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Review

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

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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

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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).

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[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).

Table 1
High amplitude anthropogenic sound introduction in UK seas.

Anthropogenic noise	Peak frequency range	Amplitude	Vibration levels (m s^{-1}) (peak)
Seismic survey	20–200 Hz	>250 dB re 1 μPa (zero-peak) @ 1 m (Popper and Hastings, 2009)	–
Percussive piling (small diameter pile)	100–300 Hz	1.5 m pile: 228 dB re 1 μPa (zero-peak) @ 1 m (ITAP, 2005 data; in Thomsen et al., 2006)	0.9 m pile: 4.10E − 003 (Roberts et al., 2016)
Percussive piling (size unspecified)	100–300 Hz	>250 dB re 1 μPa (zero-peak) @ 1 m (OSPAR, 2009)	

Such findings suggest that crustacean noises function to startle potential predators or serve as a conspecific warning mechanism (Buscaino et al., 2011a; Patek, 2001, 2002). Further support comes from Pye Henninger and Watson (2005) who found vulnerable (soft post-ecdysis) American lobsters more frequently produced audible vibrations compared with hardened counterparts. Rasps may additionally serve a territorial or courtship role as male spiny lobsters were found to become agitated when the sound was played back to them (Frings and Frings, 1977; Stocker, 2002). Buscaino et al. (2012) provide further support for a territorial function of sound signals [multi-pulsed, 0.4 ms duration, 128 dB re 1 μPa (zero-peak), mean bandwidth 20 kHz] among red swamp crayfish (*Procambarus clarkii*). Noises produced were correlated with agonistic intraspecific interactions supporting a territorial role of sound-based communication among the Decapoda.

3. Physiological effects — adults

Research compiled by Moriyasu et al. (2004) shows blue crabs (*Callinectes sapidus*) to suffer mortality as a direct result of close range underwater explosions (including unmeasured particle displacement and associated pressure waves arising) (see Anonymous, 1948; Linton et al., 1985). No lethal effects of underwater noise have been described for *C. pagurus*, *H. gammarus* or *N. norvegicus*, however a number of sub-lethal physiological and behavioural effects have been reported among *N. norvegicus* and related species.

Decapod crustaceans are believed to be physiologically resilient to noise as they lack gas filled spaces within their bodies (Popper et al., 2001). Being sensitive only to the particle displacement element of sound production at close-quarters, crustaceans should be less vulnerable to pressure waves than animals with gas filled swim bladders (see Keevin and Hempen, 1997). Further evidence of noise resistant physiology within the order comes from the snapping shrimp family (Alpheidae), which actively produce high amplitude impulsive sound (>189 dB re 1 μPa (peak–peak) @ 1 m, ~2–5 kHz) as part of their behavioural repertoire (Au and Banks, 1998; Schmitz et al., 2000; Kim et al., 2009). Being colonial dwellers snapping shrimp are exposed to high amplitude sound both through their own behaviour as well as those of neighbouring conspecifics. Though loud enough to stun prey at close distances, these sounds lack the energy and low frequency components of anthropogenic seismic and piled construction activities to which the sensitivity of the Alpheidae remains unknown. Recorded effects of low frequency high amplitude noise exposure have been found to vary even among the same species. In a report by Christian et al. (2003), no significant difference was found between acute effects of seismic airgun exposure upon adult snow crabs *Chionoecetes opilio* (haemolymph, hepatopancreas, heart, and statocysts) in comparison with control crabs [broadband received levels 197–220 dB re 1 μPa (zero-peak)]. *C. opilio* exposed to seismic survey (sound pressure levels (SPL) unspecified) have been reported to suffer bruised hepatopancreas' and ovaries in comparison with control animals at another locality (DFO, 2004). Different conditions and individual variability confound derivation of a consistent influence from this type of sound but nonetheless highlight potential for physical harm arising from sound introduction (irrespective of detection capabilities).

Long term trends in landings data can reveal effects of a known variable, for example temperature (see Heath et al., 2012) or aquaculture activity (Loucks et al., 2014), upon stock abundance. No comprehensive analyses have yet to be carried out for anthropogenic sound. One of the few studies to explore the issue found no statistically significant correlative link between seismic surveys and changes in commercial rock lobster (*Panulirus cygnus*) catch rates associated with acute to mid-term mortality over a 26-year period (Parry and Gason, 2006). In the absence of specific sound pressure levels received by the fished stock, no reliable conclusions can be drawn however. Difficulties in deriving impacts from this kind of study are highlighted by Payne et al. (2007) who note that a mortality rate in the range of 50% would have been required before direct seismic impact could have been resolved from other factors.

Nonetheless, an aquarium-based follow-on study by Payne et al. (2007) found no effect of airgun exposure [202–227 dB re 1 μPa (peak–peak) @ 1 m] relating to delayed mortality or to mechanoreceptor systems among American lobster (*H. americanus*). Sub-lethal physical and behavioural effects of exposure were however, observed. These included changes in feeding level, serum biochemistry and hepatopancreatic cells of animals exposed for months, compared with controls. Crucially SPL received by organisms are dependent upon situation specific propagation loss from source and cannot be accurately inferred simply from source levels.

Anthropogenic noise may influence crustacean fitness through indirect as well as direct mechanisms. While quieter than seismic survey or piled construction, shipping noise is the dominant contribution to ambient noise in shallow water areas close to fishing lanes around the UK (Harland et al., 2005). To date, the impact of shipping noise upon the fitness of crustaceans commercially harvested in the UK remains largely untested. Nonetheless, sub-lethal effects of continuous, low frequency anthropogenic noise have been reported among the Decapoda. Evidence includes that from *N. norvegicus* where exposure to continuous anthropogenic sound sources, characteristic of shipping, have been shown to repress burying, bioregulation and locomotory behaviour (Solan et al., 2016).

Although Solan et al. (2016) found *N. norvegicus* tissue concentrations of glucose or lactate were unaffected by anthropogenic noise (continuous and impulsive), respiration among other crustaceans has been shown to be affected by elevated ambient noise levels. Higher levels of ambient noise have been found to be associated with increased levels of respiration among brown shrimp (*Crangon crangon*) for example. Subjects were found to consume 15% more oxygen when exposed to elevated levels of ambient noise (versus silent controls) in laboratory trials (Regnault and Lagardère, 1983). Findings by Wale et al. (2013b) show that the metabolic rate of shore crabs (*Carcinus maenas*) were affected by exposure to ship playback noise [148–155 dB re 1 μPa (RMS) (received level)], subjects consuming 67% more oxygen in comparison with playback harbour noise [108–111 dB re 1 μPa (RMS) (received level)]. Although Wale et al. (2013a) found ship noise did not impair the ability of *C. maenas* to find food, those undertaking feeding were more likely to suspend feeding activity following exposure to ship noise in comparison with ambient noise. While no difference was recorded in type of reaction to predator stimulus, whether exposed to ship noise or ambient noise, crabs exposed to the former took longer to return to shelter than those experiencing ambient noise playback.

Evidence suggests that crustaceans use sound as a sensory cue for the presence of fish as it stimulates increased respiration and decreasing activity in readiness for escape responses (Hughes et al., 2014; Regnault and Lagardère, 1983). Mud crabs (*Panopeus* sp.) exhibit reduced foraging activity in the presence of acoustic stimuli from predatory fish species for example (Hughes et al., 2014). It appears that high amplitude impulsive anthropogenic sounds might elicit similar behavioural responses. *N. norvegicus* have been found to bury less deeply, flush their burrows less regularly and are considerably less active when exposed to impulsive anthropogenic noise (Solan et al., 2016). Another study on brown shrimp reveals elevated SPL are implicated in increased incidences of cannibalism and significantly delayed growth (Lagardère and Spérandio, 1981). Such findings have implications with regard to species fitness, stress and compensatory foraging requirements, along with increased exposure to predators.

4. Physiological effects — eggs and larvae

All commercially exploited decapod crustaceans pass through multiple life stages before reaching maturity and, as *r*-strategists, their juvenile abundance outnumbers adults many times over (MacArthur and Wilson, 1967; Parry, 1981). As such, any deleterious factor influencing juvenile distribution or abundance has the potential to elicit significant population level consequences. There is no direct evidence to suggest that the eggs or larvae of UK commercial crustacean stocks are at risk of direct harm from high amplitude anthropogenic underwater noise. Most studies on seismic noise have focused upon fish eggs where adverse effects of airgun sound have been reported within a few metres of seismic projections (Kostyuchenko, 1973; Booman et al., 1996). Evidence of impaired embryonic development and mortality has however been found to arise from playback of seismic survey noise among Gastropoda sp. and Bivalvia sp. (De Soto et al., 2013; Nedelec et al., 2014). Boat noise (in comparison with ambient noise) has also been shown to increase mortality of recently hatched larvae among other marine invertebrates (Gastropoda sp.) (Nedelec et al., 2014).

Scant information exists on the effect of seismic noise upon crustacean eggs, and no research has been conducted on commercially exploited UK decapod species. Preliminary findings show that seismic exposure could be implicated in delayed hatching of *C. opilio* eggs, causing resultant larvae to be smaller than controls (DFO, 2004). Supporting evidence is provided by Christian et al. (2003) who found field-based exposure of *C. opilio* eggs to seismic projections [224–227 dB re 1 μPa (zero-peak) @ 1 m] to retard development, eliciting significantly greater mortality in comparison with controls. However, the limited sample size (2000 eggs) in this instance (equivalent to 2% of a gravid female *C. opilio* brood) means that findings are preliminary and further testing is warranted. Among the few experiments to be conducted upon crustacean larvae, Pearson et al. (1994) found no statistically significant difference between the mortality and development rates of stage II Dungeness crab (*Metacarcinus magister*) larvae exposed to single field-based discharges [231 dB re 1 μPa (zero-peak) @ 1 m] from a seismic airgun. However, caution should be exercised before ascribing such resilience to other decapods and the wider Crustacea subphylum. Effects ranging from mortality to no ill-effects have variously been reported among fish larvae following airgun and playback pile driving noise exposure for example (Booman et al., 1996; Bolle et al., 2012). Playback experiments show that underwater sound can influence the physiological development rate of both temperate and tropical crab larvae. Reductions (34–60%) in time to metamorphosis are reported among the larvae of both temperate (*Hemigrapsus sexdentatus*, *Cyclograpsus lavauxi*, *Macrophthalmus hirtipes*) and tropical crabs (unidentified species of Grapsidae) following exposure to underwater reef noise in comparison with silent control conditions (Stanley et al., 2010). Underwater noise has therefore been shown to influence physiological regulatory mechanisms associated with larval crustacean growth. It remains to be seen whether such sounds could trigger similar accelerated growth responses among UK commercial species and what repercussions could result at the population level.

5. Discussion

Marine crustaceans have been shown to produce, detect and respond to sound (Staaterman et al., 2011; Radford et al., 2007; Hughes et al., 2014). Understanding in relation to the sensitivity of commercial UK crustacean species throughout their life history, including long term chronic exposure is especially warranted owing to the high value of their fisheries. If decision makers are to effectively assess fiscal and environmental implications of high amplitude noise introduction there is a need to address knowledge gaps in this area.

Few studies have defined crustacean sensitivity to underwater noise, specifically particle motion parameters of discrete sounds. Many experiments have been hampered (presumably for valid practical and budgetary reasons) by limited sample sizes, poor provision of control subjects and uncalibrated equipment. Others have conducted measurements in small tanks where reflective boundaries complicate interpretation of data. In the absence of gas filled organs, sound detection among crustaceans is believed to occur through hair and statocyst detection of the particle motion component of the sound field. Insights obtained from *N. norvegicus* and crustaceans that are phylogenetically related to other commercial UK species reveal both adult and juvenile crustacean life stages sensitive to low frequency sound, including that sharing spectral characteristics of percussive piling and seismic survey (Hughes et al., 2014; Lovell et al., 2005; Jeffs et al., 2003; Radford et al., 2007; Stanley et al., 2010; Solan et al., 2016). While studies show that larval and post-larval stages of related crustacean species use low frequency sound (e.g. reef sound) as behavioural cues for orientation (see Jeffs et al., 2003) such capabilities have yet to be determined among commercial UK species.

Experimental insights suggest that what sound-based communication exists among crustaceans is highly species-specific. Noises emitted range from low frequency rasps to ultrasonic clicks, although it remains unclear which of these are incidentally produced along with the repercussions of masking them. Little is known regarding species-specific sensitivity to seabed vibration, water-borne sound waves or particle displacement and difficulty exists in separating the relative impact of these factors upon benthic dwelling species. Less is understood about the use of these stimuli for purposes of communication and the potential for anthropogenic noise with overlapping spectral characteristics to mask such cues (Hawkins and Popper, 2012).

It is not known if the eggs, larvae or adults of *C. pagurus*, *H. gammarus* and *N. norvegicus* can suffer direct physical harm as a result of exposure to high amplitude anthropogenic noise. Findings among related species show that egg development among specific crustaceans may be retarded, metabolic rates increased and internal organs damaged following exposure to high amplitude anthropogenic sounds (Christian et al., 2003; Pearson et al., 1994; Wale et al., 2013b; Regnault and Lagardère, 1983). Controlled sound exposure trials, after André et al. (2011), would shed much needed light upon threshold tolerances in relation to injury and mortality criteria for key UK commercial crustacean species. The adaptation of such methods to assess the effect of 'live' underwater sound (versus digital analogues) in natural settings would greatly increase the reliability of findings.

The need to resolve current uncertainty surrounding injury exposure criteria is of significant consequence to the fishing industry, regulatory bodies and associated stakeholders. The former seek assurances their revenue from crustacean harvests will not be impacted through anthropogenic noise introduction from other industries and/or compensation for losses where they are. Crucially, since introduction of impulsive anthropogenic noise has been shown to influence depth and water circulation within *N. norvegicus* burrows, potential exists for broader ecosystem properties to be affected (see Solan et al., 2016). Regulatory bodies require this information to take evidence-based decisions on offshore licencing consents and marine protected area designations.

The physical capacity for slow moving benthic adult or mid-water larval crustaceans to avoid exposure to sound is limited although no significant deleterious effect of seismic prospecting upon fishing yields of shrimp and catches of *N. norvegicus* (24 h post exposure, 210 dB re 1 μPa (zero-peak) @ 1 m) have been found (Andriguetto-Filho et al., 2005; La Bella et al., 1996). Such experiments provide site-specific insights into short term effects of high amplitude sound on discrete crustacean species but do not quantify sound exposure levels (specifically particle motion measurements) experienced by the test organisms themselves. Such issues must be resolved through controlled exposure studies to determine the influence of discrete sounds. Although pressure waves arising from anthropogenic noise can spread many kilometres from a site of introduction, particle motion associated with the production of such sound is much more localised (see Urick, 1983). As no study to date has confirmed the ability of crustaceans to sense the former, caution must be exercised before assessing impacts based upon associated sound wave propagation. Sound exposure calculations for crustaceans must primarily consider the particle motion element of anthropogenic noise fields. This is especially complicated for mobile, current borne larvae and migratory life stages. Adult *C. pagurus* for example, have been recorded migrating distances > 245 km over two years (Fahy and Carroll, 2008). Cohorts may therefore be subject to repeated exposure in different localities over their life cycles.

Current research suggests that crustacean sensitivity is restricted to particle motion, primarily localised to the site of sound introduction. However, ascribing reliable statistical correlations between noise introduction and annual landings is hindered by low resolution site-specific data at the present time. Landings data for *C. pagurus*, *H. gammarus* and *N. norvegicus* are currently submitted at the ICES rectangle level (a resolution of ~30 nm^2) hindering the derivation of localised anthropogenic sound impacts. Similarly, spatio-temporal records held by licencing authorities do not currently detail high resolution, date specific, locations of high amplitude noise introduction within UK waters each year. Records retained detail activity authorised, but not necessarily undertaken, over annual periods and seismic survey locations in particular are defined broadly and allocated to 250 km^2 'hydrocarbon blocks'. Annual (high resolution) mapping of UK water ensonification is required to categorically inform upon exposure of marine organisms to underwater sound arising from industrial activity within UK seas. Broader establishment of a UK noise registry and the monitoring of underwater noise levels in fulfilment of the EU Marine Strategy Framework Directive (2010) — Descriptor 11: Underwater Noise are positive advances in this regard.

Significant variations in fishing pressures are also known to occur between years (Stelzenmüller et al., 2008) and landings alone can reflect market forces as well as true abundance. Moreover, as some stocks (e.g. North East North Sea *N. norvegicus* fishery) are exploited by several nations, official UK landings alone can only provide a coarse indication of stock abundance. Deducing trends in the abundance of discrete species from catch data in the absence of reliable effort data (only vessels longer than 12 m are fitted with VMS tracking devices)[4] makes it impossible to draw statistically robust causal relationships between crustacean landings and known levels of noise introduction. Added to this, UK landings data from the International Fish Database (iFISH, 2016) must be viewed with caution as small scale hobby fishing/potting is currently unreported and until 2006 vessels under 10 m were exempt from reporting their catches in EU logbooks. The requirement for commercial fishermen to submit Monthly Shellfish Return (MSAR) forms since 2006 goes some way to address the issue although verification of data records is problematic. In view of unknown variability in fishing effort, no clear conclusions relating to population level effects of underwater noise can be drawn from current landings data. This, combined with a range of biotic and abiotic factors affecting stock abundance, means that it is not possible to determine discrete effects of anthropogenic noise upon crustacean hearing, communication, physiology or behaviour from commercial UK crustacean species from landings data as it is currently recorded.

6. Conclusion

Assessing what sound, if any, can be detected by UK commercial crustacean species is necessary to infer ramifications of exposure. Derivation of species-specific (particle motion) audiograms is a key starting point in defining sound signal characteristics that can be detected as well as those with the potential to mask intraspecific communication or broader-scale sound cues of ecological relevance e.g. reef noise. Such knowledge is crucial to determine repercussions for individual fitness, recruitment or likelihood of fishery stock displacement. Audiograms might be derived directly in the laboratory through electrical response studies (see Lovell et al., 2005) or indirectly through attraction/repulsion experiments after Radford et al. (2007), the latter being most appropriate for larval stages. Accompanying measurements of particle motion must be taken in parallel to allow discrete identification of cause and effect (see Nedelec et al., 2016).

As fossil fuel reserves become scarcer, seismic prospecting continues and offshore wind power schemes enter the Round 3 construction phase, it is clear that low frequency, high amplitude anthropogenic sound introduction will remain a feature of the UK marine environment. Given the high economic value of UK crustacean fisheries, it is important that we progress towards a better understanding of how loud underwater noise might affect them. Most critically, we need to develop an understanding of how noise might impact reproductive success to accurately predict recruitment and inform future marine management strategies.

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