Physiological condition, short term survival and predator avoidance behaviour of discarded Norway lobsters (*Nephrops norvegicus*)

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The landing obligation of the reformed European Union Common Fisheries Policy is designed to encourage more selective fishing strategies and improve recording of catches. There are allowable exemptions to this landing obligation including for species with high post-release survivability. Discarding patterns of prawns (*Nephrops norvegicus*) were evaluated in a trawl fishery in the Firth of Clyde, West Scotland which supplies the live-catch market. Around 30% of the *Nephrops* caught were discarded but the reasons for discarding changed seasonally. Using visual indices, physiological biomarkers and video recordings this study evaluated the physiological condition linked to short-term survival and predator avoidance behaviour of the discarded animals. Although short-term survival after 48 h recovery was high (around 90%) and physiological measures indicated that discarded *Nephrops* can recover from trawling, survival was negatively affected by levels of physical damage and *Hematodinium* infection. Taking into consideration these factors a conservative estimate for discard survival was 63-88%. Underwater video showed that *Nephrops* discarded in good condition rapidly recovered normal behaviour when placed on the seabed. Moribund animals, however, took up to 10 minutes to return to an upright posture and this time was sufficient for predators to be attracted. Since around 20% of *Nephrops* were in a moribund condition immediately after trawling, the survival estimates based upon enclosed recovery experiments may need correcting by up to this amount to account for potential interactions with predators on the seabed. The post-release survival rates in discarded *Nephrops* suggested for this fishery are relatively high compared with other *Nephrops* trawl-fisheries which have been studied. This could be explained because this fishery targets the live-market, prioritises product quality over volume and uses short-duration tows leading to relatively low levels of physical damage to the *Nephrops*.

Key words: discards, physiological condition, behaviour, *Nephrops*

1. Introduction

Discards are target or non-target animals that are not retained on-board commercial fishing vessels but are returned to the sea, either alive or dead. Organisms may be discarded for a variety of reasons including lack of fisheries quota, lack of demand or where the organisms are unmarketable due to other reasons such as size, damage or disease (Catchpole et al., 2005a,b). The problem of discarding in European fisheries has been widely discussed from ecological, economic, ethical and environmental perspectives (Eliasen et al., 2014) and received increasing public attention in the run-up to the 2013 reforms of the European Union's Common Fisheries Policy (Borges, 2015). As a result a 'landing obligation' was introduced and is being sequentially applied across EU fisheries. The aims of this policy change are to reduce waste, encourage uptake of more selective fishing practices and to improve data recording of actual catches. Consequences on fisheries management of the recent United Kingdom vote to exit the EU are unclear but it is possible the 'landing obligation' will be retained as various forms of discard bans are applied in other non-EU countries such as Norway and Iceland.

Under the CFP landing obligation discarding can potentially continue where there is evidence that the species has a high rate of post-discard survival. Forcing landing of these discards, and their subsequent disposal, would only increase economic costs for little overall conservation benefit. The prawn *Nephrops norvegicus* has been identified as having potentially high post-release survival and a landing obligation exemption has been approved by the European Union for creel-caught *Nephrops* (Ungfors et al., 2013; Fox, 2014; Marine Scotland, 2015). On the other hand, scientific studies suggest that trawl-caught *Nephrops* do not necessarily survive as well as creel-caught animals. Despite having a hardened exoskeleton, *Nephrops* seem to be quite vulnerable to physical damage, particularly puncture wounds to the carapace, which can lead to a loss of haemolymph and eventual mortality (Wileman et al., 1999). Levels of physical damage will be affected by factors such as gear type, volume and composition of the catch, trawling time, locations of animals within the cod-end, the care with which the catch is hauled and handled on board as well as the size and condition of the animals (Milligan et al., 2009). The eyes of *Nephrops* are also particularly vulnerable to light exposure at levels typically found at the sea surface, although there is no evidence linking such damage with subsequent reduced survival (Gaten et al., 2013). From a physiological perspective, the process of being caught in a trawl is stressful with anaerobic metabolism being activated in an attempt to maintain energy levels (Ridgway et al., 2006b; Albalat et al., 2009). Nevertheless, *Nephrops* do show considerable ability to recover from such stress if post-harvest practices are optimised and aerial exposure is minimised (Albalat et al., 2010). In such situations key physiological parameters, such as the replenishment of muscle ATP, have been reported to recover to un-stressed levels within 6 h post-capture with other anaerobic metabolites (i.e. $_{L}$-lactate and muscle glycogen) returning to rested conditions within 24-48 h (Albalat et al., 2010). The potential of *Nephrops* to recover from trawling is also influenced by season (Lund et al., 2009; Albalat et al., 2010) although it is not clear if this is mainly due to temperature or other seasonally varying factors, such as animal size, sex and moult status (Milligan et al., 2009).

Most post-release survival studies conducted to date have monitored the recovery of animals in tubes or cages, for example Harris and Andrews (2005). These approaches provide estimates of physiological recovery but because the recovering *Nephrops* are protected from predation they may under-estimate true post-discard mortality (STECF, 2015). In behavioural terms survival will be related to (i) the length of time taken to regain normal predator avoidance behaviour (ii) the abundance of potential predators in the immediate area (iii) the ability of the animals to escape predators using their tail-flip response and (iv) whether the animals are discarded over suitable muddy habitat allowing them to find burrows in which to hide.

In the Firth of Clyde there are around 18 registered under 10 m *Nephrops* trawlers the majority of which fish locally (Fox et al., 2015) and supply the live-market. Fishing is typified by relatively short tows (<2.5 hours) using single-rig trawls fishing relatively close to port. The *Nephrops* are generally sorted from the catches within 60-90 mins of hauling, and placed into boxes of tubes according to size (Supplementary Fig. 1). The tubed animals are then held in seawater tanks on-board before being transferred to shore-based tanks where they are stored for up to 3 days before being shipped by truck, mainly to continental Europe. Prawns unfit for market are discarded during sorting over muddy grounds as the vessels prepare for the next tow. Using a commercial day vessel operating in this fishery this study analysed 1) composition of retained and discarded *Nephrops* 2) the physiological condition and short-term survival of captive *Nephrops* 3) predator avoidance behaviour using underwater video and 4) which variables are linked to survival.

2. Materials and Methods

2.1 Trawling and data collection

Trials were conducted in the Firth of Clyde, Scotland using a commercial vessel (Eilidh Anne GK2) which targets *Nephrops* for the live market. Fishing was undertaken using a single-rig Harkess (Prestonpans, Scotland), rock-hopper trawl fitted with an 85 mm diamond mesh net and a square-mesh 120 mm Cod Recovery Zone Panel (standard commercial net and rig). Three sets of *Nephrops* recovery trials were conducted in February, March and June and a behavioural trial in July 2015. Environmental conditions and trawling coordinates were recorded for each tow (Supplementary Table 1). Temperature and salinity profiles were recorded in February and March using an YSI Castaway CTD. In the June trial surface temperature readings were obtained from the vessel but no salinity measures could be taken due to instrument failure.

The skipper was asked to follow his normal fishing practices and once the catch was on board he began sorting the *Nephrops* into four commercial size categories: Large, medium, small and extra-small. In this fishery animals in the first three categories are destined for the live market while the extra-small *Nephrops* are marketed as whole fresh or frozen langoustines. Animals below the Minimum Conservation Reference Size (carapace length <20 mm) or not fit for market according to the skipper's criteria were placed in a separate basket as 'discards'. After sorting of each tow was completed animals in the large, medium and small categories were counted and their carapace lengths recorded using digital calipers. Because of the numbers of animals in the extra-small and discarded grades, size profiles were based on measuring animals within a weighed sub-sample, which was then raised by the total catch weight of that grade.

2.2 Physiological condition and short-term survival of captive discarded Nephrops

Fifteen *Nephrops* were taken from the discards category as soon as practical after the skipper had begun sorting the catch and sampled to provide baseline physical and physiological information (time = 0). This generally took place within 15 minutes of the catch being hauled aboard. For each individual, carapace length (CL), sex, damage, damage (described below), vigour index (described below), moulting stage, the presence of mature gonads in females (green gonads) and any obvious *Hematodinium* symptoms were recorded.

Visible damage was scored against the three-levels (0=no damage, 1=slight damage, 2=severe damage) as introduced by Ridgway et al. (2006a). Injuries were not counted if there was evidence of tissue regeneration, indicative of an old injury. Vigour was assigned to five categories: A, B, C, moribund or dead according to the posture of the animal when held midair, the position of the antennae and claws, the degree of tail tension indicative of reflex impairment and movement of walking legs (Supplementary Table 2). Infection by *Hematodinium* was evaluated based on their body colour (Field et al., 1992) as symptomatic of patent infection or as asymptomatic (which includes both truly uninfected and also sub-patently infected individuals). The validity of these visual criteria for indicating patent infection has recently been confirmed using molecular methods for detecting and quantifying the parasites in the haemolymph (Beevers et al., 2012). Carapace hardness was used as a straightforward measure of the moulting stage of individual *Nephrops*. Animals were classified as 'soft' if gentle squeezing just behind the eyes gave a clear distortion (Milligan et al., 2009). 'Soft' animals included those recently moulted and at late inter-moult (i.e. with calcium withdrawn from exoskeleton). For consistency visual indices (vigour, damage, body colour and carapace hardness) were recorded by same observers in all trips.

Around 200 µl of haemolymph was then extracted to establish baseline physiological condition using 1 mL syringes coupled with 25G needles. A sub-sample of 100 µl of haemolymph was then de-proteinased in 100 µl of 6 M perchloric acid (PCA), mixed and stored on dry ice. Muscle samples were excised and immediately frozen in liquid nitrogen.

Thereafter, another 150 animals were randomly selected from the discard category and damage and vigour indexes scored as above as they were placed into indexed tube-sets (Supplementary Fig. 1) for the short-term survival trial of captive specimens. Sex and length were not recorded at this stage so as not to delay returning these animals to the sea. Air temperatures during catch sorting and sampling procedures were recorded, as well as the overall time taken for the sampling and stocking of the tube-sets to be completed (Supplementary Tables 1 & 3). Tube-sets containing 150 discarded animals per tow were enclosed in perforated plastic boxes and returned to the sea suspended on a rope mooring at a depth (usually ~ 30 m) below the upper lower salinity layer.

The *Nephrops* stocked in the suspended tube-sets were left to recover for 48 hours and after this time the boxes were collected. Sex, CL, damage index and vigour index were then recorded for all these animals. A random sub-sample of 30 animals per tow were then sampled for physiology as described above.

2.3 Measurement of physiological parameters - Haemolymph and muscle L*-lactate*

L-lactate concentration was measured following Bergmeyer & Bernt (1974) and modified by Hill et al. (1991). Samples were thawed, de-proteinized and homogenized using an Ultra Turrax T25 homogeniser. Homogenates (50 µl) were added to microcentrifuge tubes (Eppendorf) containing 50 µl of NAD^+ (50 mM), 0.85 ml of hydrazine buffer (0.6 M hydrazine hydrate, 5.6 mM EDTA, 1 M glycine) at pH 9.5 and 1 unit of lactate dehydrogenase (LDH, Sigma) and incubated for 2 h at 37 °C. Absorbance readings at 340 nm (Shimadzu, UV Mini 1240) were converted to concentrations of L-lactate using a calibration curve constructed from lactic acid standards (0.5-10.0 mM).

2.4 Measurement of physiological parameters - ATP and its breakdown products

Nucleotide analysis was performed using High Performance Liquid Chromatography (HPLC) as described by Ryder (1985) and modified by Albalat et al. (2009). The system consisted of a Spectra system P4000 pump coupled to a SN4000 autosampler and a UV1000 detector set at 254 nm. A Kinetex 5u C18 100A column 250 x 4.6 mm with an internal particle of 5 µm was used to conduct the separations (Phenomenex, Cheshire, UK). Standard curves were prepared from adenosine 5'-triphosphate (ATP), adenosine 5'-diphosphate (ADP), adenosine 5'-monophosphate (AMP), inosine 5'-monophosphate (IMP), inosine (HxR) and hypoxanthine (Hx) using concentrations ranging from 0.1 to 1.0 mM (Sigma-Aldrich, Dorset, UK). The Adenylate Energy Charge (AEC) was calculated based on the nucleotide profiling of the muscle samples following Atkinson (1968).

$$AEC = \frac{[ATP] + 0.5 * [ADP]}{[ATP] + [ADP] + [AMP]}$$

2.5 Statistical analyses of physiological data

Differences of L-lactate (in haemolymph and muscle) and AEC ratios between trials (February, March and June) at time zero and time 48 h were analysed using analysis of variance (ANOVA) following homogeneity of variance checks using Levene's test. Post-hoc multiple comparisons (Tukey post-hoc or Games-Howell test according to outcome Levene's test) were applied to determine statistical differences between samples. Differences between time zero and time 48 h within each trial were analysed by independent sample t-tests. In all cases p-values lower than 0.05 were considered statistically significant.

2.6 Predator avoidance behavioural trials using video surveillance

Six, 50 m depth submersible 12 V cameras (VN37CSHR-W36, Visionhitech Co., Ltd, Korea) were mounted in a custom-built lander frame in a grid layout so that they would cover a larger area of seabed. The cameras were connected to a multi-channel Digital Video Recorder (Hybrid 16 DVR, Huviron Ltd., Korea) on-board the research vessel 'Calanus' which was anchored next to the rig. The rig was deployed on 29th July 2015 at 55.805°N 004.882°W at a depth of just under 30 m. Temperature and salinity profiles were recorded using a Valeport Castaway CTD (Supplementary Fig. 2). The bottom type was sandy-mud with some shell debris. Discard category *Nephrops* were sorted on board the commercial fishing vessel following the normal commercial procedures described above and were transferred to the research vessel as soon as possible once catch sorting was completed. Ten animals were selected at random and placed in a perforated plastic container and taken directly to the camera rig by diver. Five deployments were made with animals having been exposed to varying total air-times and recovery intervals (Supplementary Table 4). The recorded videos were subsequently transferred from the DVR and individual video streams merged into a composite montage using a custom script written in Matlab. Behaviour of *Nephrops* and interactions with other organisms were then summarised based on visual analysis.

2.7 Modelling overall survival of discarded Nephrops

Survival proportions of all discarded *Nephrops* were analysed using binomial logistic regression, with resulting coefficients converted to 95% confidence intervals. Three analyses were performed: (1) modelling actual survival at 48 h with trawl date, CL, sex, vigour, damage, infection status, moulting status and females showing mature gonads as explanatory variables; (2) modelling actual survival at 48 h using only date, sex and carapace length as explanatory variables (in order to create a model that can be extrapolated to other catch compositions in each season) and (3) modelling probable survival using the same explanatory variables as in model 2, where it was assumed that all infected or damaged (class 1 or 2) animals after 48 h recovery would die shortly after (in order to produce a more conservative survival estimate as studies such as Wileman *et al*., 1999 have suggested mortality in recovering trawled *Nephrops* can take longer than 48 h to stabilise. For each of these models stepwise regression was performed with non-significant explanatory variables being removed. All statistical analyses were conducted using R version 3.2.3.

3. Results

3.1 General information and fractions of retained and discarded Nephrops

Air temperatures during the trials in February and March were between 7 and 8.5°C whilst in June temperatures ranged from 12.5°C in the early morning to 15°C by the afternoon. The time taken to sort the catches on board the fishing vessel was 83 ± 9 min.

Sorting times in February and June were slightly longer (between 95-103 min) compared to March where the sorting time was around 60 min due to the smaller catches. The visual impression was that total catch volumes (*Nephrops* plus by-catch) were largest in February. The total numbers of *Nephrops* caught were noticeably lower during the March trial (234-739 tow^{-1}) compared to February (1180-1830 tow^{-1}) and June (763-1478 tow^{-1}). This was due to the stronger tides during the March trial, conditions that are often associated with reduced catches of *Nephrops* in this fishery (skipper, personal communication).

The overall *Nephrops* discarding rate when expressed as a percentage of the total number caught was 29.9 ± 8.1%. The most abundant size category caught was 'extra-small' (32.5 ± 0.9 mm) followed by 'small' (37.7 ± 1.1 mm), 'medium' (44.4 ± 1.4 mm) and 'large' (49.3 ± 1.1 mm) categories. Animals in the 'extra-small' category are marketable and normally landed by this fishery. The average size of the 'discard' category animals was 28.2 ± 1.0 mm which was still above the MCRS and *Nephrops* below the legal size limit only comprised <1% of the animals being discarded. Significant seasonal-related differences in discards were also observed with larger animals being rejected in June, compared to March and February (Fig. 1A). This pattern is explicable because the percentage of females in the discard fraction was higher in June and the majority of these animals were soft and had mature gonads (Fig. 2B). These animals have low market value and are therefore normally discarded (skipper, personal communication).

3.2 Physiological condition and short-term survival of captive discarded Nephrops

Overall, discard fraction *Nephrops* were predominantly in vigour category 'C' (51%) immediately after trawling (Fig. 1A) while animals in top vigour categories A+B accounted for around 25%. After a 48 h recovery period, the proportion of discarded animals in the top vigour categories (A+B) had increased to 64% while 12% were moribund or dead. From a seasonal perspective, a higher proportion of the *Nephrops* were classified as being in vigour category A after the 48 h recovery period in February (Fig. 1B). Moreover, the number of moribund animals was lowest although the numbers of prawns dying was actually higher. In June more animals were in vigour categories B+C after 48 h recovery but the number which had died was lower than in other months.

Immediately after trawling 87% of the discard fraction *Nephrops* had no visible signs of damage. There was also no obvious seasonal effect on the damage scores with values being low throughout (data not shown) neither did damage appear to be related to sex, size or moulting stage of the animals. After the 48 h recovery period there was an increase in the proportion of animals with some visible damage (13% at T0 to 18% at T48). Potential contributing factors could include handling the animals in and out of the tube-sets or moving the boxes in and out of the water. Although in this study, damage percentages were low, damage did have an impact on the recovery potential of the animals. As shown in Fig. 3A, the proportion of dead and moribund animals after 48 h recovery increased with damage. Indeed, more than 50% of the *Nephrops* which were classified as being in damage category 2 immediately after trawling were dead or moribund after 48 h.

The percentages of prawns with *Hematodinium* infection varied seasonally; 10.2% of animals infected in February, 12.9% in March but only 0.4% in June. Infected animals did not show as good recovery potential as un-infected animals. After 48 h recovery more than 50% of animals classified as visually infected immediately after trawling were dead or moribund (Fig. 3B).

Baseline physiological data for prawns immediately post-catch were indicative of capture stress with elevated muscle $_{L}$-lactate (Fig. 3A) and low AEC ratios indicative of anaerobic respiration (**Error! Reference source not found.**B). In June, muscle $_{L}$-lactate values after 48 h were significantly higher than in February or March (Fig. 3A) but seasonal effects were not so obvious in post-recovery AEC ratios (Fig. 3B). Despite some indications that physiological recovery was poorer in June (lower percentage of animals in vigour category A and significantly higher muscle $_L$-lactate concentration) the percentage of dead animals after 48 h was actually lowest in that month (Fig. 2B).

3.3 Predator avoidance behavioural observations on released discard fraction Nephrops

During the behavioural trial the air temperature rose from 9.5^{o}C in the early morning to around 17^{o}C by 10:00 whilst CTD casts showed a layer of lower salinity water reaching down to around 5 m depth (Fig. S2). All animals used were in the discard size class (22–32 mm CL) and all test animals, except one, were in damage category 0. Prawns caught in the morning were all in vigour index A, B or C after transfer to the research vessel. The vigour indices of *Nephrops* caught in the afternoon were slightly lower (mainly B/C) (Table S4). In the main deployments (2 to 5), delays in returning the animals to the sea were relatively short (30-45 mins to re-immersion). The exposure to seawater during their descent seemed to act as a stimulant and nearly all the *Nephrops* (38/40) exhibited almost immediate righting action and began moving around when placed on the seabed (Table S5). The majority of these animals appeared to exhibit normal locomotory behaviour and dispersed out of the camera view within a few minutes. In the initial test deployment the animals had been held on the research vessel in air for around 90 mins while the equipment and dive team were being prepared. These *Nephrops* were mostly in vigour category C or were moribund when taken down to the camera rig. Some of these animals took up to 10 minutes to recover and this time period was sufficient to attract several shore crabs (*Carcinus maenas*) and squat lobsters (likely *Munida rugosa*) which attacked any un-righted *Nephrops*. Although several prawns exhibited tail-flip escape responses this tended to be a single or double flip rather than a series which would have carried them away from the predators. At least one prawn would probably have failed to survive (the individual in question being attacked by two crabs and eventually dragged out of the observation arena (Table S5).

3.4 Modelling overall survival of discarded Nephrops

Of the available co-variables (date, CL, sex, damage, vigour, softness, infection and gonad status) only date, damage index, infection status and moulting stage were found to be statistically significant explanatory variables for 48 h survival overall. Table 1 shows confidence intervals for the baseline probability of survival in each season and also the increase in the odds ratio of death according to each contributory factor. Only date was found to be statistically significant for the model of likely long-term survival (in this more conservative model it was assumed that damaged, infected or soft animals would all die in the longer-term, Table 2).

As a caveat it should also be noted that there was an increase in the proportion of animals with some damage during the 48 h recovery period from 12.8% at T0 to 18.0% at T48. It was not possible to correct survival estimates for this because the additional damage could have occurred at any time during the 48 h recovery, or during inspection of the animals after this time. Nevertheless, such accidentally induced additional damage would only decrease survival meaning that the estimated survival rates will be conservative.

4. **Discussion**

Although other studies have described the annual emergence of recently moulted female *Nephrops* in spring and early summer (Milligan et al., 2009) this is the first time that discarding of soft females as a low quality product has been reported. Similarly, although several studies have reported the seasonal patterns of *Nephrops* infection by *Hematodinium* (Field et al., 1992; Stentiford et al., 2001; Beevers et al., 2012), this is the first time that it has been observed that fishers are able to recognise symptomatic patent infected animals (on the basis of their body colour) and that these animals are then being discarded. The choice to discard soft or infected animals is driven by the fact that this particular fishery is serving the live market and prioritising product quality over volume. Although such high-grading is often considered to be an undesirable fisheries practice, the actual impacts will vary depending on the survivability of the discarded fraction.

In the present study more than 90% of the discarded *Nephrops* were alive after 48 h re-immersion in tube-sets. These values are higher than reported in most other post-discard studies in *Nephrops* trawl fisheries (e.g. Castro et al., 2003; Méhault et al., 2016). Guéguen and Charuau (1975) reported a survival rate of ~25% after three days recovery in cages immersed at around 60 m depth, following aerial exposure of 90 min but later studies have reported higher survival rates ranging from 31% (Charuau et al., 1982); 30-48% (Castro et al., 2003) to 45-65% (Méhault et al., 2016). There are multiple potential reasons for the wide disparities in estimates of post-discard survival including differences in the fishing gears and practices; differences in water and air temperatures and the length of air exposure and differences in how the catches are handled. The higher survival rates in the present study are likely related to the specific nature of this Clyde fishery that prioritises quality over volume resulting in short tows and rapid catch sorting.

Nevertheless the lack of standardisation in experimental designs does cause problems when comparing results between studies (Méhault et al., 2016, ICES, 2014). This is apparent not only in terms of the number of vessels which should be used (most survival trials conducted to date have been carried out in single vessels felt to be 'representative' of the wider fleet practices) but also in relation to the length of time that experiments need to be run for (Wassenberg and Hill, 1993; Castro *et al*., 2003; Campos *et al*., 2015). A report by STECF (2015) suggested observations on *Nephrops* recovery should be continued until mortality rates have stabilised which in some studies took as long as 10-14 days (Wileman et al., 1999). Measurements in the present study and in Albalat *et al*. (2010) suggest that physiological recovery to resting values occurs within 24-48 h. Delayed mortality thus appears to be mainly the result of physical damage (Wileman *et al*. 1999). Our model 2 survival estimate therefore assumed that any animals which were damaged or infected after 48 h recovery would die over the following few days and so this represents a conservative assumption of survival of around 63% (the lowest 95% CI). This approach might prove useful as establishing mortality curves over 10-14 days means that recovery cages must be inspected regularly. Regular inspection requires either raising them to the surface, which causes increased aerial exposure and stress, or the use of divers (feasible down to about 30 m) or potentially inspection using remotely-operated vehicles (ROV). Monitoring of recovery cages by divers has been used in some previous studies (Wileman *et al*., 1999) but considerably increases experimental costs. A final alternative is to allow animals to recover in tanks on-board fishing vessels or ashore (Edwards and Bennett, 1980; ICES, 2014). Whether tanks, however, adequately replicate natural recovery conditions is debateable especially where it is difficult to control factors such as temperature and salinity. Exposure to low salinity water in particular is known to cause stress to *Nephrops* (Harris and Ulmestrand, 2004). Because of these problems most studies on *Nephrops* have not monitored individual survival over time but have used start-end comparisons in recovery cages deployed for periods of between 2-9 days (Castro *et al*., 2013; Campos *et al*., 2015).

Because mortality in discarded *Nephrops* seems to be more related to physical damage than physiological stress, changes in fishing practice aimed at reducing damage should increase post-catch survival. Implementing such changes may be difficult within a commercial fishery context. For example the use of short tows, which appears beneficial in this fishery, may not be acceptable in other *métiers* where catch volume is more important and tow durations are up to four hours (Milligan et al., 2009; Fox, 2010). Improved survival of discarded *Nephrops* has also been reported with some gear modifications, such as in-trawl sorting grids and SELTRA panels (STECF, 2015). This may be related to reductions in the overall bulk of catch in the cod-end leading to reduced damage (Broadhurst et al., 2009). Nevertheless, these results remain to be confirmed as the higher survivals reported could also have a seasonal, rather than gear modification, basis (STECF, 2015).

Although the majority of discard survivability trials have allowed animals to recover in predator-free enclosures (Wileman et al., 1999; Bergmann and Moore, 2001; Castro et al., 2003; Revill et al., 2005; Mandelman and Farrington, 2007; Rulifson, 2007; Enever et al., 2009; Campos et al., 2015), it is widely recognised that this may over-estimate post-discard survival (Raby et al., 2014). Animals returned to the sea must escape potential predators and, in the case of *Nephrops*, seek protection in existing, or newly excavated burrows. In the present study around 80% of the discarded *Nephrops* were in vigour categories A-C immediately after being trawled (Fig. 3A) and results from our underwater observations suggested that these animals could right themselves, begin active movement and adopt natural defensive postures and escape responses within a few minutes of being returned to the seabed. On the other hand, animals in a moribund condition, as a result of longer air exposure, took up to 10 minutes to recover on the seabed. This time period was sufficient to attract predators, such as shore crabs and squat lobsters, which were observed to successfully capture at least one of these *Nephrops*. The metabolic capacity of moribund *Nephrops* thus appears to be compromised to the point where they struggle to make repeated escape tail-flips when attacked by predators (Gornik et al., 2008). Since moribund animals made up around 20% of the discard category immediately after trawling (Fig. 3A) these animals are likely to be more vulnerable to predation after reaching the seabed. Unfortunately our behavioural observations only extended over the immediate post-release period because we did not want to use fences around the camera arena which would exclude benthic predators. The relatively rapid attraction of predators to the discarded *Nephrops*, as also observed by Bergmann *et al*. (2002), suggests that future studies need to place more emphasis on such behavioural interactions. Discarded *Nephrops* might also be vulnerable to predation during the descent to the seabed but based on measurements of sinking rates and estimates of midwater predation, Bergmann *et al*. (2002) suggested that most discards in the Firth of Clyde would reach the seabed. For longer term survival studies STECF (2015) have suggested that tag and release programs may be required. Such programs would have to be run over extensive periods, tag loss rates evaluated, large numbers of *Nephrops* marked and a large percentage of the fishing vessels in the area equipped to detect the presence of the internal tags which would have to be used. The costs involved in such large-scale discard-survival programs are such that they may only be worth undertaking for animals with higher conservation concern and which are occasionally caught in *Nephrops* trawls, such as the flapper skate *Dipturis intermedia* (Neat et al., 2015).

Given the many factors which vary between fishing fleets, grounds, seasons and even individual vessels, producing realistic survival estimates for animals discarded in commercial fisheries remains extremely challenging. This study was conducted in a commercial vessel thought to be representative of practices in the Firth of Clyde trawl fishery that targets the live market. Further studies may be required to confirm that the data presented are representative of the wider fleet.

The fishery studied here is characterised by day vessels that perform short tows (typically < 2.5h) and practices which prioritise the quality of the animals over catch volume (Combes, 2007). This makes this fishery quite specialised compared with the majority of *Nephrops* trawling where tow durations and sorting times tend to be longer and the catches larger. Data from this study should therefore not be extrapolated to other trawl-based

Nephrops fisheries where further studies will be required to estimate the survival of discarded animals.

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Table 1: 95% confidence intervals for results of model 1. Results are expressed as baseline probability of mortality in each season, and increase in odds ratio of mortality according to each contributory factor.

Season	**95% confidence interval of probability of survival (healthy un-damaged *Nephrops*)**
Feb	93.4 – 97.1%
Mar	95.6 – 98.8%
June	98.8 – 99.9%
Category	**Increase in odds ratio of death comparing undamaged and uninfected animals with other categories**
Damage class 1	1.3 – 5.4 times
Damage class 2	2.0 – 35.8 times
Visually Infected	2.2 – 11.4 times
Soft	3.1 – 31.3 times

Table 2: 95% confidence interval for probability of survival for each season.

Model	February	March	June
(1) Actual survival, based on percentage of animals alive after 48 h recovery	90.1 – 95.8%	91.8 – 96.9 %	96.1 – 98.9 %
(2) Likely survival, assuming damaged or infected animals will not survive in the longer term	68.0 – 77.7 %	63.4 – 73.8 %	81.3 – 88.0 %

Fig. legends

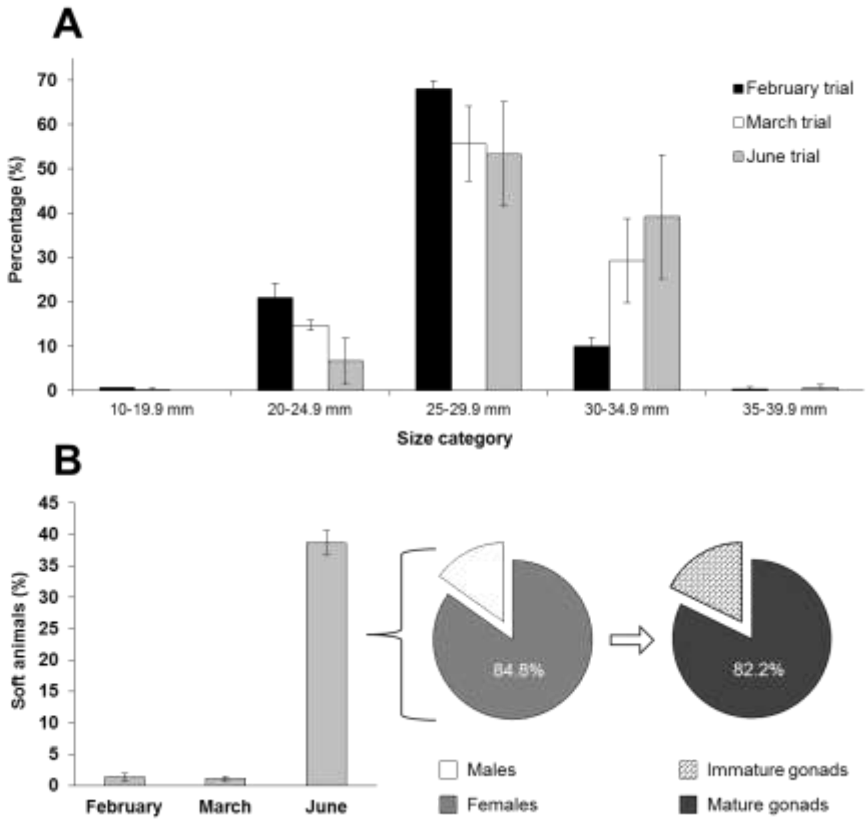
Fig. 1. (A) Size distribution of discarded *Nephrops* in the discard fraction by carapace length (mm) in the different trials **(B)** Percentage of 'soft' prawns in the discard fraction. From the soft category discarded in June the percentage of females and also the percentage of soft females that showed mature gonads are also shown. Vertical whiskers indicate mean ± S.E.

Fig. 2. (A) Percentage of discarded *Nephrops* classified according to the vigour index just after trawling (time 0) and 48 hours after recovery at sea from all discarded animals used in the survival trials **(B)** Percentage of discarded *Nephrops* classified according to the vigour index 48 h after recovery period in each trial.

Fig. 3. Percentage of discarded *Nephrops* alive (vigour A-C), moribund or dead after 48 hours recovery categorised by their initial **(A)** external damage and **(B)** visual infection with *Hematodinium***.**

Fig. 4. (A) Abdominal muscle and haemolymph L-lactate concentrations and **(B)** AEC ratio in the muscle of discarded *Nephrops* immediately after capture and after 48 h recovery. Values represent the mean ± S.E. of n=30 (for T0) and n=60 (for T48) animals for each trial. * indicates significant differences ($p<0.05$) between T0 and T48 while different letters indicate significant differences between trials. For reference, AEC values in rested Nephrops have been reported as being >0.8 (Albalat et al., 2010).

Fig 1.



A
February trial
March trial
June trial
Percentage (%)
70
60
50
40
30
20
10
0
10-19.9 mm
20-24.9 mm
25-29.9 mm
30-34.9 mm
35-39.9 mm
Size category
B
Soft animals (%)
45
40
35
30
25
20
15
10
5
0
February
March
June
84.8%
82.2%
Males
Females
Immature gonads
Mature gonads

Fig. 2

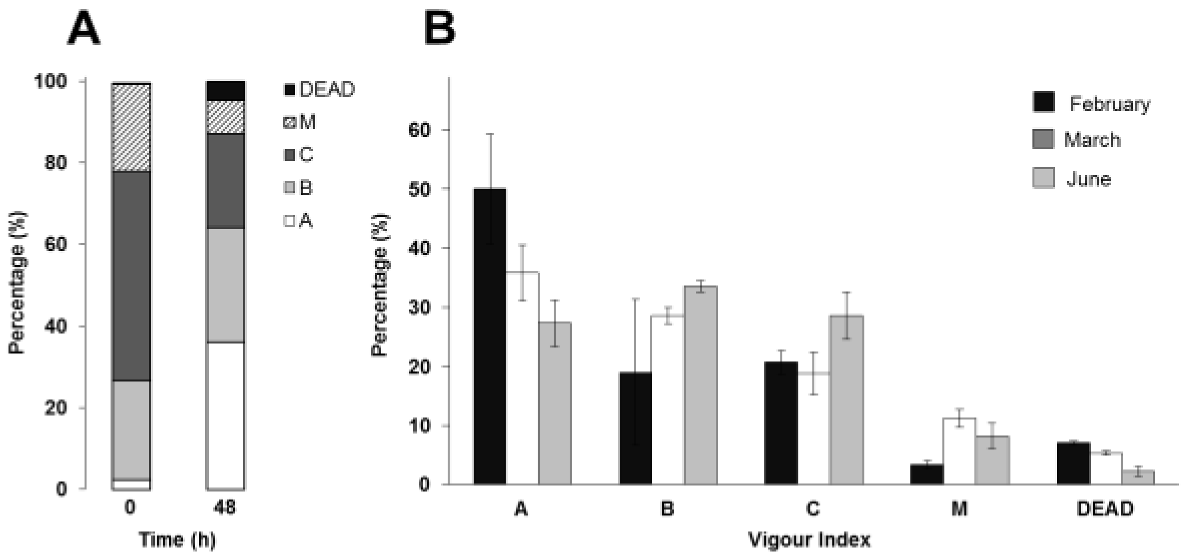

A
B
100
80
60
40
20
0
Percentage (%)
0
48
Time (h)
DEAD
M
C
B
A
60
50
40
30
20
10
0
Percentage (%)
February
March
June
A
B
C
M
DEAD
Vigour Index

Fig. 3

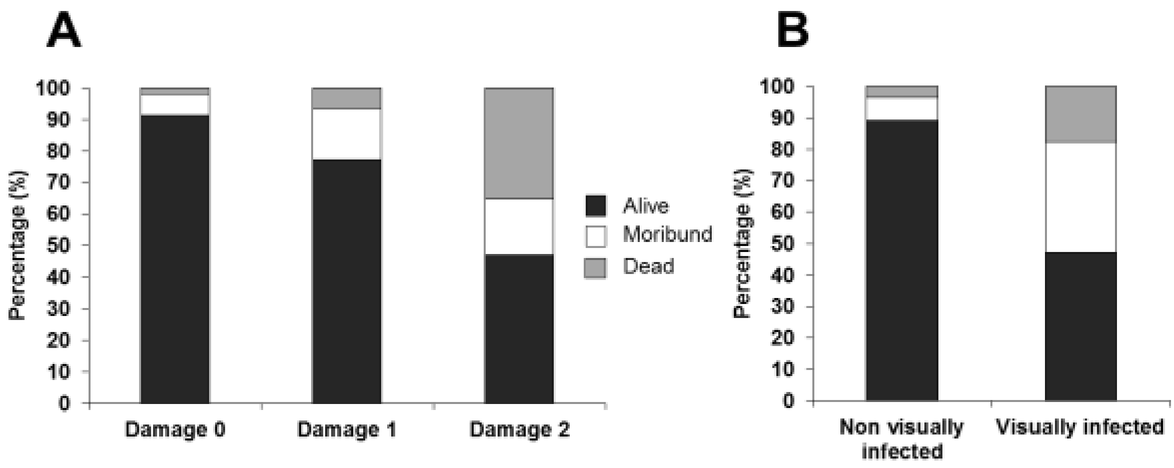
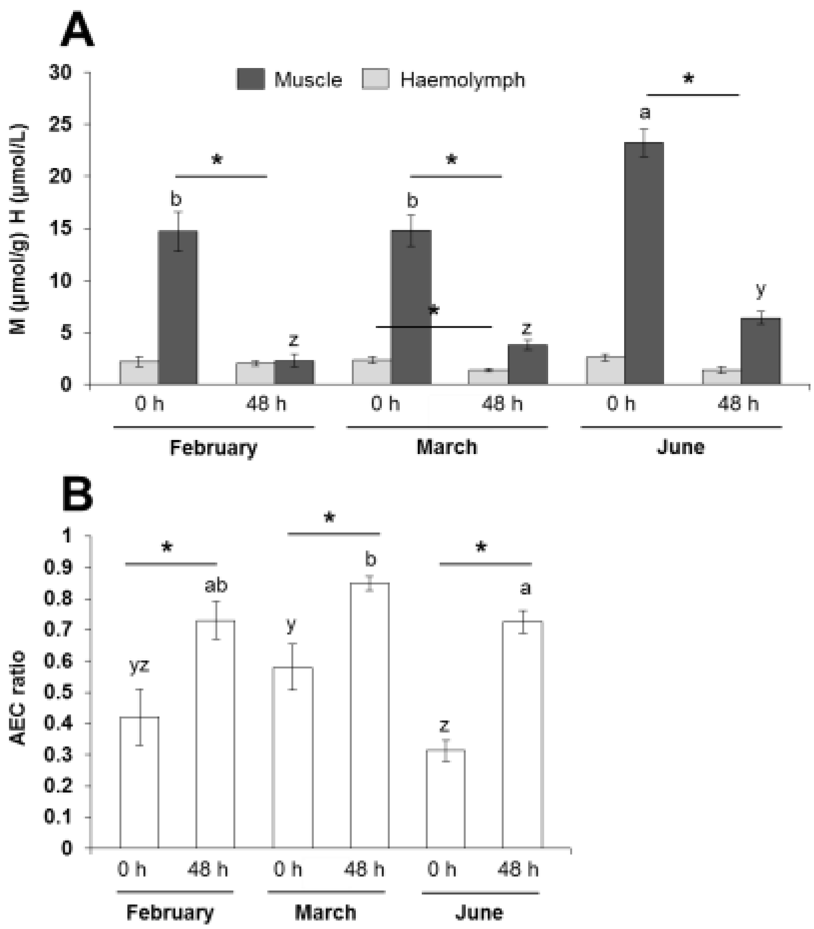

A
B
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
Damage 0
Damage 1
Damage 2
Alive
Moribund
Dead
Non visually infected
Visually infected

Fig. 4


A
Muscle
Haemolymph
M (µmol/g) H (µmol/L)
30
25
20
15
10
5
0
*
a
b
b
*
z
z
y
0 h
48 h
February
March
June
B
AEC ratio
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
yz
ab
y
b
z
a

Supplementary material

The following supplementary material is available online. **Table S1** General information and environmental conditions during the trawls and initial sampling of *Nephrops* for the recovery trials. **Table S2** General information and environmental conditions during the recovery of tubed animals. **Table S3**. Definition of the different Vigour Index categories used. **Table S4**: Deployment details (times UTC) of the behavioural studies. **Table S5**: Summary of video clips accompanying this report. **Fig. S1.** A representative tube-set used for the survival trial, a tube-set box closed ready to be re-immersed for survival trial. **Fig. S2.** Temperature and salinity water column profiles from the camera deployment locations.

Table S1. General information and environmental conditions during the trawls and initial sampling of *Nephrops* for the recovery trials.

Date	11/02/15		24/03/15			16/06/15		
Tow	1	2	1	2	3	1	2	3
Weather	Cloudy	Cloudy	Cloudy	Sunny	Sunny	Cloudy	Sunny	Cloudy
Start time trawl	08:00	11:25	07:45	11:00	14:11	07:47	11:35	15:10
End time trawl	09:15	13:00	09:06	12:30	15:58	09:25	13:13	16:24
Trawl duration (min)	75	95	81	90	107	98	98	74
Trawl start	55.757°N 4.895°W	55.800°N 4.884°W	55.799°N 4.882°W	55.802°N 4.888°W	55.820°N 4.899°W	55.814°N 4.903°W	55.803°N 4.893°W	55.802°N 4.719°W
Trawl end	55.128°N 4.889°W	55.127°N 4.888°W	55.129°N 4.889°W	55.129°N 4.890°W	55.156°N 4.900°W	55.036°N 4.070°W	55.031°N 4.901°W	55.005°N 4.908°W
Start trawl depth (m)	35	55	60	80	66	86	85	63
End trawl depth (m)	60	60	80	60	60	84	88	96
Towing Speed (knots)	2.1	2.1	2.1	2.1	2.2	2.0	2.1	2.0
Air temp (°C)	7.1	7.4	7.6	8.5	8.4	12.5	14.0	15.0
Water Surface Temp (°C)	7.9	7.6	7.5	7.9	7.9	11.8	12.0	12.0
Water Bottom Temp (°C)	8.0	8.0	7.3	7.3	7.3	-	-	-
Salinity water Surface (PSS)	32.6	32.2	32.0	31.7	31.7	-	-	-
Salinity water Bottom (PSS)	32.8	33.2	33.1	32.9	32.9	-	-	-
Time animals arrived on-board	09:20	13:08	09:18	12:41	16:11	09:38	13:27	16:35
Time animals put back in water	11:22	14:30	10:32	13:36	17:00	11:13	14:44	18:27
Sorting time (min)	122	84	74	55	49	95	77	112
Depth animals were returned to sea (m)	25	25	30	28	25	36	35	35
Location animals returned to sea to recover	55.132°N 4.874°W		55.778°N 4.895°W			55.777°N 4.894°W		

Table S2. Characteristics of the different Vigour Index categories used in the trials.

Vigour A	Vigour B	Vigour C	Moribund	Dead
Animal displays defensive posture, and/or vigorous and possibly prolonged (>10 flips) tail flipping	Bouts of tail flipping are less frequent and vigorous, lasting for shorter periods (<10 flips approx). Animal less likely to adopt defensive posture	Bouts of tail flipping are infrequent and do not normally exceed 5 flips per bout (approx)	Tail flips are very infrequent and weak and are limited to 1 or 2 flips per bout	No limb movements even if animal is stimulated
Antennae and claws are held high and may be 'waved' by the animal	Antennae and claws are raised but moved less vigorously	Antennae and claws are drooped but animal can raise them for short periods (a few seconds)	Antennae and claws are drooped and animal is unable to raise them	
Tail is held rigid up-right in an angle (when animal is not tail flipping). Related to reflex response.	Tail is held horizontally retains some tension. Related to reflex response.	Tail is drooped and retains very little tension. Related to reflex response.	Tail is limp. Related to reflex response.	
Walking legs are strong and animal will often right itself	Walking legs are moved but animal normally cannot right itself	Walking legs are moved by the animal but it will not be able to right itself	Walking legs are moved very slowly if animal is stimulated	

Table S3. General information and environmental conditions during the recovery of tubed animals.

Month	13/02/15		26/03/15			18/06/15		
Tow	1	2	1	2	3	1	2	3
Air temp (°C)	6.5	7.5	6.4	8.3	9.7	12.0	11.5	11.0
Water temp Surface (°C)	7.5	7.5	7.5	7.5	7.5	11.5	11.0	11.0
Water temp Bottom (°C)	8.1	8.1	7.4	7.4	7.4	-.	-	-
Salinity water Surface (PSS)	32.6	32.6	31.3	31.3	31.3	-	-	-
Salinity water Bottom (PSS)	33.2	33.2	32.9	32.9	32.9	-	-	-
Time animals arrive on-board	10:09	10:07	09:45	13:04	13:04	09:51	11:30	14:25
Time start sampling	10:15	11:42	09:50	13:23	14:04	09:53	11:30	14:28
Time finish sampling	11:40	13:15	11:26	14:02	14:55	11:22	12:50	15:37
Total time aerial exposure (min)	91	188	101	58	111	89	80	69

Table S4. Deployment details (times UTC) performed on behavioural discards *Nephrops*.

		Prawn	1	2	3	4	5	6	7	8	9	10
Deployment 1	Trawl began	06:00										
	Trawl tow ended	07:30										
	Prawns transferred to Calanus	07:45										
	Prawns placed under camera	09:09										
	Post-trawl treatment	~90 mins in air										
	Air temperature (°C)	9.5										
	Vigour	Individual vigour not recorded but a mix of C and Moribund										
	Comments	Test dive (sizes of animals not recorded)										
Deployment 2	Trawl began	07:45										
	Trawl tow ended	09:45										
	Prawns transferred to Calanus	10:00										
	Prawns placed under camera	10:50										
	Post-trawl treatment	~ 60 mins in air										
	Air temperature (°C)	16.5										
	Size (mm)		28	30	30	28	28	30	30	30	31	29
	Vigour		B	A/B	A	A/B	B	B	B	A/B	B	B
	Comments	Spare animals were sunk in tubes at 20 m and also used in deployment 3										
Deployment 3	Trawl began	As above										
	Trawl tow ended	As above										
	Prawns transferred to Calanus	As above										
	Prawns placed under camera	11:20										
	Post-trawl treatment	~ 30 mins air, 65 mins recovery at 20 m										
	Air temperature (°C)	17.0										
	Size (mm)		25	27	28	28	29	27	28	28	31	32
	Vigour		B	B	B	A	A/B	C	B/C	B	B	B
	Comments											
Deployment 4	Trawl began	10:30										
	Trawl tow ended	12:30										
	Prawns transferred to Calanus	12:43										
	Prawns placed under camera	13:04										
	Post-trawl treatment	~ 30 min air										
	Air temperature (°C)	17.3										
	Size (mm)		28	26	25	28	26	26	29	26	27	27
	Vigour		A	B/C	B/C	B	B	A/B	B	B	B	B
	Comments											
Deployment 5	Trawl began	13:00										
	Trawl tow ended	14:40										
	Prawns transferred to Calanus	15:00										
	Prawns placed under camera	15:30										
	Post-trawl treatment	~ 50 mins air										
	Air temperature (°C)	17.3										
	Size (mm)		25	25	25	25	25	28	26	29	26	22
	Vigour		B/C	B/C*	B/C	B/C	B/C	B/C	B/C	B/C	B/C	B/C
	Comments	Deployment used to diver observations and to take flash stills photographs, video not analysed further										

Table S4. Deployment details (times UTC) performed on behavioural discards *Nephrops*.

Supplementary Table 1. Summary of video clips.

Filename	Timestamp (hh:min:sec)	Time since release (min:sec)	Summary main events
Montage_Deploy1	09:09:23	00:00	Prawns released into arena
	09:09:44	00:21	2 prawns show almost immediate recovery
	09:09:48	00:25	Diver withdraws from site
	09:10:11	00:48	Prawn at top of group exhibits a flick-tail escape response, another prawn begins to recover and move around
	09:10:53	01:30	Another prawn recovers and moves away; 5 unrecovered animals remain
	09:12:00	02:37	Four more prawns begin to show signs of recovery, limb movement, attempts at righting
	09:14:53	05:30	All prawns except one showing some signs of recovery although three animals have still failed to fully right themselves.
	09:16:23	07:00	All prawns except two have either left the arena or are moving within the arena
	09:18:13	08:50	Prawn at top left interacts with another recovering animals and exhibits a flick-tail escape
	09:18:53	09:30	All prawns righted, all except one moving around, squat lobster enters arena and one prawn evades
	09:19:33	10:10	Prawn nips squat lobster which moves away, one prawn still only partially righted (camera 5)
	09:20:07	10:44	Squat lobster attacks partially righted prawn
	09:20:36	11:13	First crab arrives and chases off squat lobster
	09:20:39	11:16	Crab attacks recovered prawn but prawn exhibits escape response
	09:21:13	11:50	Crab attacks damaged prawn which exhibits a flick-tail response but then fails to right itself (moving from camera 5 to 6)
	09:21:31	12:08	Second crab then moves in to attack a separate prawn (camera 5)
	09:21:37	12:14	Both crabs then attack the prawn
	09:21:53	12:30	Prawn is dragged out of camera arena by one crab and second crab resumes searching
Montage_Deploy2	10:49:54	00:00	Prawns placed in camera arena
	10:50:01	00:07	Eight or nine prawns seem to recover almost immediately and begin to disperse
	10:50:08	00:14	Remaining prawns right themselves and

Table S4. Deployment details (times UTC) performed on behavioural discards *Nephrops*.

			begin moving around
	10:51:01	01:07	All animals appear to be moving around within, or have exited the arena, rate of tidal flow picking up compared with earlier deployment
	10:51:44	01:50	Single prawn re-enters arena, moving around on seabed
	10:51:50	01:56	Second prawn re-enters after exhibiting tail-flick escape response from some unseen stimulus
	10:53:05	03:11	End
Montage_Deploy3	11:20:54	00:00	Tide had picked up and diver reported that the prawns were all active but dispersed very rapidly, video of a single animal walking within the arena
	11:21:35	00:39	End
Montage_Deploy4	13:04:35	00:00	Prawns placed in arena, camera 3 not working
	13:04:40	00:05	Four animals show good recovery and move away
	13:04:45	00:10	All animals have righted themselves and are beginning to recover
	13:05:02	00:27	Three animals remain within arena
	13:05:44	01:09	Four prawns continue moving around within arena
	13:06:31	01:56	Two prawns show interaction then move apart
	13:06:49	02:14	
	13:10:00	05:25	End
Montage_Deploy5			Not analysed, divers using flash still photography

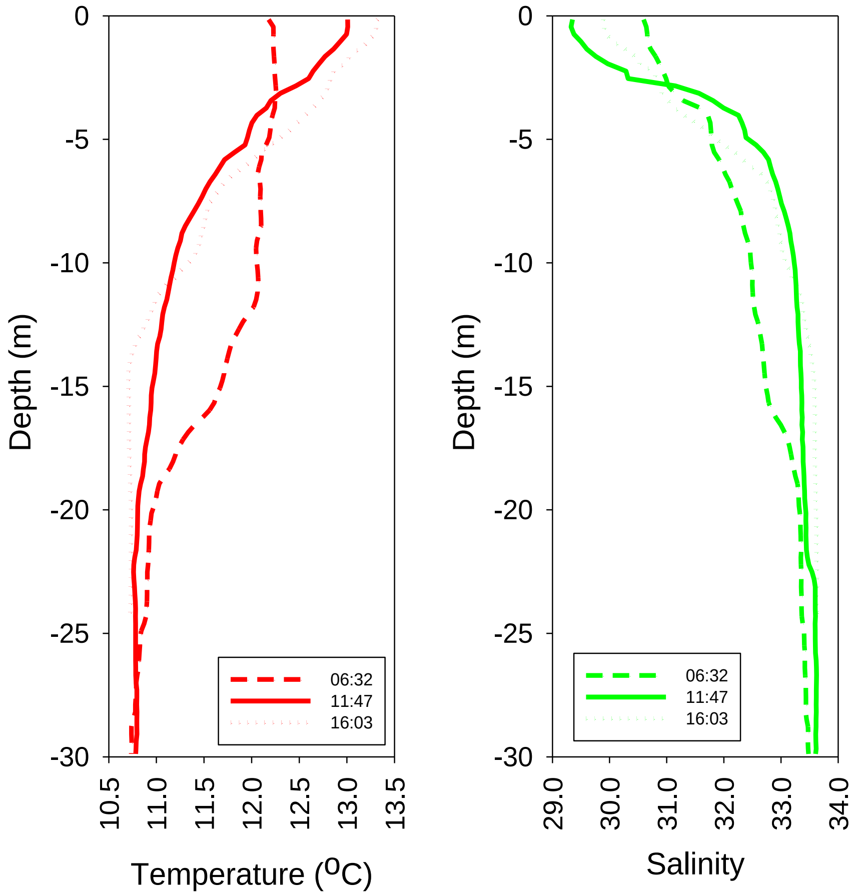
0

Suppl. Fig. 1

A)

B)

Suppl. Fig. 2.


0
-5
-10
-15
-20
-25
-30
Depth (m)
06:32
11:47
16:03
10.5
11.0
11.5
12.0
12.5
13.0
13.5
Temperature (°C)
0
-5
-10
-15
-20
-25
-30
Depth (m)
06:32
11:47
16:03
29.0
30.0
31.0
32.0
33.0
34.0
Salinity