Marine Pollution Bulletin xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Review

A review of crustacean sensitivity to high amplitude underwater noise: Data needs for effective risk assessment in relation to UK commercial species

Nathan J. Edmonds *, Christopher J. Firmin, Denise Goldsmith, Rebecca C. Faulkner, Daniel T. Wood

Centre for Environment, Fisheries and Aquaculture Science (CEFAS), Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK

ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form 4 May 2016
Accepted 5 May 2016
Available online xxxx

Keywords:
Lobster
Crab
Fisheries
Noise
Piling
Seismic

ABSTRACT

High amplitude anthropogenic noise is associated with adverse impacts among a variety of organisms but detailed species-specific knowledge is lacking in relation to effects upon crustaceans. Brown crab (*Cancer pagurus*), European lobster (*Homarus gammarus*) and Norway lobster (*Nephrops norvegicus*) together represent the most valuable commercial fishery in the UK (Defra, 2014). Critical evaluation of literature reveals physiological sensitivity to underwater noise among *N. norvegicus* and closely related crustacean species, including juvenile stages. Current evidence supports physiological sensitivity to local, particle motion effects of sound production in particular. Derivation of correlative relationships between the introduction of high amplitude impulsive noise and crustacean distribution/abundance is hindered by the coarse resolution of available data at the present time. Future priorities for research are identified and argument for enhanced monitoring under current legislative frameworks outlined.

Contents

1. Introduction

Research on the general effects of underwater noise on marine life has been carried out for many years (e.g. Payne and Webb, 1971). Marine mammals are the most studied group although effects upon fish and reptile species have also been investigated (Williams et al., 2015). Relatively few studies have been conducted on invertebrates, including crustacean species, and little is known about the effects of anthropogenic underwater noise upon them (Hawkins and Popper, 2012; Morley et al., 2013; Williams et al., 2015). While thresholds for harmful sound exposure levels have been derived for marine mammals (Southall et al., 2007; Lucke et al., 2009) and estimated for fish (Popper et al., 2006; Halvorsen et al., 2011), no such injury criteria have been developed for marine invertebrates. Variable documentation of units and measurement methods in the literature, make firm conclusions difficult and can lead to subjective interpretation of findings.

Shellfish are the UK's most valuable (£/tonne) fishing resource (Defra, 2014). In economic terms, brown crab (*Cancer pagurus*), European lobster (*Homarus gammarus*) and Norway lobster (*Nephrops norvegicus*) are the most important, comprising 60% of the market price of all UK landed shellfish in 2011 (Elliott et al., 2013). Despite the high economic value of these crustaceans, very little is known about the potential for individual or population level effects arising from introduction of underwater noise and associated particle motion. A mismatch exists between the requirements of fishing industry

* Corresponding author.
E-mail address: nathan.edmonds@cefas.co.uk (N.J. Edmonds).

http://dx.doi.org/10.1016/j.marpolbul.2016.05.006
0025-326X/© 2016 Published by Elsevier Ltd.

stakeholders and the availability of robust scientific data at the present time. Given the high value of the industry, stakeholders are increasingly keen to resolve uncertainty around effects of high amplitude anthropogenic noise upon target stocks. In particular, offshore windfarm construction is expanding rapidly with twice as much operating capacity consented during 2014/2015 as within the preceding 15 years (Renewable UK, 2015). In reducing uncertainty of impacts associated with such developments, we review current understanding of crustacean sound detection, sound-based communication and physiological effects of sound upon crustaceans to determine knowledge gaps and known sensitivity of commercially exploited UK stocks.

2. High amplitude noise sources

Loud (high amplitude) impulsive, low frequency, anthropogenic noise sources are of particular relevance owing to their high energy characteristics and ability to propagate over large distances. Loud underwater noise is typically produced by seismic surveys, piling, military sonar[1] and explosions.[2] As examples of impulsive sound, these are known to be much more harmful than a continuous noise (Khopkar, 1993). Impulsive sounds are characterised by a relatively rapid rise from ambient pressure to the maximal pressure value (Southall et al., 2007). Specific sound characteristics arising from these activities are variable and fundamentally influenced by a range of factors including: pile material, pile diameter, hammer size, airgun displacement volume and transducer size. Table 1 provides a brief summary of the typical characteristics of these sound sources.

2.1. Sound detection

To establish if anthropogenic noise can affect crustaceans, it is important to ascertain the extent to which it can be sensed. Underwater sound is characterised by pressure variations (sound pressure) and the oscillation of the water molecules, referred to as particle motion.[3] Crustaceans lack gas filled organs (e.g. swim bladders) required for sound pressure detection but appear sensitive to low frequency acoustic stimuli arising from particle motion (Roberts et al., 2016; Salmon, 1971; Goodall et al., 1990). Awareness of sound is believed to be associated with mechanical disturbances of surrounding water/sediment as detected by a pair of statocysts organs in the cephalothorax, chordotonal organs associated with joints of antenna, legs and an array of internal and external hair like mechano-receptors (sensilla) (for further information see Popper et al., 2001; Breithaupt, 2001). The relative role and sensitivity of each in detecting particle motion is unknown. No audiograms have yet been produced detailing the frequency-specific hearing/particle motion detection capability of *C. pagurus*, *N. norvegicus* and *H. gammarus* although preliminary experiments have shown *N. norvegicus* to exhibit specific postural responses to water vibrations arising in the frequency range 20–180 Hz (Goodall et al., 1990). More recently controlled laboratory tests have shown the hermit crab (*Pagurus berhnardus*) to exhibit behavioural responses (antenna/maxilliped movement and bursts of forward locomotion) in response to particle motion [5–400 Hz at particle velocities of 0.03–0.044 m s^{-2} (RMS)] (Roberts et al., 2016). Electrophysiological, auditory evoked potential (AEP) analyses of *Panopeus* crab species provides additional support for low frequency particle motion sensitivity among crustaceans. (Hughes et al., 2014) found *Panopeus* crabs capable of detecting predatory fish sounds (or vibrations elicited as a consequence thereof) between 90 and 200 Hz, where vibrations <0.01 m s^{-2} could be sensed. This is of particular relevance as this response range spans peak frequencies associated with airgun, piling and sonar activities (see Table 1) and overlaps with biologically relevant sources of underwater noise (Jeffs et al., 2003; Radford et al., 2007).

In assessing the hearing capabilities of crustaceans, their entire life history must be taken into account. Studies indicate that an ability to detect specific underwater sounds/vibrations plays a particularly important role in the orientation and settlement of pelagic crab larvae (Stanley et al., 2012; Simpson et al., 2004; Montgomery et al., 2006). Though the sensory abilities of crustacean larvae are poorly understood, both larval and post-larval stages of Brachyuran (e.g. *Helice crassa*) and Anomuran crabs (e.g. *Petrolithes elongates*, *Pagurus* sp.), all closely related to commercial UK species, have been shown to use coastal reef sound as behavioural cues for orientation (Jeffs et al., 2003; Radford et al., 2007). Anthropogenic underwater sound from tidal and wind turbines has also been shown to delay metamorphosis behaviour among the megalopae of other crab species (*Austrohelice crassa* and *Hemigrapsus crenulatus*) (see Pine et al., 2012). Such discoveries raise the question of how anthropogenic underwater sound might influence the spatial distribution of juvenile commercial crustaceans depending upon life cycle stage and timing of exposure.

2.2. Sound production

Analysing sounds produced by animals can provide insight into their hearing sensitivity. Though sound production has been recorded in >50 crustacean genera, no studies have reported sound production or evidence of auditory communication among *C. pagurus*, *H. gammarus* or *N. norvegicus*. Decapods are among the best studied of the crustaceans and are known to produce a range of acoustic signals (Au and Banks, 1998; Lohse et al., 2001; Buscaino et al., 2011a; Staaterman et al., 2011). It is unclear what proportion of sounds are used for intra/extra-species communication or incidentally produced.

The pervasive noise of snapping shrimp (family Alpheidae) may represent the greatest single contribution to biological sound in shallow temperate and tropical waters (Au and Banks, 1998). Snapping shrimp produce explosive clicks and propel streams of water forward by rapidly closing an enlarged front chela, snapping the ends together. Source levels of clicks are loud [~175–220 dB re 1 μPa (peak-peak) @ 1 m] and span a broad frequency spectrum from 2 to >200 kHz with (peak energy at 2 kHz among *Synalpheus paraneomeris*) (Au and Banks, 1998; Schmitz et al., 2000; Kim et al., 2009; Versluis et al., 2000). The primary function of the clicks is to stun prey or interspecific opponents at close range using cavitation and bubble collapse (arising from the click). However, this behaviour has also been found to be important in the territorial behaviour of the shrimp (Au and Banks, 1998) and may facilitate other social interactions.

The acoustic signals emitted by crustaceans span a broad range of frequencies. Low frequency rumblings (20–60 Hz) are produced by stomatopod mantis shrimp (*Hemisquilla californiensis*) and American lobsters (*Homarus americanus*) (182.9 ± 21.7 Hz) while ultrasonic signals (20–55 kHz) are emitted by European spiny lobsters (*Palinurus elephas*) (Patek and Caldwell, 2006; Staaterman et al., 2011; Pye Henninger and Watson, 2005). A broad spectrum of sound may also be produced by discrete species. *P. elephas* were found to produce audible rasps in the 2–75 kHz range (15 kHz peak frequency) using a stridulating organ (plectrum) and rigid file (Buscaino et al., 2011a). These sounds and undefined rasps have been found to occur following human manipulation and appear to be associated with anti-predator responses elicited by the introduction of an octopus (Patek and Oakley, 2003; Bouwma and Herrnkind, 2009; Buscaino et al., 2011a,b).

[1] Data relating to low frequency active military sonar are limited owing to the classified nature of the activity. Sound pressure levels (SPL) arising are cited in publicly available documents as 215 dB re 1 μPa @ 1 m (zero-peak) (100–500 Hz) (Johnson, 2002). Because of the highly limited availability of data on military sonar activities this sound source is not considered within this review.

[2] Explosions around the UK are mostly constrained to a few locations used with naval training. Occasional decommissioning explosions are also carried out. In both cases the events are relatively few in number and are therefore not considered further within this review.

[3] Particle motion is described by displacement (the linear distance in a given direction between a point and a reference position), velocity (the linear speed of an object in a specified direction) and acceleration (the rate of change of velocity with respect to magnitude or direction).

Please cite this article as: Edmonds, N.J., et al., A review of crustacean sensitivity to high amplitude underwater noise: Data needs for effective risk assessment in relation to UK commercial species, Marine Pollution Bulletin (2016), http://dx.doi.org/10.1016/j.marpolbul.2016.05.006