group were more likely to leave the area during dredging operations.

The observed response to dredging activity despite the high baseline level of anthropogenic disturbance can be interpreted as an acute reaction to a stimulus that is not regularly experienced by the dolphins. While the movement of commercial boats in and out of the harbour is highly constrained and therefore predictable (i.e. the perceived risk is reduced), dredging noise is a discontinuous and rarely occurring stimulus, which is likely to elicit a response analogous to the risk of predation (Frid and Dill, 2002; Beale and Monaghan, 2004a). The irregular nature of the disturbance could also explain the absence of any apparent changes in tolerance across the years. Alternatively (or, most probably, in combination), the high noise levels and the suspended sediment could have an impairing effect on dolphin sight and communication abilities (Morris et al., 1985; Jefferson et al., 2009). The dolphins would therefore face a trade-off between the quality of the food resources available, the importance of this location during specific times, and the increased stress levels and/or energy required to successfully capture prey when dredging boats are operating (Frid and Dill, 2002). This could lead them to leave the area during periods of high dredging intensity to other patches where they can forage more efficiently, only returning to the harbour when the proportion of dredging time decreases. Finally, dredging operations could also affect the behaviour of dolphin fish prey (Wilber and Clarke, 2001), thus temporarily compromising the quality of the foraging patch.

The Dee River is an important salmon river in Scotland, and salmon plays a large role in the ecology of this population (Lusseau et al., 2004; Bailey and Thompson, 2010). The movement of fish in and out of the river could therefore be crucial in determining when and how the dolphins respond to disturbance. While we expect tides to influence salmon movements, the modelled relationships between dolphin occurrence and the tidal variables and their variation over time suggest that accurate information on the mechanistic process behind the patterns of usage of this area is still lacking. This conclusion was reinforced by the high degree of overdispersion estimated in the day-level GLM, which indicates that a large amount of the observed variability remained unexplained by the model, and therefore that relevant explanatory variables are missing from its current formulation. Alternatively, we could conclude that the usage of this recently established patch has yet to stabilize into predictable patterns. Whatever the cause of the observed variability, this makes it harder to predict any potential behavioural response in the future.

Interestingly, the presence and number of other boats was also found to affect dolphin occurrence. The scan-level analysis showed that individuals responded to high levels of traffic in a dynamic manner, leaving and coming back to the harbour according to the number of boats transiting, which was then translated into a lower proportion of time spent in the harbour over an entire sampling occasion when the median number of boats per scan was higher. Hence, dolphins seem to accommodate for boat traffic, which was expected considering that these disturbances were a pre-existing condition of the site when the animals started to use it. This finding implies that increased levels of boat traffic resulting from the expansion of the harbour may also modify the dolphins' long-term patterns of use.

The present study is the first to conclusively link the occurrence of dredging operations to a quantifiable behavioural response by a marine predator, providing essential information for the management of future construction in the coastal area. Dredging operations associated with the development, maintenance and extension of harbours are predicted to increase in scale and frequency over the next years as a result of the growing exploitation of offshore energy resources together with the rising levels of boat traffic (International Association of Dredging Companies (IADC), 2011). While our results offer a basis for the design of appropriate mitigation measures to prevent behavioural impacts on key marine species (Jefferson et al., 2009), future studies should aim at characterizing the exact mechanism by which dredging affects dolphin occurrence. Moreover, the biological significance of the observed short-term behavioural responses remains to be understood (New et al., 2013). For Aberdeen harbour, information on the presence and distance of alternative foraging patches, the importance of the area during exposure times and the proportion of the population normally using the site is currently unavailable (Cheney et al., 2013). However, population-level consequences are more likely to arise when populations are already facing other ecological constraints in their landscape (Gill et al., 2001). Hence, the severity of dredging impacts should be ranked during the Environmental

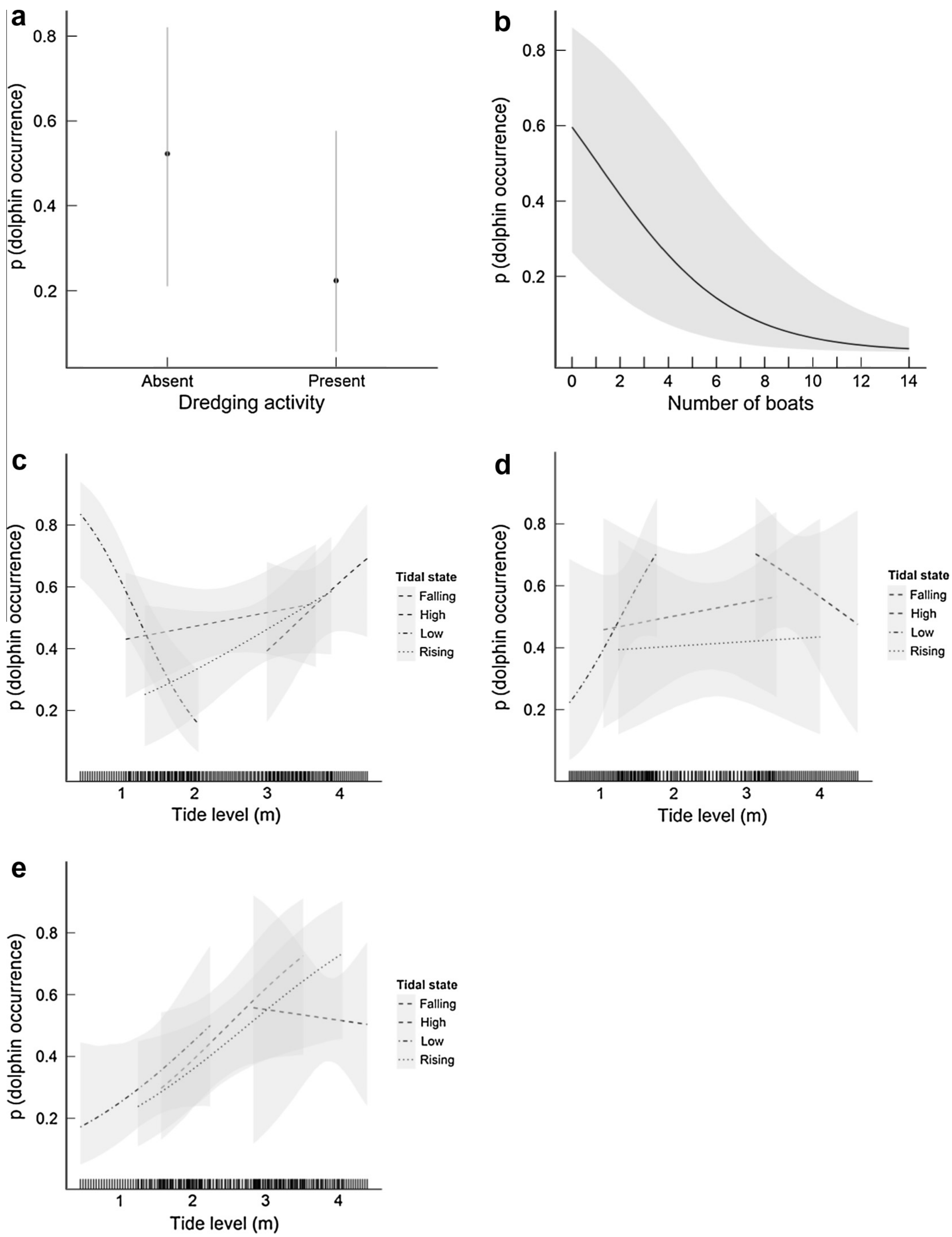

Fig. 4. Results of the binary GLM with Generalised Estimating Equations for the presence/absence of dolphins in each scan sample. (a) Estimated relationship between the response variable and the presence of dredging operations. (b) Estimated relationship with the number of other boats in the area. (c), (d) and (e) Estimated relationships with the interaction between tidal state and tide level in 2008, 2009 and 2012, respectively. The shaded areas represent the 95% confidence intervals around the estimated relationships, and the rug plot shows the actual data values.

Impact Assessment depending on the ecology of the exposed populations.

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