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Survival rates for *Nephrops norvegicus* discarded from Northern European trawl fisheries

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Abstract

When discarded from bottom trawl fisheries, survival of *Nephrops norvegicus* may be sufficiently high that this species can be exempted from the EU Landing Obligation. In three studies, *Nephrops* were sampled from trawlers in northern European waters and the fate of individuals monitored for a minimum of 13 days in onshore tanks. Winter estimates of captive survival (means ± 95% confidence intervals), including immediate mortality during catch sorting, were 62 ± 2.8% for the West of Scotland, 57 ± 1.8% for the Farne Deeps (North Sea), and 67 ± 5.4% for the Skagerrak. The Farne Deeps fishery is not active in summer, but captive survival rates in summer in the other two areas were reduced to 47 ± 3.4% for West of Scotland and 40 ± 4.8% for the Skagerrak. Linear modelling of the West of Scotland and Skagerrak data suggested that higher survivals in winter were related to colder water or air temperatures although temperatures during captive observation may also have had an impact. Net modifications in the Skagerrak study had an effect on survival, which was higher for *Nephrops* sampled from nets equipped with the more selective Swedish sorting grid compared with Seltra trawls.

Keywords: Discards survival; *Nephrops norvegicus*; Trawl fisheries; Landing Obligation

Introduction

One of the main aims of the European Union's reformed Common Fisheries Policy (Regulation (EU) No. 1380/2013) is to reduce unwanted catches through a phased landing obligation for regulated species, the obligation being fully implemented in 2019. Whilst technical measures that allow unwanted animals to escape before being brought onto the vessel are encouraged (Catchpole *et al.*, 2017), such measures rarely eliminate the unwanted components of the catch completely (Broadhurst *et al.*, 2006). The landing obligation thus includes exemptions and flexibility tools including for "species for which scientific evidence demonstrates high survival rates, taking into account the characteristics of the gear, of the fishing practices and of the ecosystem". Producing robust estimates of post-discard survival has thus become a focus for research because evidence from such studies influences whether exemptions will be granted (Morfin *et al.*, 2017). Allowing continued discarding of organisms with demonstrated high survivability does make conservation sense since a high proportion should survive and contribute to the stock (Rihan *et al.*, 2019).

Nephrops norvegicus is a small decapod crustacean that has become increasingly important in many European fisheries from Norway to the Bay of Biscay (Ungfors *et al*., 2013). Because individual *Nephrops* are encased in a strong exoskeleton, and lack gas-filled body cavities, it has been suggested that this species should be a suitable candidate for the high survivability exemption from the landing obligation. Most discard survival estimates have come from captive observation where *Nephrops* are sampled from fishing vessels and held in captivity, recording their survival over time. However, historical survival estimates from trawl fisheries have been rather variable. Published rates include 17–18% (Campos *et al.*, 2015); 19% or 31% depending on area (Charuau *et al.*, 1982); 42% or 75% dependent on area, trawler type and sea conditions (Edwards and Bennett, 1980); 51% (Méhault *et al.*, 2016) and 56–70% (Guéguen and Charuau, 1975). Some of this variation may be due to differences in fishing gears, methods of handling or environmental conditions but the ICES Workshop on Methods for Estimating Discard Survival (WKMEDS) suggested that variable experimental approaches might also be an important factor (ICES, 2014). For example, some studies have monitored survival using cages or containers placed on the seabed (Guéguen and Charuau, 1975; Campos *et al.*, 2015; Méhault *et al.*, 2016), whilst other studies have monitored survival in aquaria. In some studies, monitoring times may have been too short because mortality can be delayed (Wileman, 1999). As one of their outputs, WKMEDS produced methodological guidance with the aim of improving the robustness and reproducibility of results from discard survival experiments (ICES, 2014). For captive observations, recommendations included assessing initial animal condition using standardised criteria, monitoring for a sufficient time and incorporating control subjects to evaluate the effect of holding conditions.

The main aim of the present study was to compare the survival of discarded *Nephrops* across three distinct northern European trawl fisheries. Although the research followed the WKMEDS recommendations, there were inevitably some methodological differences as the three studies were conducted by different research groups (Valentinsson and Nilsson, 2015; Armstrong *et al.*, 2016; Fox and Albalat, 2018). Links between survival and biological (sex, damage and vitality), environmental (sea and air temperature) and operational factors (haul duration, catch weights and sorting times), were also examined in order to suggest changes in trawling practice that might increase the survival of discarded *Nephrops*.

Methods

Operational factors

Study 1 was undertaken using the MFV Ocean Trust (PD787), a 24 m stern trawler operating out of Mallaig (Scottish west coast, ICES Divivision VIa, Figure 1). Fishing took place in winter and summer on commercial grounds that were reasonably close to Mallaig to allow experimental animals to be returned to the Scottish Association for Marine Science (SAMS) aquarium, which is approximately 86 miles south by road, in reasonable time. Fishing gear comprised a commercial twin-rig *Nephrops* trawl with both nets fitted for half the hauls with 80 mm and half the hauls with 100 mm diamond mesh cod-ends. A 200 mm square-mesh escape panel (SMP) was fitted in the top-sheet of each net in accordance with local regulations, but the nets did not have any further selectivity modifications (Table 1).

Study 2 was undertaken using the MFV Luc (SN36), an 18 m single-rig stern trawler operating out of North Shields (English northeast coast, ICES Division IVb). Experimental fishing took place at the southern edge of the Farne Deeps in winter only (Figure 1). The net had an 80 mm diamond mesh cod-end and incorporated a NetGrid selectivity device (Table 1). The NetGrid consists of a four-panel box section with a fish escape hole inserted into a standard two-panel trawl with an inclined netting sheet (Armstrong *et al.*, 2016).

Study 3 was undertaken in winter and summer using two commercial, twin-rig stern trawlers, the Canopus (LL377; 12 m) and the Ternö (LL388; 14.9 m) fishing on commercial grounds in the eastern Skagerrak (Swedish southwest coast, ICES Division IIIa, Figure 1). Each vessel deployed a standard Swedish grid trawl (hereafter abbreviated as SweGrid) comprising 35 mm bar-spacing with a 70 mm square-mesh cod-end as described in Valentinsson and Ulmestrand (2008), and a Seltra trawl with 90 mm diamond mesh cod-end and a 270 mm diamond-mesh escape window as described in Krag *et al.* (2016).

Environmental factors

Sea surface temperatures were measured at least once a day using a Sonetek Castaway (Sontek, San Diego, CA, USA) CTD (Study 1), an Oxyguard Handy Polaris 2 (Study 2) and an SD204 (SAIV A/S, Bergen, Norway) CTD (Study 3). Vertical water column profiles were only recorded in studies 1 and 3. However, thermal and salinity stratification is typically minimal in Feb. – Mar. at the trawl sites in study 2 (Janssen *et al.*, 1999), so surface values for these parameters should have been close to those at the seabed. In all three studies, air temperatures were recorded in the catch sorting area of the fishing vessel for each haul using digital thermometers.

Catch sorting, sampling and biological factors

In all three studies, the trawler crews were asked to follow their normal fishing and catch sorting practices. On all four of the fishing vessels, the catch is dropped into a flat-bottomed metal hopper, from where it is raked via a hatch to a sorting table. Drop height in study 1 was 1.5 m, in study 2 it was less than 1 m and in study 3, 0.8–1 m. In study 1, we had to assume that effects on *Nephrops* (levels of physical damage etc.) would be similar in both cod-ends as the catches were not kept separate but dropped sequentially into the hopper, following the normal fishing practice. In study 3, the catch from each net was kept separate by dividing the hopper using wooden boards.

In study 1, the catch length profiles were based on measurements of at least 100 *Nephrops* taken unselectively from different parts of the catch. For studies 2 and 3, only those *Nephrops* selected for captive survival observation were measured on-board. For these regions, the typical size ranges of *Nephrops* in the catches and discards were estimated using fisheries observer data collected between 2011–2017 for ICES Division IVb, functional unit 6 and from 2015 for ICES Division IIIa.

In all four vessels, the normal practice is that discards are returned continuously to the sea throughout catch sorting via a chute at the end of the sorting table. For each haul in study 1 (summer), scientific staff sampled *Nephrops* being discarded from the start of catch sorting until a target of 100 live animals was reached. This was subsequently modified (winter season) to take a target of 100 *Nephrops* from the start, and an additional 50 towards the end of catch sorting. For study 2, around 200 *Nephrops* were sampled randomly throughout catch sorting across the whole size range from each haul. For study 3, observers firstly estimated the amount of *Nephrops* likely to be discarded from the catches and then adjusted the rate of sampling to cover the catch sorting period. The number of dead *Nephrops* encountered during sampling was also recorded and used to estimate immediate mortality for each haul. In all three studies, individual carapace lengths of the sampled *Nephrops* were measured using digital callipers. Sex was recorded during studies 1 and 3, but not during study 2. In all three studies, each animal selected for captive observation was examined for signs of visible damage (Table 2) with care taken to examine both ventral and dorsal surfaces. The vitality of each animal was also assessed (excepting Study 3, summer hauls). *Nephrops* sampled for captive observation were then placed into individual compartments in commercial tube-sets (Figure 2). Once sampling was completed, the tube-set boxes were closed using perforated lids and placed into insulated containers filled with seawater. Water in the on-board holding tanks was renewed periodically to ensure conditions did not deteriorate during transport to the onshore holding facilities.

Transport and onshore holding

For study 1, the tube-set boxes were then transported by road from Mallaig to the SAMS aquarium. Cold blocks were added to the insulated containers and air supplied using a portable compressor during transportation. For study 2, once the trawler had returned to port, the tubeset boxes were placed directly into onshore holding tanks located at the quay. In study 3, boxes were moved directly from the fishing vessels into the Kristineberg Marine Research station aquarium. Oxygen levels, temperature and ammonia were checked in the transport containers on arrival at the onshore holding facilities.

Control animals

In study 1, controls were recovered discard fraction *Nephrops* from the previous trip that showed no visual injuries. Between experiments, the control animals were held in a common tank containing pieces of plastic pipe to act as refuges and fed on finely chopped mussel (*Mytilus edulis*) every second day. Ten control animals were added to each box of test animals when the box was transferred to the onshore aquaria, except for the first hauls in each season when recovered *Nephrops* were not yet available. For study 2, control animals were sourced from a local creel fisher working in a different part of the Farne Deeps. These creel caught controls were transferred to the quayside aquaria and held unfed for the two weeks before the first treatment monitoring. The next opportunity to collect control animals was for the third of three monitoring periods, during which the collection of the control and treatment animals was synchronised. For study 3, control *Nephrops* were caught using creels from an area where trawling is not allowed but with similar habitat, depth and environmental conditions to the experimental trawl locations. The creels had a smaller than usual mesh size (20 mm) in order to catch smaller *Nephrops* of sizes comparable to those normally discarded by the trawlers. Control animals were added to the observation boxes on return to the quay i.e. control animals were not held in captivity prior to the experiments.

Observation tanks

Observation tanks were supplied with running seawater at a sufficient rate for replacement at least every 2 h. Seawater for the SAMS aquarium is drawn from a sub-sand beach filter and incoming water temperatures can become high in summer. Observation tanks in study 1 were therefore housed in a constant temperature room with additional chilling of the incoming water. For study 2, temperatures in the observation tanks followed those of the ambient pumped seawater because the observation tanks were located on the dockside. In study 3, seawater is drawn from a deep supply. The observation tanks were housed in a constant temperature room but additional water chilling was not used. Observation tanks were also aerated in studies 1 and 3. In study 1, temperatures in the observation tanks were monitored every 10 minutes using Hobo TidbiT loggers (Onset Computer Corp., Bourne, Massachusetts) and salinity was checked daily using a Castaway CTD (Sontek, San Diego, California). Dissolved oxygen (DO) was monitored daily using an YSI (Yellow Springs, Ohio) Pro20 portable oxygen meter, but only during the winter studies due to equipment availability. Ammonia levels were checked daily using API saltwater test strips (Mars Fishcare, Chalfont, Pennsylvania). In study 2, temperature and dissolved oxygen in the onshore holding tanks were measured daily using a portable meter (OxyGuard Handy Polaris2) but salinity was not monitored. In study 3, temperature, salinity and DO were measured daily using portable meters (WTW Multi 3510) and water samples collected and analysed for ammonia.

Captive observations

Nephrops were not fed during captive observation. In study 1, *Nephrops* survival was monitored every two days from 1 – 13 days post-sampling. For study 2, inspections occurred daily up to 15 days, plus an additional evaluation of remaining survivors at 21 days. For study 3, *Nephrops* were monitored daily up to 15 days post-sampling. In all cases, the boxes were lifted out of the observation tanks and the individual *Nephrops* checked in air. Exposure to air was usually sufficient to cause live individuals to move but any that showed no movement were gently stimulated with blunt forceps. If they still failed to react to physical stimuli, they were recorded as dead and removed from the box.

Statistical analyses

Nephrops sizes are reported as carapace lengths in mm. All statistical analyses were performed using R version 3.5.0 (R Core Team, 2018) with additional packages 'boot', 'ordinal', 'survival' and 'wrs2'. Statistical test results were considered significant at the $p<0.05$ level.

Statistical analyses —data collected on board the fishing vessels

Exploratory analysis of sea and air temperatures, haul durations, catch weights and catch sorting times by study was conducted using pairs-plots and Kendall's tau to screen for potential collinearity . *Nephrops* size data were visualised using length frequency histograms.

Differences in immediate mortalities within each study were explored using boxplots and tested using a non-parametric two-way median test. Potential relationships between immediate mortality and available covariates (sea surface and air temperatures, haul duration, catch weights, catch sorting times, plus gear modification in study 3) were explored using scatterplots and Kendall's tau. Immediate mortalities were then modelled as the total count of alive versus dead *Nephrops* in each haul using quasi-binomial GLMs that were sequentially simplified by eliminating non-significant factors, starting with the full model (Crawley, 2014). The final model fits were assessed using Pearson residuals.

Data for physical damage at the time of sampling were summarised and ranked to identify the most common injuries in each study. The mean rate of occurrence of the top five injury types in each study was computed. Non-symmetrical 95% confidence intervals for these means were estimated by boot-strapping as the percentage of occurrence for some injury types was close to zero. Exploratory analysis of potential relationships between the percentages of injured *Nephrops* and available covariates were conducted as described above for immediate mortality. Analysis of the vitality scores from study 2 showed an unexplained increase in the proportions in the 'Excellent' category comparing hauls on the 3rd and 4th February with later dates. To standardise the vitality scores as much as possible within and across the three studies, the 'Excellent' category was combined with the 'Good' category to create E/G, and the 'Poor' category combined with the 'Moribund' category to create P/M. This was based on the argument that the criteria for separating high vitality from low vitality animals was likely to be more consistent than when assigning animals to the finer divisions (Table 2), under challenging field conditions. Because vitality might be related to the presence of physical injuries, chisquare tests were applied to the frequencies of animals with injury presence or absence by E/G or P/M categories. Data on physical injury and vitality were then combined by assigning individual

Nephrops to one of four categories: Uninjured and E/G; Uninjured and P/M; Injured and E/G; Injured and P/M. Potential relationships between the percentage of *Nephrops* in each category and available environmental and operational covariates (sea surface and air temperatures, haul duration, catch weights, catch sorting time, plus gear for Study 3) were explored using scatterplots and Kendall’s tau and modelled using ordinal regression with a logit link for each study. Non-significant terms based on the Wald F-statistics were sequentially removed from the regression models and the proportional odds assumption of final models tested using the ‘nominal_test’ in the R ‘ordinal’ package. *Statistical analyses — data from the captive observations*

Survival of control *Nephrops* was evaluated by study and the effect of season for studies 1 and 3 tested using Fisher’s exact test. The effect of biological factors (sex, presence of damage and vitality at time of sampling) on the survival of individual *Nephrops* in the captive observations was visualised using Kaplan-Meier survival curves with differences being tested using log-rank tests (Moore, 2016; Kleinbaum and Klein, 2012). Because the assumption of independence between each *Nephrops* within an observation box might be invalid, we firstly estimated mean survivals (plus standard errors and 95% confidence intervals) for each haul from the Kaplan-Meier estimator at the time of the final mortality event. These survival estimates were then used to generate group mean survivals by study, season and gear. To account for the uncertainty in the underlying haul-based mean survival estimates, 95% confidence intervals were computed as twice the standard error incorporating propagation of error following formula [1], assuming each haul-based estimate to be independent within the group.

$$SE = \frac{\sqrt{\sum_i \sigma_i^2}}{n} \qquad [1]$$

where n is the total number of contributing estimates and σ are the variances of each contributing estimate in the group $_i$.

Potential relationships between mean survival in each study and available biological (percentages of *Nephrops* in each damage presence/absence, E/G or P/M group), environmental (sea surface and air temperatures) and operational covariates (haul duration, catch weights, sorting time, plus gear for Study 3) were explored using scatterplots and modelled using multiple linear regressions with sequential removal of non-significant terms (Crawley, 2014). Whilst percentage data, such as survival, infringe the limits for Gaussian error-distributions this only becomes a serious issue for linear modelling if the response variable values lie close to 0 or 100. For a range of 30 – 70%, ordinary linear modelling can be reasonably applied (Long, 1997). Final model fits were assessed visually using Pearson residual plots.

Results

Environmental conditions during trawling

Winter air temperatures in studies 1 (West of Scotland) and 2 (North Sea) were between 6.9 – 11.5ºC, but were colder in study 3 (Skaggerak). In summer, the air temperatures in both regions reached as high as 19ºC. There was also a greater seasonal difference in sea surface temperatures comparing the West of Scotland with the Skagerrak. In study 1, there was little thermal stratification, even in summer but this was apparent in study 3 (Table 3). In studies 1 and 3, near bottom salinities were around 34 but surface waters in the Skagerrak were fresher with salinities of 24 – 29. Salinity was not recorded in study 2.

Catches and discarding practices

Based on pairs plots (Figures S1–S4), there were no obvious relationships between haul duration and catch weight in any of the three studies but total catch sorting times were significantly related to the *Nephrops* catch weight in study 1 (Figure S1), and to the total catch weight in study 2 (Figure S2). For study 3, there did not seem to be any strong relationships between total sorting times and catch weights (Figure S3 and S4). There was a noticeable difference in the relative weights of *Nephrops* versus non-*Nephrops* in the catches, this being much lower in study 3, where *Nephrops* comprised as little as 20 kg per net haul (Table 1). In study 1, the non-*Nephrops* components of the catches were mainly spotted dogfish (*Scyliorhinus canicula*), rays (Rajidae), ling (*Molva molva*), mackerel (*Scomber scombrus*), various flatfish including dab (*Limanda limanda*) and juvenile gadoids such as cod (*Gadus morhua*), hake (*Merluccius merluccius*) and haddock (*Melangrammus aeglefinus*). In study 2, the non-*Nephrops* components of the catches were mostly small gadoids. In study 3, the majority of the catches were comprised of flatfishes, gadoids and other benthic invertebrates. Details of the individual hauls are given in Table S1.

In study 1, the size range of *Nephrops* caught was 15 – 66 mm with a dominant mode at 28 mm and the size range of discarded *Nephrops* was 16 – 36 mm (Figure 3a). The majority of discards (96%) in study 1 were larger than the Minimum Conservation Reference Size (MCRS) for this fishing area. In study 2, the size range of *Nephrops* in the catch was 20 – 55 mm with a dominant mode at 28 mm (Figure 3b). This size range also closely matches that recorded over seven years by fisheries observers on English trawlers fishing in the Farne Deeps. Observer data for ICES Division IVb showed that similar sizes of *Nephrops* are typically discarded as in study 1 but, because the MCRS is larger in Division IVb, a smaller percentage (54%) of these discarded *Nephrops* were above the MCRS (Figure 3b). In study 3, fisheries observer data for 2015 showed that *Nephrops* in trawl catches from this area ranged from 20 – 69 mm. Discarded *Nephrops* in study 3 ranged from 20 – 58 mm with a minority (8%) being above MCRS (Figure 3c). Compared with the other areas this reflects the larger MCRS in ICES Division IIIa at the time (Hornborg *et al.*, 2017). Thus, in all three study areas *Nephrops* were being discarded for reasons other than the animals being below the minimum legal size, this being a particularly prominent feature in studies 1 (ICES Division VIa) and 2 (ICES Division IVb).

Immediate mortality

In study 1 in winter, the mean immediate mortality (± 95% lower confidence level (LCL), upper confidence level (UCL)) was 9.7% (7.8, 11.9) and in summer, it was 14.5% (11.9, 19.7). However, because of variability in the immediate mortalities, neither season nor cod-end mesh size were statistically significant (Figure 4; med2way test: Season p=0.13, Cod-end p=0.51). Plotting immediate mortality by haul against available covariates (Figure S5) suggested that immediate mortality might be related to total catch weight, *Nephrops* catch weight, sorting time and air temperature with a possible effect of sea surface temperature. However, sequential removal of least significant terms in the GLM resulted in retention of sorting time alone (Table 4), although this factor was itself correlated with *Nephrops* catch weight (Figure S1). In study 2, no immediate mortality was observed. In study 3 in winter, mean immediate mortality (± 95% LCL, UCL) was 1.6% (0, 3.2) but in summer increased to 14.6% (11.6, 17.8). Median immediate mortality was significantly related to season, but not to gear (Figure 4; med2way test: Season p<0.001, Gear modification p=0.08). Scatterplots for study 3 (Figure S6) suggested that immediate mortality might be related to sea surface temperature and this term was retained in the final GLM (Table 4). Residual plots for the GLM models for studies 1 and 3 indicated reasonable fits.

Injury and vitality during catch sorting

The percentage of discarded *Nephrops* with at least one visible injury ranged between 23 – 67% of the animals examined from each haul. The most common injuries were loss or damage to one or both chelae, puncture and crush wounds to the thorax or abdomen and damaged rostra

(Table 5). Damage to one or more legs, the telson or the eye occurred in less than 1% of the *Nephrops* examined. Scatterplots of the percentage of damaged *Nephrops* against available covariates failed to reveal significant relationships, except in study 1 with non-*Nephrops* catch weight and in study 3 with sea surface temperature (Figures S7, S8). For vitality, the percentage in the E/G category in each haul was related to sea surface temperature in studies 1 and 2, and to haul duration in the winter hauls of study 3 (Figures S9, S10). In all three studies, the presence of at least one physical injury tended to reduce the vitality score of individual *Nephrops* (Study 1: Chisq = 107, df=1, $p<0.001$; Study 2: Chisq = 228, df=1, $p<0.001$; Study 3: Chisq = 13, df=1, $p<0.001$) justifying combining the presence of at least one physical injury with vitality. However, ordinal regression of *Nephrops* assigned to these combined injury plus vitality categories failed to identify any significant environmental or operational covariates.

Conditions on-board and during transport

In study 1, the time elapsed between sampling and transfer of tube-boxes into the observation tanks varied from 3 – 9 h with the road transport normally taking around 2 h. Oxygen levels on arrival at the aquarium were between 7.8 – 8.8 mg l^{-1}. Ammonia levels were elevated but not above 1 mg l^{-1}. In study 2, *Nephrops* were held in on-board tanks on the fishing vessel for 2.5 – 5.5 hours, oxygen saturation remained above 90% and the animals were then transferred directly to the quayside facility. In study 3, time elapsed between sampling aboard and the transfer of the boxes into the observation tanks varied from 2 – 4 h. Oxygen saturation was always above 90%, and ammonia levels never exceeded 0.15 mg l^{-1}.

Conditions in the captive observation tanks

In study 1, the mean water temperature in the observations tanks was 7.6ºC in winter fluctuating by less than 1ºC (Table 3). In summer, the mean water temperature was 9.4ºC but with larger fluctuations when the chillers struggled to cope with high temperatures of the incoming seawater. However, temperatures did not exceed those measured at the trawling sites during summer (Table 3). Salinities in the observation tanks were slightly lower than equivalent bottom salinities at the trawling sites, reflecting the location of the SAMS aquarium seawater intake. Dissolved oxygen was always above 8 mg l^{-1} and ammonia levels were usually undetectable but peaked at 1 mg l^{-1} on a single occasion when the water flow to one recovery tank became temporarily reduced. In study 2, water was drawn directly from the quayside and the tanks were not under temperature control. Nevertheless, as this study was only conducted in the winter, temperatures were generally close to the sea surface temperatures measured at the haul locations (Table 3). In study 3, observation tank temperatures only fluctuated by 1ºC, averaging 5.5ºC in winter and 14.5ºC in summer. However, in summer water temperatures were up to 5ºC warmer than the bottom temperatures measured at the haul sites. Salinities were close to those measured at the haul sites (Table 3). Oxygen levels remained above 80% saturation throughout all experiments and ammonia levels were barely detectable.

Size and survival of control animals

The size (mean ± stdev.) of control *Nephrops* in study 1 was 25 ± 2.2 versus 24 ± 2.4 mm in the test animals. In study 2, the relative sizes were 40 ± 3.8 mm and 32 ± 6.4 respectively, and in study 3, 38 ± 2.7 mm and 38 ± 4.6 respectively. Survival for controls during the monitoring of captive *Nephrops* was 96% in study 1 (n=170), 94% in study 2 (n=214) and 97% in study 3 (n=390). For studies 1 and 3, seasonal differences in control survival were not statistically significant (Fisher's exact tests; p>0.05). This was not tested for study 2, which took place only in winter.

Factors affecting survival of individual Nephrops

Based on Kaplan-Meier curves and log-rank tests, sex was not a significant factor affecting individual survival in either study 1 or 3 (Figure S11, Log-rank tests: study 1, Chisq=1.0, p=0.3;

study 3 Chisq=1.9, p=0.2). Sex was not recorded in study 2. The presence of physical injuries affected individual survival with puncture and crush injuries having the greatest negative impacts (Figure S12). Kaplan-Meier curves (Figure 5) showed significant effects on individual survival for the *Nephrops* in the four presence of injury combined with vitality categories (Logrank tests df = 3: Study 1, Chisq = 299, p<0.001; Study 2, Chisq = 610, p<0.001; Study 3, Chisq = 126, p<0.001). In all three studies, survival of undamaged animals in excellent or good vitality was significantly higher than for injured *Nephrops* in a poor of moribund state at the time of sampling.

Survival estimates

Based on the overall survival curves (Figure S13), about 90% of the observed mortalities had occurred by 8 days and further mortalities had largely ceased by 10 days of observation. Final survival estimates by haul including immediate mortality are given in Table S2, illustrated in Figure S14, and presented grouped by study, season and fishing gear in Table 6 and Figure S15.

Final survival, biological, environmental and operational factors

In study 1 (Scottish west coast), final survival estimates were significantly higher in winter than summer (winter 62 ± 2.8% versus summer 47 ± 3.4%; ANOVA: Survival ~ Season, Season F=13.0, df=1, P=0.002). In this study, *Nephrops* were only sampled from the start of the catch sorting for the summer hauls and this could have resulted in some over-estimation of survival. The approach was subsequently changed so that the entire catch sorting time was sampled for the winter hauls. In study 2 (Farne Deeps, North Sea), mean final survival was 57 ± 1.8% but only assessed in winter. In study 3 (Skagerrak), final survival was again higher in winter than in summer (winter 67 ± 5.4% versus summer 40 ± 4.8%). However, gear also had an effect with final mean survival being higher for *Nephrops* caught using trawls fitted with the Swedish grid (ANOVA: Survival ~ Season*Gear modification, Season F=67.5, df=1, P<0.001, Gear modification F=9.71, df=1, P=0.01, Gear modification by Season, P>0.05). Scatterplots and Kendall's tau suggested that the seasonal effect in study 1 might be linked to differences in air temperature but catch sorting time were also significantly correlated with survival (Figure S16). In the simplified multiple linear regression model of survival, sea surface temperature, and not air temperature, along with catch sorting time were retained (Table 7). Seasonal effects were not tested for in study 2 as this was conducted in winter only. The weight of non-*Nephrops* catch was just significantly correlated with final survival, but in a positive manner (Figure S16). Multiple regression simplification failed to identify any significant predictors of survival for study 2. Although neither sea nor air temperature were selected as significant, the temperature range in study 2 was limited since all hauls were conducted in winter. For study 3, although there were apparent effects of sea surface and air temperature on final survival by gear, the correlations were not statistically significant (Table S17). Sea surface temperature was however retained in the simplified multiple linear regression models of survival for study 3 (Table 7). Final survival results across all three studies did appear consistent with an overall temperature effect (Figure 6). However, because sea surface and air temperatures were correlated it is not possible to say with any certainty which factor was having the stronger impact. In relation to biological factors, scatterplots and Kendall's tau failed to identify any patterns of mean survival for each haul with the proportions of *Nephrops* in the injury presence/absence combined with E/G or P/M vitality groups (Figures S18, S19).

Discussion

Factors affecting immediate Nephrops mortality

Being caught in trawls results in a range of physiological and physical responses in *Nephrops*. Animals will exhibit vigorous tail flipping as they try to escape from the ground gear (Newland and Chapman, 1989) and such activity results in depletion of muscle ATP and increased levels of anaerobic metabolites (Albalat *et al.*, 2009). Exposure of *Nephrops* to low salinity surface waters during net hauling may lead to further physiological stress, but this is only likely to be important in strongly salinity-stratified waters such as the Kattegat and Skagerrak (Harris and Ulmestrand, 2004). Although haloclines were present in our third study in the Skagerrak, the surface salinities were not as low as the salinity of 15 used in the laboratory experiments conducted by Harris and Ulmestrand (2004). Once on board fishing vessels, *Nephrops* are usually held in air during catch sorting resulting in multiple physiological and immunological changes associated with oxygen deprivation (Spicer *et al.*, 1990; Albalat *et al.*, 2009; Lund *et al.*, 2009; Campos *et al.*, 2015). These changes are potentially reversible when *Nephrops* are returned to seawater, but the temperature of the aerial exposure appeared to influence immediate mortality in study 3. In study 1, immediate mortality was related to total catch sorting time, possibly because of prolonged aerial exposure of *Nephrops* in the hopper.

Factors affecting final survival

Consistent with previous studies (Symonds and Simpson, 1971; Wileman *et al.*, 1999; Campos *et al.*, 2015; Albalat *et al.*, 2016), we found clear links between the survival of individual *Nephrops* during captive observation and the presence of physical damage plus vitality at the time of sampling. Puncture and crush injuries in particular are known to lead to loss of haemolymph often resulting in eventual circulatory collapse (Wileman *et al.*, 1999). However, despite the clear link between physical damage plus vitality and survival at the individual level, only sea surface temperature consistently emerged as a significant predictor of final mean survival in studies 1 and 3. However, because sea surface and air temperatures were correlated, it was difficult to determine which factor was having more impact. Although several studies have highlighted the negative link between increased air temperatures and *Nephrops* survival (Spicer *et al.*, 1990; Ridgway *et al.*, 2006), being returned to warmer water in summer, either by being discarded at sea or when placed into observation tanks, might also reduce survival. Since metabolic costs are linked to temperature, elevated energetic costs might reduce an animal’s capacity for recovery during summer months. In addition, bacterial and fungal growth rates are likely to be higher in summer, perhaps resulting in poorer survival of injured *Nephrops* recovering in warmer water. Broadhurst *et al.* (2006) suggested that simple measures to keep catches cool, such as ensuring hopper covers are closed after the nets have been emptied or installing chillers, might improve discard survival. However, such measures could be less beneficial in summer if lower survival rates are also due to animals recovering in warmer water. This could be tested in further captive observation trials if the water temperatures in the recovey tanks were kept constant between seasons.

Experimental design

The conclusion that final survivals were linked to temperature must be treated with some caution because most of the hauls at the higher temperatures were from the third study. There is thus scope for inter-study effects to have contributed to the overall relationship. This problem could be overcome by randomly allocating hauls across the full range of covariates but this is difficult to achieve in field-based studies where the activity, in this case trawling and its associated environmental conditions, are not under direct experimental control. Furthermore, temperatures in the observation tanks did not always coincide with those measured in the field. In particular, temperatures were colder in the observation tanks for study 1 summer hauls but warmer in study 3 summer captive observations. We are not aware of any discard recovery studies with *Nephrops* where the effects of different water temperatures during recovery have been investigated, but water temperatures in the observation tanks could have had some impact on the results.

The considered opinion of WKMEDS (ICES, 2014) is that to date, there are no satisfactory methods for adjusting discard-survival estimates using control data. Therefore, it is currently recommended that the magnitude of the control mortality should be used as a measure of the validity of the observation method, where control mortalities close to zero suggest a more valid method for accurately estimating discard survival. In the present studies, mortality of control animals was less than 5% suggesting that the observational setups were not causing high levels of stress. It must be noted that control animals were added to the observation boxes when they reached the aquaria. Adding control animals to the observation boxes on-board the trawlers was impractical because the control *Nephrops* would have had to be transported back to the haul locations, in some cases on the previous evening, and thus exposed to even more unrealistic stressors. However, any mortality in the test subjects resulting from being placed into insulated containers on board the trawlers and transported to the aquaria could not be identified with the approach used. Sourcing appropriate control animals for discard survival studies is also challenging (ICES, 2014; Campos *et al.*, 2015; Méhault *et al.*, 2016; Morfin *et al.*, 2017; Mérillet *et al.*, 2018). Although previous studies have also used recovered (Mérillet *et al.*, 2018) or creel-caught *Nephrops* (Wileman *et. al.*, 1999), both approaches are open to challenge. The use of recovered animals might not represent the full health and robustness range of *Nephrops* caught in the trawls since recovered animals might be those more resilient to such stresses. However, this approach did ensure that control animals are of similar size to those being discarded. For creel-caught controls, their larger size compared with those being discarded may be an issue but this potential problem was minimised in study 3 by using creels with a reduced mesh size.

Studies 1 and 2 were based on single vessels whilst study 3 used two vessels. Any extrapolation of results must be made cautiously because of the variety of operations in the wider fishing fleet. Given the logistical challenges and costs of conducting discard survival experiments across multiple fishing vessels, relationships between survival during captive observation and vitality have been used to extrapolate captive observation findings to a larger number of vessels (Morfin *et al*., 2017). However, this approach relies on the assumption that survival depends only on vitality plus any environmental covariates identified as statistically affecting captive survival. In the present studies, mean survival by haul did not appear to be strongly linked to such factors, suggesting that a substantial part of the variability in survival is being driven by additional, un-measured factors.

Limitations with captive observation survival estimates

Several publications have pointed out that tank-based discard survival experiments are likely to over-estimate true survival by ignoring predation mortality that may occur at the sea surface, in the water column or when discarded animals reach the seabed (Symonds and Simpson, 1971; Raby *et al*., 2014, Morfin *et al*., 2017; Mérillet *et al*., 2018). Although seabirds probably do not take a large proportion of discarded *Nephrops* (Catchpole *et al*., 2006; Depestele *et al.*, 2016), this predation risk can be minimized by releasing discards below the sea surface using a protective chute. Little work has been undertaken on predation of discarded *Nephrops* during their descent through the water column but Bergmann *et al.* (2002) suggested that discards would reach the seabed in a few minutes. As far as we are aware, there are no estimates of predation rates of live, discarded *Nephrops* once they reach the seabed although the behaviour of small *Nephrops* released at depths of around 100 m has been observed using a remotely operated vehicle (Fox and Albalat, 2018). It was reported that undamaged *Nephrops*, even after aerial exposure for up to 3 h, recovered rapidly and began exploring their environment and entering available burrows within 10 min. However, these observations were only made on a limited number of dives and the *Nephrops* could only be followed for a short time. The conclusions reached might not apply to grounds with higher abundances of predators, to damaged *Nephrops* or to those previously exposed to prolonged elevated air temperatures.

Furthermore, if *Nephrops* are discarded over un-suitable habitat, for example whilst steaming back to port, they will have no chance of finding suitable protection in burrows (Evans *et al.*, 1994).

The longer-term effects of discarding on *Nephrops* are also difficult to assess. Evans *et al.* (1994) demonstrated that animals lacking one chela were less successful in competing for food and shelter compared with un-injured *Nephrops*. In the present studies, this injury was seen in around 20% of the discards and these animals may be at a competitive disadvantage when returned to the sea. Reducing the occurrence of such injuries should improve survival potential but is challenging as levels of physical damage are related to animal condition, gear type, haul duration, seabed condition, size of catches and composition, catch handling and hopper design (Campos *et al.*, 2015; Méhault *et al.*, 2016). Oliver *et al.* (2017) suggested that trawls that are more selective will result in less physical damage to *Nephrops* in the net, thus potentially increasing discard survival. However, across all three studies we were unable to establish a statistical link between the proportions of *Nephrops* with physical damage and final survival by haul, even though such injuries led to reduced survival at the individual level. Within study 3 (Skagerrak), there was an effect of gear with captive survival of discarded *Nephrops* from nets equipped with Swedish grids being higher. Swedish grid trawls are considered more selective than Seltra trawls (Madsen and Valentinsson, 2010). Unfortunately, vitality was only recorded on the winter hauls making it difficult to reach firmer conclusions regarding the interplay of gear selectivity, *Nephrops* condition and subsequent survival.

Comparison with other published studies

Levels of immediate mortality recorded in studies 1 and 3 were quite similar to the 15.6% immediate mortality reported by Mérillet *et al.* (2018) when using a discard chute. In study 2, no immediate mortality was observed. This was unexpected and not explained by any obvious differences between the studies, such as tow lengths or catch weights (Table 1).

There are a limited number of published *Nephrops* survival studies undertaken at different seasons but Mérillet *et al.* (2018) reported higher survival in summer (57%) compared with spring (42%). This contrasts with findings of reduced final survival at higher temperatures in the present studies, and with other publications reporting a negative link between *Nephrops* survival and temperature (Méhault *et al.*, 2016). Mean summer survival estimates in study 1 (47%) and study 3 (40%) were lower than a recent result of 64% reported by Oliver *et al.* (2017) off the west coast of Ireland using Seltra trawls and of 57% reported by Mérillet *et al.* (2018) for the Bay of Biscay using a modified discarding chute. This may reflect genuine differences between the fisheries because the experimental methodology across all these recent studies largely followed the WKMEDS guidelines.

Conclusions and recommendations for future work

Despite some operational differences between the three studies, the final survival estimates were reasonably consistent. In all three winter studies, over half the observed *Nephrops* survived a minimum 13 days captive observation whilst in the two studies conducted in summer, survival was between a third and half. Although what constitutes “high-survivability” is not defined in the Landing Obligation (Regulation (EU) No. 1380/2013), the results presented in the present paper have been reviewed by the Scientific, Technical and Economic Committee for Fisheries (STECF) and accepted by the European Commission as the basis for exemptions in the North Sea and west of Scotland.

In the two studies conducted across seasons, final survival of discarded *Nephrops* was significantly higher in winter than summer. Sea surface temperature was identified as affecting both immediate mortality and final survival in study 3, but only final survival in study 1. However, the effect of air temperature was only marginally weaker in the models making it hard to conclude which of these two correlated environmental factors might be driving the seasonal response. Altering fishing practices to keep catches cool during catch sorting may thus improve discard survival, particularly in summer. However, poorer captive observation survival in summer could also be related to animals recovering in warmer water, in which case chilling during catch sorting may have less positive effect. Further studies where water temperatures in the captive observation tanks are manipulated could be undertaken to test this. Our results also confirmed that physical damage to *Nephrops* significantly reduces their survival potential with puncture and crush injuries being most deleterious. Although we were unable to link statistically the overall levels of damage within hauls to resultant mean final survival, better survival was observed from catches made with trawls equipped with a Swedish sorting grid compared to a Seltra trawl. Weights for the non-*Nephrops* component of the catches were lower in hauls made with the Swedish grid. Furthermore in study 1, immediate mortality was lower in lighter hauls where the overall sorting times were also lower. Recording levels of physical damage and vitality of *Nephrops* when gear selectivity studies are conducted in future could provide valuable additional data.

Once on board, catch-handling practices that may lead to further damage should be avoided. There is potential that changes in hopper design, such as sloping floors allowing the catch to be pulled onto the sorting tables with the assistance of gravity (Albalat *et al.*, 2016), or seawater hoppers (Broadhurst *et al.*, 2006), might be beneficial in reducing damage and improving discard survival. Although we are not aware of any research into this in northern European

Nephrops fisheries, the benefits of seawater hoppers for improving discard survival have received attention in Australian prawn fisheries (Ocean Watch Australia, 2004). However, it must be cautioned that placing catches into hoppers filled with low salinity seawater may cause additional stress, such measures may therefore not be effective in improving survival in areas with reduced surface salinity, such as the Skagerrak. Similar considerations would apply during summer months if un-chilled seawater hoppers were filled with warm surface seawater.

Given that discard survival studies are expensive to conduct (Morfin *et al*., 2017), it is recognised that future studies need to be standardised as much as possible (ICES, 2014). Despite efforts at standardisation, some differences were apparent between the three studies reported here. For example, physical water column parameters were not measured in a consistent manner, analysis of the vitality data raised some doubts about the consistency of scoring and temperatures in the observation tanks did not always reflect those in the field. Such problems need to be tackled through further training and inter-calibration between laboratories conducting discard survival studies.

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Table 1: Summary of study locations, season (W — winter; S — summer), fishing gears, number of hauls, dates, tow durations and catch weights (mean ± std dev.) and the biological factors recorded on board the fishing vessels (Y — yes; N — no): CL — Catch length profile; DL — Discard length profile; DS — Discard sex profile; DM — Discard immediate mortality; DP — Discard physical damage; DV — Discard vitality.

Study	ICES Div.	Season	Cod-end mesh	Gear mods	Number of hauls	Year	Dates	Tow duration	*Nephrops* catch	Non-*Nephrops* catch	Biological factors recorded					
											CL	DL	DS	DM	DP	DV
			(mm)					(h)	(kg)	(kg)	Y	Y	Y	Y	Y	Y
1	VIa	W	80	SMP	6	2017	06/03-08/03	3.6±0.3	189±55	40±11	Y	Y	Y	Y	Y	Y
			100	SMP	6	2017	15/02-17/02	3.9±0.2	183±81	58±15	Y	Y	Y	Y	Y	Y
		S	80	SMP	6	2016	19/08-17/09	3.6±0.3	152±43	95±41	Y	Y	Y	Y	Y	Y
			100	SMP	6	2016	15/07-18/08	3.4±0.5	309±120	57±31	Y	Y	Y	Y	Y	Y
2	IVb	W	80	NetGrid	12	2016	03/02-11/03	3.2±0.4	121±95	29±12	N	N	N	Y	Y	Y
3	IIIa	W	70	SweGrid	3	2015	05/03-17/03	4.1±0.8	29±28	63±39	N	Y	Y	Y	Y	Y
			90	Seltra	3	2015	05/03-17/03	4.1±0.8	20±26	212±78	N	Y	Y	Y	Y	Y
		S	70	SweGrid	3	2015	31/08-03/09	4.0±0.1	28±13	91±12	N	Y	Y	Y	Y	N
			90	Seltra	3	2015	31/08-03/09	4.0±0.1	23±14	167±167	N	Y	Y	Y	Y	N

Table 2: Codes for scoring *Nephrops* semi-quantitative assessments of vitality and damage.

Criterion	Description	
Excellent	Vigorous body movement; all limbs moving and tail extends horizontally, flexed or tail-flips	
Good	All limbs moving but tail hangs limp, no tail-flips	
Poor	Limited or no body movement but movement of maxillipeds	
Moribund	Only slight movement of maxillipeds or limbs in response to gentle prodding	
Dead	0	No response/movement to physical stimuli
No injury	1	Alive with no obvious visible injuries
Chelae	D1	Either claw missing or damaged
	D2	Both claws missing or damaged
Rostrum	DR	Rostrum damaged
Body	PUN	A puncture injury on thorax or tail
Thorax	THC	A crush injury on the thorax
	THP	A puncture injury on the thorax
Tail	TAC	A crush injury on the tail
	TAP	A puncture injury on the tail
Eye	EYE	Damage to one or both eyes
Leg	LEG	One or more walking legs missing or damaged

Table 3: Field and observation tank environmental conditions as ranges. Season: W — winter; S — summer hauls. CT — constant temperature room.

Study	Season	Field sampling environmental conditions					Captive observation tanks		
		Air temp. (ºC)	Sea surface temp. (ºC)	Bottom temp. (ºC)	Sea surface sal.	Sea bottom sal.	CT set air temp. (ºC)	Water temp (ºC)	Salinity
1	W	6.9–11.5	7.9–8.4	8.0–8.5	34.5–34.7	34.5–34.7	5	6.7–8.2	30.0–34.0
	S	13.8–19.0	13.3–14.7	12.3–14.3	34.0–34.9	34.0–34.9	5	5.7–13.0	31.0–33.0
2	W	8.0–10.0	6.5–7.6	-	-	-	-	5.2–9.2	-
3	W	2.0–5.9	3.6–4.3	4.9–6.1	24.5–26.4	32.9–34.9	10	5.0–6.0	32.0–33.0
	S	14.9–18.7	16.7–17.9	10.0–10.8	23.9–29.1	33.5–34.2	14	14.0–15.0	33.0–34.0

Table 4: GLM model results for immediate mortality modelled as counts of Nephrops alive versus dead during catch sorting, family=quasi-binomial, link=logit. Final models resulting from sequential removal of insignificant terms are shown for models where residual patterns were acceptable. Note in study 2 no immediate mortality was observed.

	Estimate	SE	t-value	p
Study 1 Intercept	2.67	0.24	11.2	<0.001
Study 1 Sorting time	0.32	0.10	-3.2	0.005
Null deviance	86.3	df = 22		
Residual deviance	59.0	df = 21		
Dispersion	2.9			
Study 3 Intercept	4.83	0.66	7.27	<0.001
Study 3 Sea surface temperature	0.17	0.04	-4.42	0.001
Null deviance	67.1	df = 11		
Residual deviance	15.6	df = 10		
Dispersion	1.5			

Table 5: Percentages of *Nephrops* showing at least one injury by type during catch sorting as mean (95% LCL– 95% UCL from bootstrap in parentheses). Note that individual *Nephrops* may have had more than one injury type and that abdominal and cephalothorax injuries have been combined.

Injury	Study 1 SMP	Study 2 NetGrid	Study 3 Seltra	Study 3 SweGrid
Damaged – at least one injury	40 (36–43)	32 (30–34)	45 (32–54)	37 (32–41)
One chela missing/damaged	24 (22–26)	21 (19–23)	15 (8–25)	11 (6–15)
Puncture wound	8 (6–10)	2(4–5)	24 (9–41)	19 (9–32)
Crush wound	5 (4–10)	6 (3–7)	4 (1–9)	5 (1–11)
Damaged rostrum	3 (2–4)	4 (3–5)	4 (1–6)	3 (1–4)
Two chelae missing/damaged	4 (3–5)	4 (3–5)	3 (1–7)	2 (1–3)

Table 6: Final survival estimates from the tank-based observation experiments including immediate mortality. Season as W — winter, S — summer. LCL and UCL are the 95% upper and lower confidence limits for the mean survival estimates averaged by gear, season and study with error propagation from the individual haulbased survival estimates.

Study	Season	Codend	Gear mod.	N	Final survival estimates (%)			
		(mm)			Mean	Std. err.	LCL	UCL
1	W	80	SMP	6	60.7	2.8	57.3	64.0
	W	100	SMP	6	64.6	2.9	61.2	68.0
	W	Both	SMP	12	61.7	1.4	59.3	64.0
	S	80	SMP	6	52.0	3.6	48.2	55.8
	S	100	SMP	6	42.1	3.3	38.5	45.8
	S	Both	SMP	12	47.1	1.7	44.4	49.7
	Both	Both	SMP	24	55.3	0.7	53.6	57.0
2	W	80	NetGrid	12	57.2	0.9	55.3	59.2
3	W	70	SweGrid	3	75.2	3.1	69.1	81.4
	W	90	Seltra	3	58.6	4.5	49.6	67.6
	W	Both	Both	6	66.9	2.7	61.5	72.4
	S	70	SweGrid	3	41.7	3.1	35.4	48.0
	S	90	Seltra	3	37.7	3.5	30.7	44.7
	S	Both	Both	6	39.7	2.4	35.0	44.4
	Both	Both	Both	12	53.3	1.8	49.7	56.9

Table 7: Linear model results for mean final survival estimates including immediate mortality by haul against available operational covariates for each study. Final models, resulting from sequential removal of insignificant terms are shown where residual patterns were acceptable.

Study 1 — SMP	Estimate	Std. err.	t-value	p
Intercept	90.07	8.79	10.25	<0.001
Sea surface temperature	-1.90	0.79	-2.42	0.025
Sorting time	-6.52	2.60	-2.52	0.020
Residual standard error	10.52			
Multiple R^2	0.47			
F statistic	9.34	df = 2,21		0.001
Study 2 —_NetGrid	No significant operational covariates			
Study 3 — Seltra	Estimate	Std. err.	t-value	p
Intercept	64.83	1.41	45.98	<0.001
Sea surface temperature	-1.56	0.11	-13.96	<0.001
Residual standard error	1.83			
Multiple R^2	0.98			
F statistic	194.9	df = 1,4		<0.001
Study 3 — SweGrid	Estimate	Std. err.	t-value	p
Intercept	84.91	6.51	13.05	<0.001
Sea surface temperature	-2.47	0.52	-4.79	0.009
Residual standard error	8.46			
Multiple R^2	0.85			
F statistic	23.0	df = 1,4		0.009

Figures

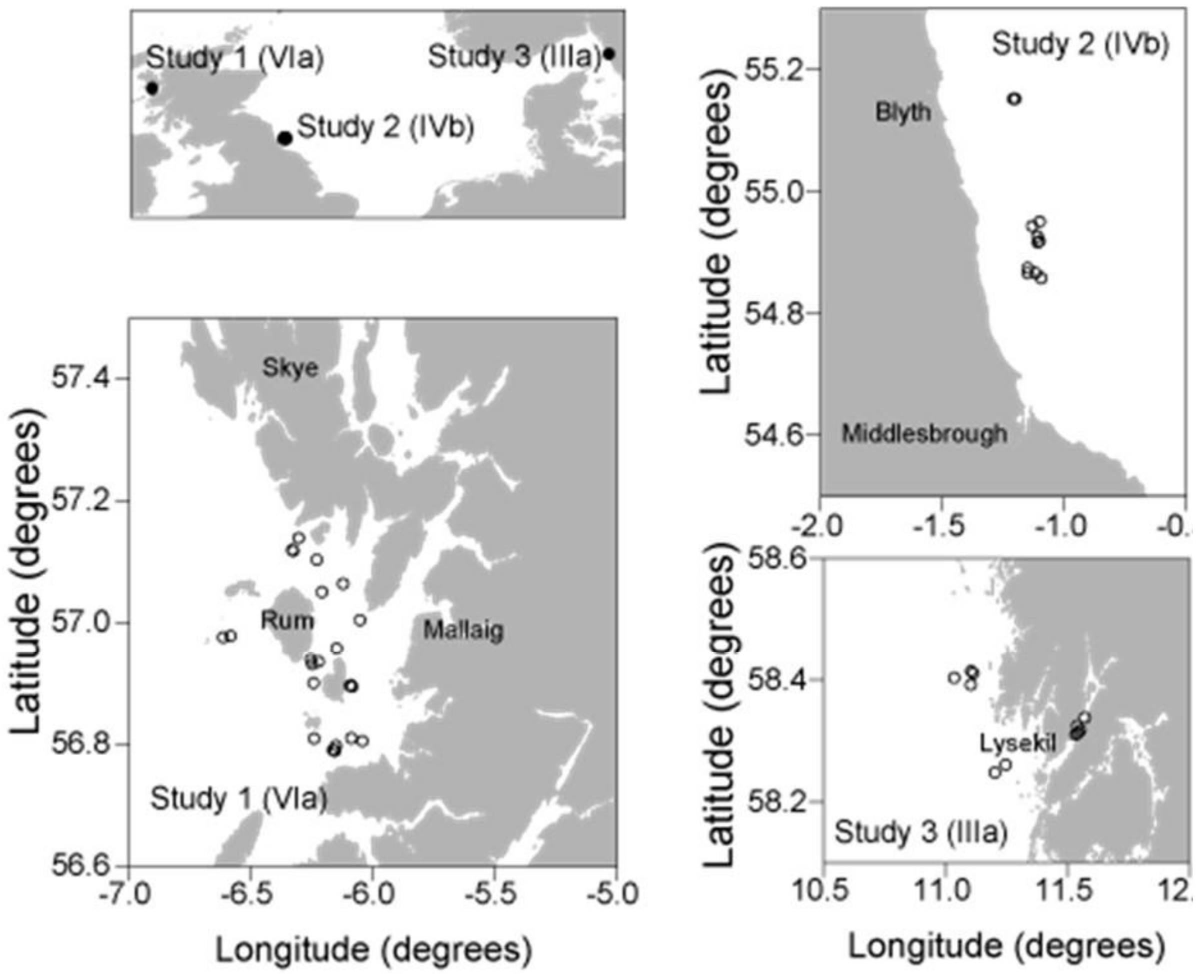
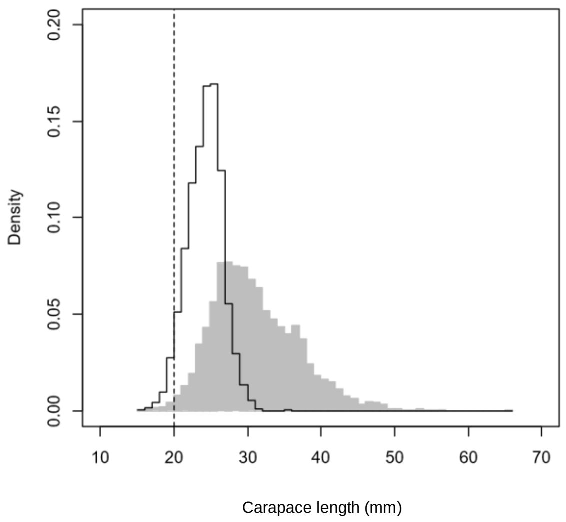
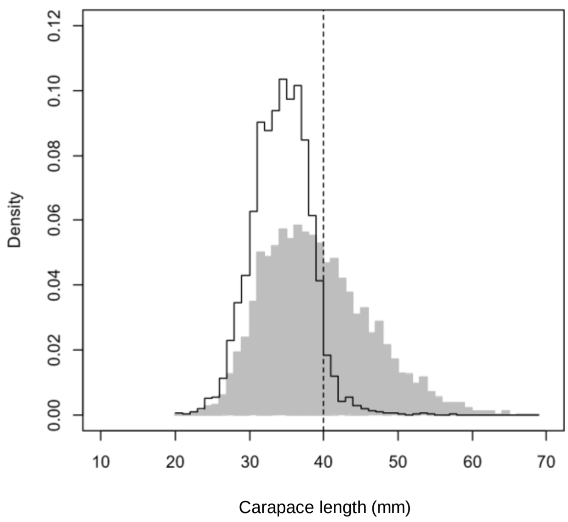


Figure 1: Locations of experimental hauls.

Figure 2: Tube-set box used to retain *Nephrops* in individual compartments for captive observation.

(a) (c)





(b)

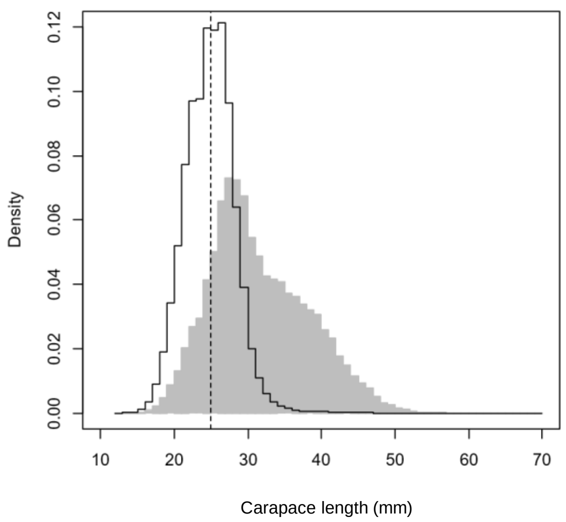


Figure 3: Histograms of *Nephrops* length frequencies in the total catches (grey histograms) and discarded portions of the catches (open histograms) in the three study areas. Vertical dashed lines are the minimum landing size (MCRS) at time studies were completed. Figure 3a: Length frequencies in study 1 (ICES Division VIa). Figure 3b: Length frequencies 2011–2017 in ICES Division IVb. Figure 3c: Length frequencies for 2015 in ICES Division IIIa.

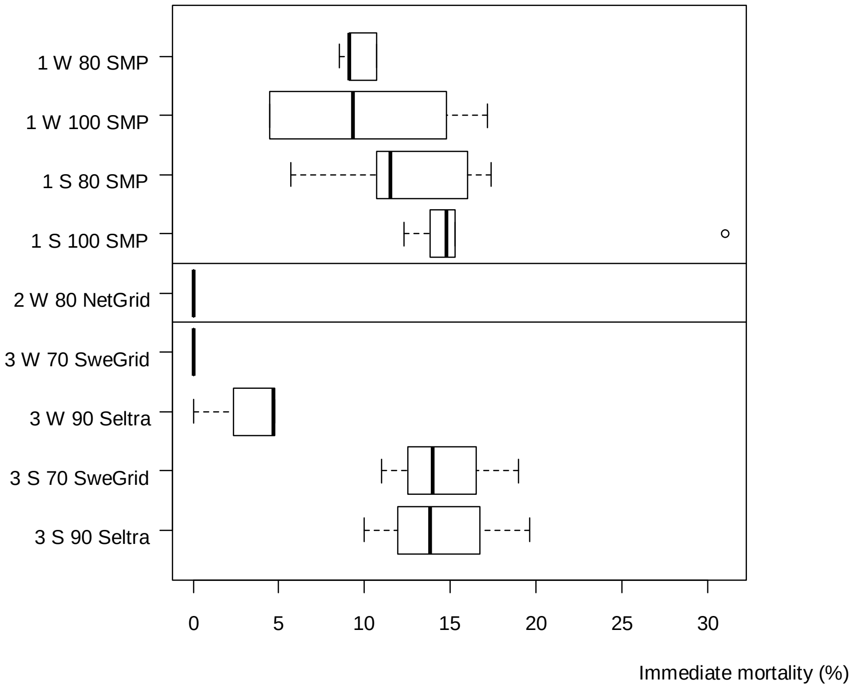


Figure 4: Estimates of immediate mortality during catch sorting by study (1–3), season (W — winter, S — summer) and gear (cod-end mesh size and gear modification). Heavy vertical bar indicates median, box is the inter-quartile range, whiskers extend up to 1.5 time the interquartile range, circle is an outlier beyond the whisker range.

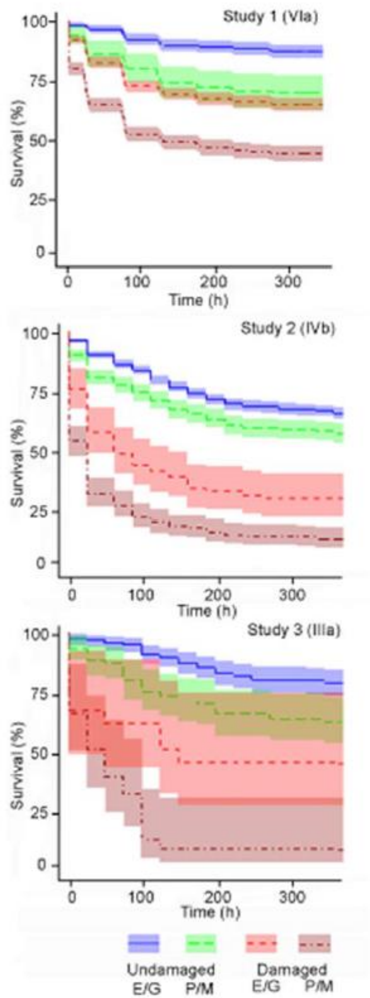


Figure 5: Kaplan-Meier survival curves relating the probability of survival of individual *Nephrops* in the observation tanks against presence of physical damage combined with the vitality categories (E/G — 'Excellent' or 'Good' versus P/M — 'Poor' or 'Moribund').

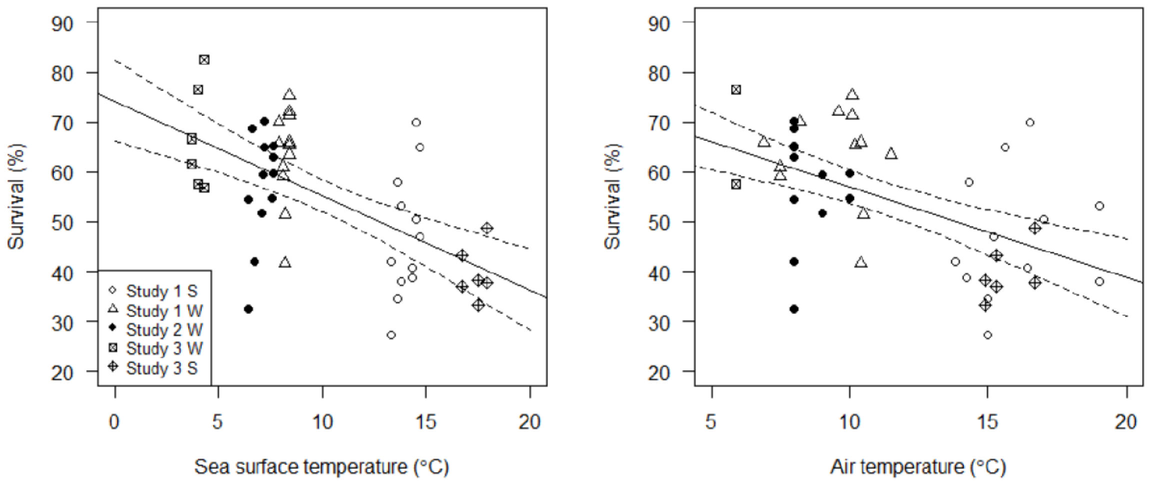


Figure 6: Relationship between *Nephrops* final mean survival from each haul and recorded sea surface (left hand panel) and air temperatures (right hand panel) across all three studies. Solid lines linear regressions, dotted lines 95% CIs. Points labelled as study number plus season (W — winter, S — summer). The linear regressions are: Survival = 74.0 - 1.9*Sea surface temperature ($F = 26.0$, df = 1,46, $p = <0.001$, $r^2 = 0.36$); Survival = 75.3 - 1.8*Air temperature ($F = 22.2$, df = 1,46, $p<0.001$, $r^2 = 0.33$).

Table S1: Details of the individual trawl hauls in the studies.

Haul	Study	Date	Season	Cod-end Mesh (mm)	Gear mods	Shoot time	Haul time	Shoot lat (dec deg)	Shoot lon (dec deg)	Haul lat (dec deg)	Haul lon (dec deg)	Shoot depth (m)	Haul depth (m)	Haul speed (kts)	Weather
1	1	15/07/2016	S	100	SMP	03:28	07:00	56.799	-5.994	56.813	-6.095	79	73	2.5	Slight chop, overcast
2	1	15/07/2016	S	100	SMP	07:35	10:20	56.795	-6.150	56.785	-6.164	104	90	2.5	Slight swell, rain
3	1	29/07/2016	S	100	SMP	05:15	08:30	56.799	-6.155	56.797	-6.152	93	106	2.6	Calm, dry
4	1	29/07/2016	S	100	SMP	09:25	12:30	56.816	-6.243	56.804	-6.243	93	150	2.5	Calm, dry, sunny
5	1	18/08/2016	S	100	SMP	04:48	08:55	57.116	-6.329	57.124	-6.336	106	88	2.8	Calm, clear, sunny
6	1	18/08/2016	S	100	SMP	09:36	13:25	57.121	-6.334	57.116	-6.323	95	148	2.7	Calm, clear, sunny
7	1	19/08/2016	S	80	SMP	04:33	07:53	56.789	-6.055	56.832	-6.125	60	75	2.5	Cloudy, slight swell, dry
8	1	19/08/2016	S	80	SMP	08:46	12:16	56.887	-6.092	56.903	-6.082	119	73	2.4	Cloudy, swell, dry
9	1	16/09/2016	S	80	SMP	06:10	10:04	57.013	-6.595	56.940	-6.636	88	95	2.6	Clear, sunny, slight breeze
10	1	16/09/2016	S	80	SMP	10:30	14:35	56.940	-6.642	57.017	-6.529	97	90	2.7	Clear, sunny, slight breeze
11	1	17/09/2016	S	80	SMP	05:37	09:05	57.128	-6.310	57.151	-6.303	128	144	2.7	Overcast, slight breeze, slight chop
12	1	17/09/2016	S	80	SMP	10:12	13:28	57.104	-6.232			100		2.5	Overcast, breezy, slight swell
13	1	15/02/2017	W	100	SMP	07:50	12:00	56.963	-6.142	56.953	-6.160	86	110	2.5	Breeze, slight swell, overcast
14	1	15/02/2017	W	100	SMP	12:50	16:45	57.031	-6.090	56.979	-6.020	101	128	2.7	Breeze, slight swell, overcast
15	1	16/02/2017	W	100	SMP	07:20	11:08	57.044	-6.219	57.058	-6.203	104	117	2.8	Calm, overcast, slight precipitation
16	1	16/02/2017	W	100	SMP	11:30	15:35	57.077	-6.208	57.052	-6.041	90	88	2.5	Calm, overcast, slight precipitation
17	1	17/02/2017	W	100	SMP	06:46	10:45	56.935	-6.249	56.929	-6.252	104	121	2.4	Calm, overcast
18	1	17/02/2017	W	100	SMP	11:15	14:49	56.923	-6.250	56.879	-6.241	104	128	2.5	Calm, overcast
19	1	06/03/2017	W	80	SMP	07:45	11:40	56.940	-6.257	56.939	-6.258	115	118	2.4	Breeze, slight swell
20	1	06/03/2017	W	80	SMP	12:15	16:15	56.939	-6.254	56.933	-6.196	126	127	2.7	Breeze, slight swell
21	1	07/03/2017	W	80	SMP	08:20	11:25	56.801	-6.149	56.781	-6.183	100	130	2.5	Strong breeze, swell, cloudy
22	1	07/03/2017	W	80	SMP	12:00	15:20	56.781	-6.171	56.798	-6.149	55	62	2.5	Strong breeze, swell, cloudy
23	1	08/03/2017	W	80	SMP	07:10	10:45	56.893	-6.092	56.900	-6.099	55	51	2.6	Windy, strong swell to rough
24	1	08/03/2017	W	80	SMP	11:15	15:00	56.894	-6.089	56.901	-6.096	49	51	2	Windy, strong swell to rough

Table S1 con/td: Details of the individual trawl hauls in the studies

Haul	Study	Date	Season	Cod-end mesh (mm)	Gear mods	Shoot time	Haul time	Shoot lat (dec deg)	Shoot lon (dec deg)	Haul lat (dec deg)	Haul lon (dec deg)	Shoot depth (m)	Haul depth (m)	Haul speed (kts)	Weather
25	2	03/02/2016	W	80	NetGrid	07:15	11:20	55.083	-1.184	55.221	-1.218	59	73	2.6	Slight/Mod
26	2	03/02/2016	W	80	NetGrid	11:50	14:20	55.221	-1.218	55.083	-1.200	73	66	2.6	Mod
27	2	04/02/2016	W	80	NetGrid	07:25	11:05	55.003	-1.196	54.886	-1.067	64	64	2.6	Slight
28	2	04/02/2016	W	80	NetGrid	11:35	15:00	54.886	-1.067	55.017	-1.134	64	62	2.6	Slight
29	2	18/02/2016	W	80	NetGrid	07:15	11:00	54.933	-1.183	54.800	-1.051	55	55	2.6	Slight
30	2	18/02/2016	W	80	NetGrid	11:30	14:45	54.800	-1.051	54.917	-1.138	55	55	2.6	Slight
31	2	19/02/2016	W	80	NetGrid	06:50	09:50	54.933	-1.167	54.800	-1.133	55	55	2.6	Slight/Mod
32	2	19/02/2016	W	80	NetGrid	10:25	13:00	54.817	-1.133	54.933	-1.167	55	51	2.6	Mod
33	2	10/03/2016	W	80	NetGrid	06:30	09:30	54.967	-1.150	54.888	-1.069	51	55	2.6	Slight
34	2	10/03/2016	W	80	NetGrid	10:00	13:00	54.888	-1.069	54.967	-1.151	55	51	2.6	Slight
35	2	11/03/2016	W	80	NetGrid	06:30	09:45	54.967	-1.150	54.867	-1.068	51	55	2.6	Slight
36	2	11/03/2016	W	80	NetGrid	10:00	13:15	54.872	-1.069	54.967	-1.133	55	51	2.6	Slight
37	3	05/03/2015	W	70	SweGrid	07:50	12:00	58.243	11.229	58.253	11.176	52	59	2.5	W 7 m/s, 1.5 m waves, dry
38	3	05/03/2015	W	90	Seltra	07:50	12:00	58.243	11.229	58.253	11.176	52	59	2.5	W 7 m/s, 1.5 m waves, dry
39	3	14/03/2015	W	70	SweGrid	10:35	14:35	58.374	11.082	58.455	11.128	63	54	2.5	NE 8 m/s, 0.5 m waves, mist
40	3	14/03/2015	W	90	Seltra	10:35	14:35	58.374	11.082	58.455	11.128	63	54	2.5	NE 8 m/s, 0.5 m waves, mist
41	3	17/03/2015	W	70	SweGrid	05:50	09:50	58.382	11.057	58.425	11.014	61	68	2.5	E 8 m/s, 0.5 m waves, overcast
42	3	17/03/2015	W	90	Seltra	05:50	09:50	58.382	11.057	58.425	11.014	61	68	2.5	E 8 m/s, 0.5 m waves, overcast
43	3	31/08/2015	S	70	SweGrid	09:23	13:23	58.257	11.240	58.265	11.254	50	50	2.5	SE 3 m/s, calm, overcast
44	3	31/08/2015	S	90	Seltra	09:23	13:23	58.257	11.240	58.265	11.254	50	50	2.5	SE 3 m/s, calm, overcast
45	3	01/09/2015	S	70	SweGrid	06:00	10:04	58.391	11.120	58.393	11.088	50	58	2.5	E 11 m/s, 1 m waves, overcast
46	3	01/09/2015	S	90	Seltra	06:00	10:04	58.391	11.120	58.393	11.088	50	58	2.5	E 11 m/s, 1 m waves, overcast
47	3	03/09/2015	S	70	SweGrid	06:20	10:20	58.413	11.118	58.409	11.110	52	53	2.5	S 8 m/s, 1 m waves, cloudy
48	3	03/09/2015	S	90	Seltra	06:20	10:20	58.413	11.118	58.409	11.110	52	53	2.5	S 8 m/s, 1 m waves, cloudy

Table S2: Kaplan-Meier based survival at the time of the final death in the captive observations from each haul. N observed is the number of test *Nephrops* in the captive observation, excluding additional control animals; LCL and UCL are the 95% confidence limits of the survival; SMP is square mesh panel. The final survival estimates include the immediate mortality estimated during catch sorting.

Haul	Study	Season	Cod-end (mm)	Gear modification	N observed	Time final death (h)	Survival	SE	LCL	UCL
1	1	S	100	SMP	77	218	57.9	5.1	48.8	68.7
2	1	S	100	SMP	100	261	34.5	4.0	27.6	43.2
3	1	S	100	SMP	100	266	41.9	4.6	33.8	51.8
4	1	S	100	SMP	100	261	27.2	4.2	20.1	36.7
5	1	S	100	SMP	100	266	38.1	4.5	30.3	48.0
6	1	S	100	SMP	100	218	53.2	4.5	45.1	62.8
7	1	S	80	SMP	100	240	50.4	4.6	42.2	60.2
8	1	S	80	SMP	100	293	70.0	4.6	61.6	79.6
9	1	S	80	SMP	100	264	47.1	4.6	38.9	56.9
10	1	S	80	SMP	100	118	65.0	4.8	56.3	75.1
11	1	S	80	SMP	99	267	40.7	4.6	32.6	50.9
12	1	S	80	SMP	100	168	38.7	4.7	30.4	49.2
13	1	W	100	SMP	149	264	63.5	3.9	56.3	71.5
14	1	W	100	SMP	150	215	71.3	3.7	64.5	78.9
15	1	W	100	SMP	150	268	65.4	3.7	58.5	73.2
16	1	W	100	SMP	150	264	72.0	3.7	65.2	79.6
17	1	W	100	SMP	150	266	66.0	3.9	58.8	74.0
18	1	W	100	SMP	150	262	75.3	3.5	68.7	82.6
19	1	W	80	SMP	150	266	41.7	3.8	34.8	49.8
20	1	W	80	SMP	150	262	51.5	3.9	44.4	59.7
21	1	W	80	SMP	147	264	70.1	3.8	63.0	77.9
22	1	W	80	SMP	150	264	65.9	3.7	59.0	73.5
23	1	W	80	SMP	136	269	61.0	4.2	53.4	69.8
24	1	W	80	SMP	149	215	59.1	3.8	52.1	67.2
25	2	W	80	NetGrid	212	324	65.1	3.3	59.0	71.8
26	2	W	80	NetGrid	202	324	62.9	3.4	56.5	69.9
27	2	W	80	NetGrid	212	276	54.7	3.4	48.4	61.8
28	2	W	80	NetGrid	199	324	59.8	3.5	53.4	67.0
29	2	W	80	NetGrid	212	348	70.3	3.1	64.4	76.7
30	2	W	80	NetGrid	202	348	64.9	3.4	58.6	71.8
31	2	W	80	NetGrid	212	300	59.4	3.4	53.2	66.4
32	2	W	80	NetGrid	199	300	51.8	3.5	45.3	59.2
33	2	W	80	NetGrid	212	300	32.5	3.2	26.8	39.5
34	2	W	80	NetGrid	202	300	42.1	3.5	35.8	49.5
35	2	W	80	NetGrid	206	300	54.4	3.5	48.0	61.6
36	2	W	80	NetGrid	205	300	68.8	3.2	62.7	75.4

Table S2 con/td: Kaplan-Meier based survival at the time of the final death in the captive observations from each haul. N observed is the number of test *Nephrops* in the captive observation, excluding additional control animals; LCL and UCL are the 95% confidence limits of the survival; SMP is square mesh panel. The final survival estimates include the immediate mortality estimated during catch sorting.

Haul	Study	Season	Cod-end (mm)	Gear modification	N observed	Time final death (h)	Survival	SE	LCL	UCL
37	3	W	70	SweGrid	81	216	66.7	5.2	57.2	77.8
38	3	W	90	Seltra	26	216	61.5	9.5	45.4	83.4
39	3	W	70	SweGrid	40	48	82.5	6.0	71.5	95.2
40	3	W	90	Seltra	77	336	56.8	5.5	47.0	68.7
41	3	W	70	SweGrid	81	240	76.5	4.7	67.9	86.4
42	3	W	90	Seltra	38	336	57.5	7.8	44.1	75.1
43	3	S	70	SweGrid	67	240	48.7	5.6	38.9	61.0
44	3	S	90	Seltra	34	48	37.8	7.2	26.0	55.0
45	3	S	70	SweGrid	62	192	33.3	5.2	24.5	45.4
46	3	S	90	Seltra	68	336	38.3	5.4	29.0	50.5
47	3	S	70	SweGrid	71	144	43.2	5.5	33.7	55.5
48	3	S	90	Seltra	72	216	37.0	5.4	27.9	49.2

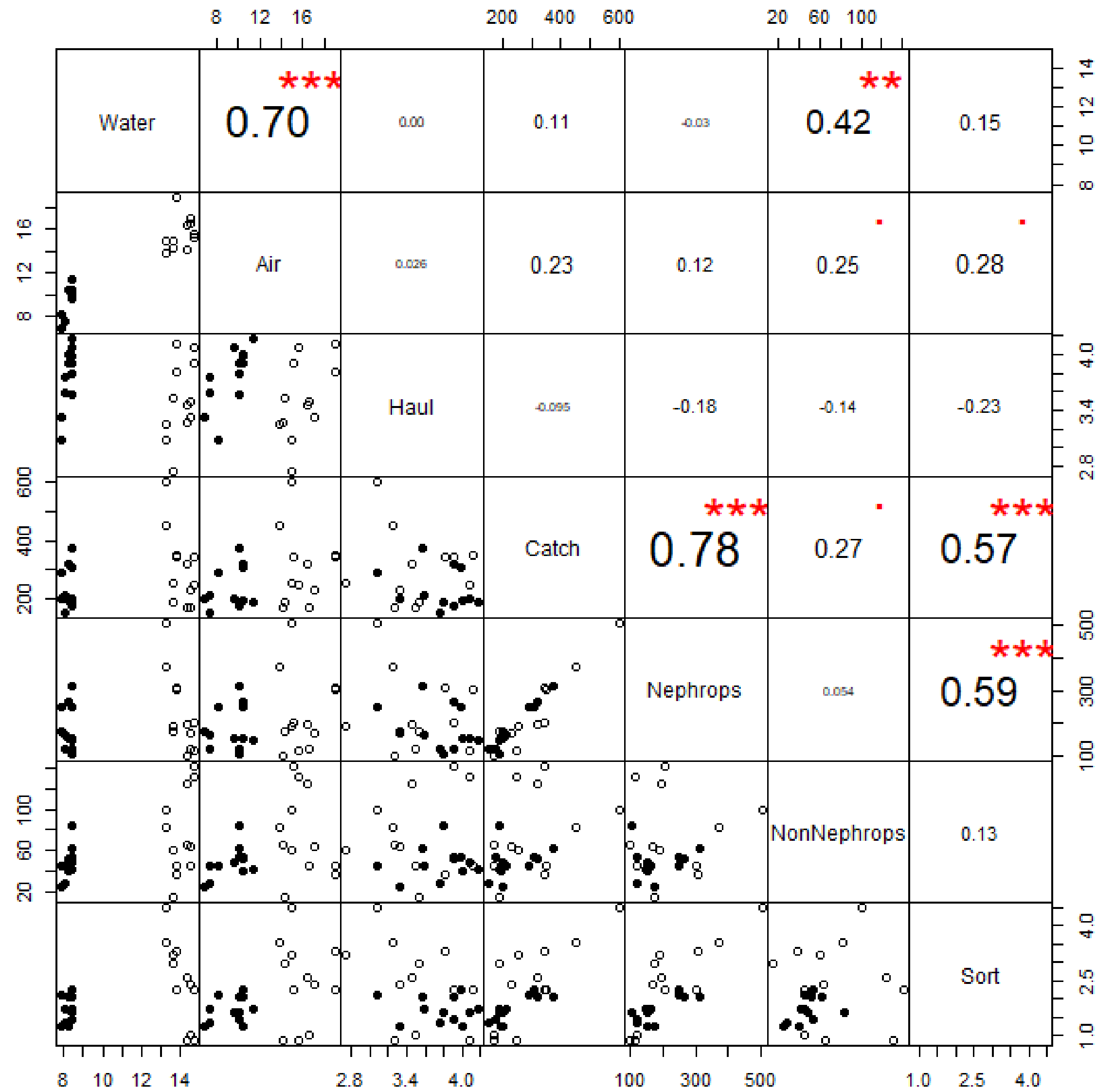


Figure S1: Pairs plot for Study 1 operational co-variables. Panels above the diagonal give Kendall correlation coefficients with font size related to significance and significance (p< 0.05*> p<0.01**> p<0.001***). Symbols are open circles - summer hauls; solid circles — winter hauls. Water — sea surface temperature (ºC); Air — hopper air temperature (ºC); Haul — haul duration (h); Catch — total catch weight (kg); *Nephrops* — catch weight of *Nephrops* (kg); Non-*Nephrops* — catch weight of organisms other than *Nephrops* (kg); Sort — total sorting time (h).

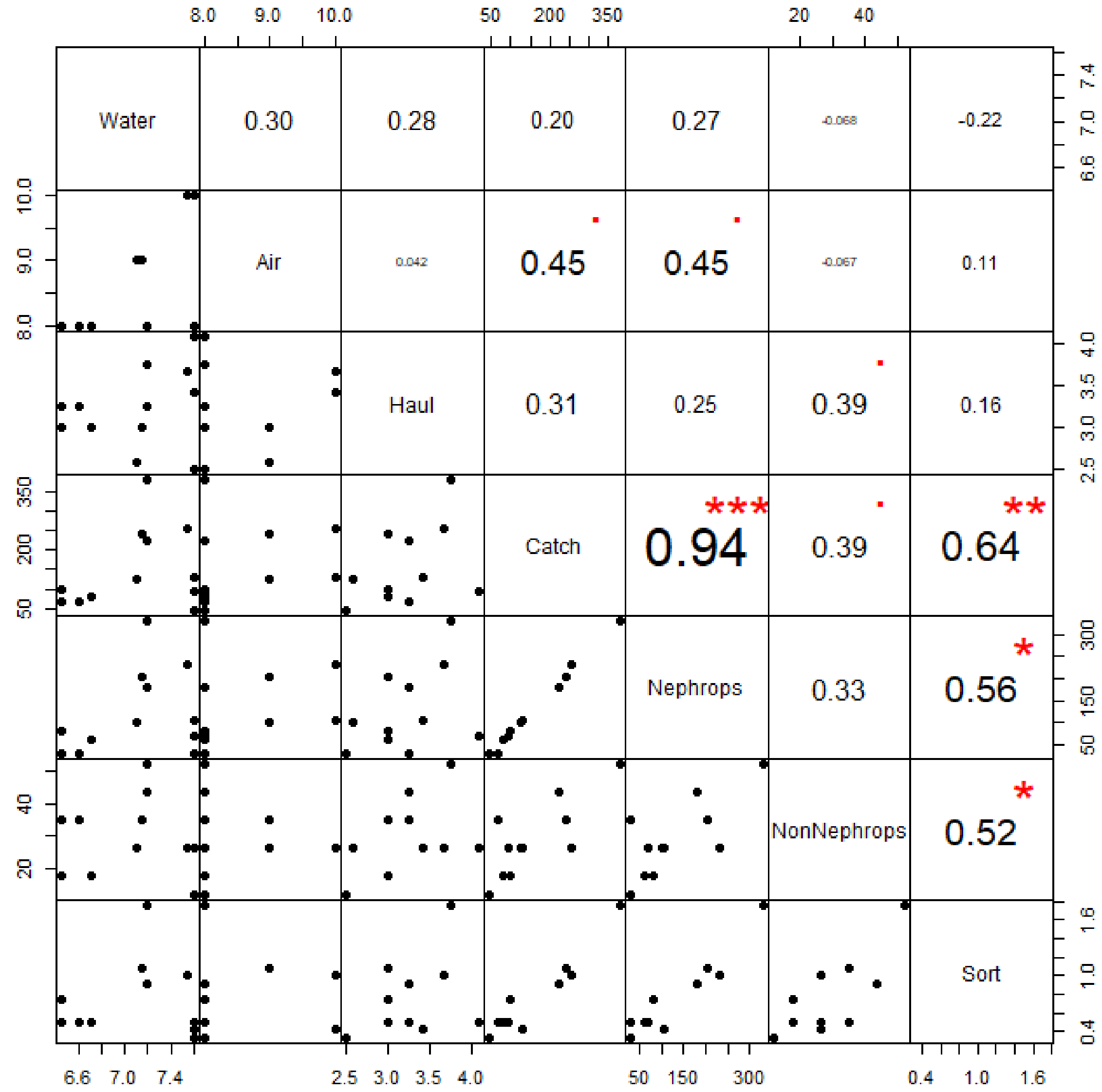


Figure S2: Pairs plot for Study 2 operational covariables. Panels above the diagonal give Kendall correlation coefficients with font size related to significance and significance (p< 0.05*> p<0.01**> p<0.001***). Symbols are solid circles — winter hauls. Water — sea surface temperature (ºC); Air — hopper air temperature (ºC); Haul — haul duration (h); Catch — total catch weight (kg); *Nephrops* — catch weight of *Nephrops* (kg); Non-*Nephrops* — catch weight of organisms other than *Nephrops* (kg); Sort — total sorting time (h).

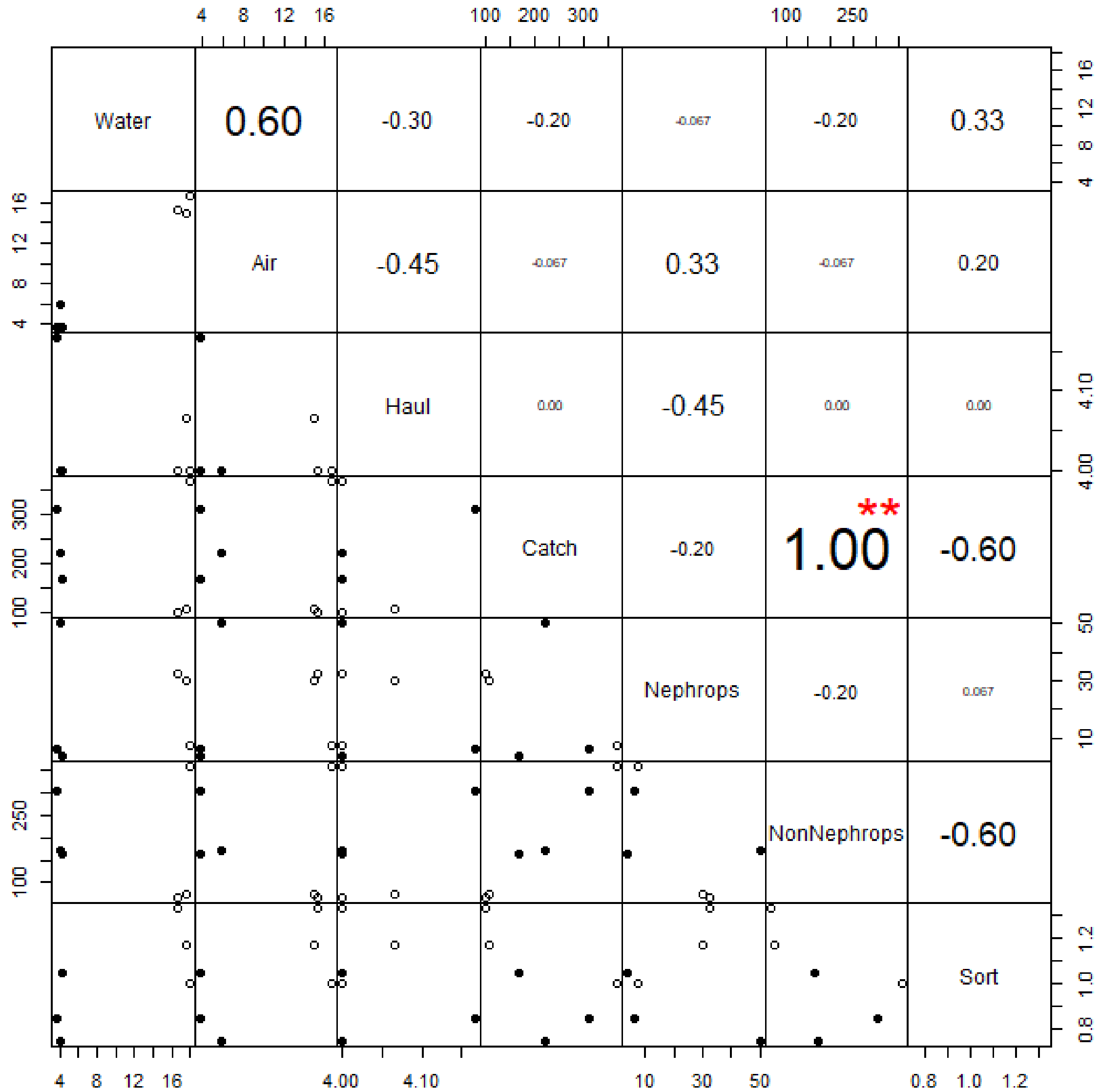


Figure S3: Pairs plot for Study 3 Seltra trawl hauls operational co-variables. Panels above the diagonal give Kendall correlation coefficients with font size related to significance and significance (p< 0.05*> p<0.01**> p<0.001***). Symbols are solid circles — winter hauls; open circles — summer hauls. Water — sea surface temperature (ºC); Air — hopper air temperature (ºC); Haul — haul duration (h); Catch — total catch weight (kg); *Nephrops* — catch weight of *Nephrops* (kg); Non-*Nephrops* — catch weight of organisms other than *Nephrops* (kg); Sort — total sorting time (h).

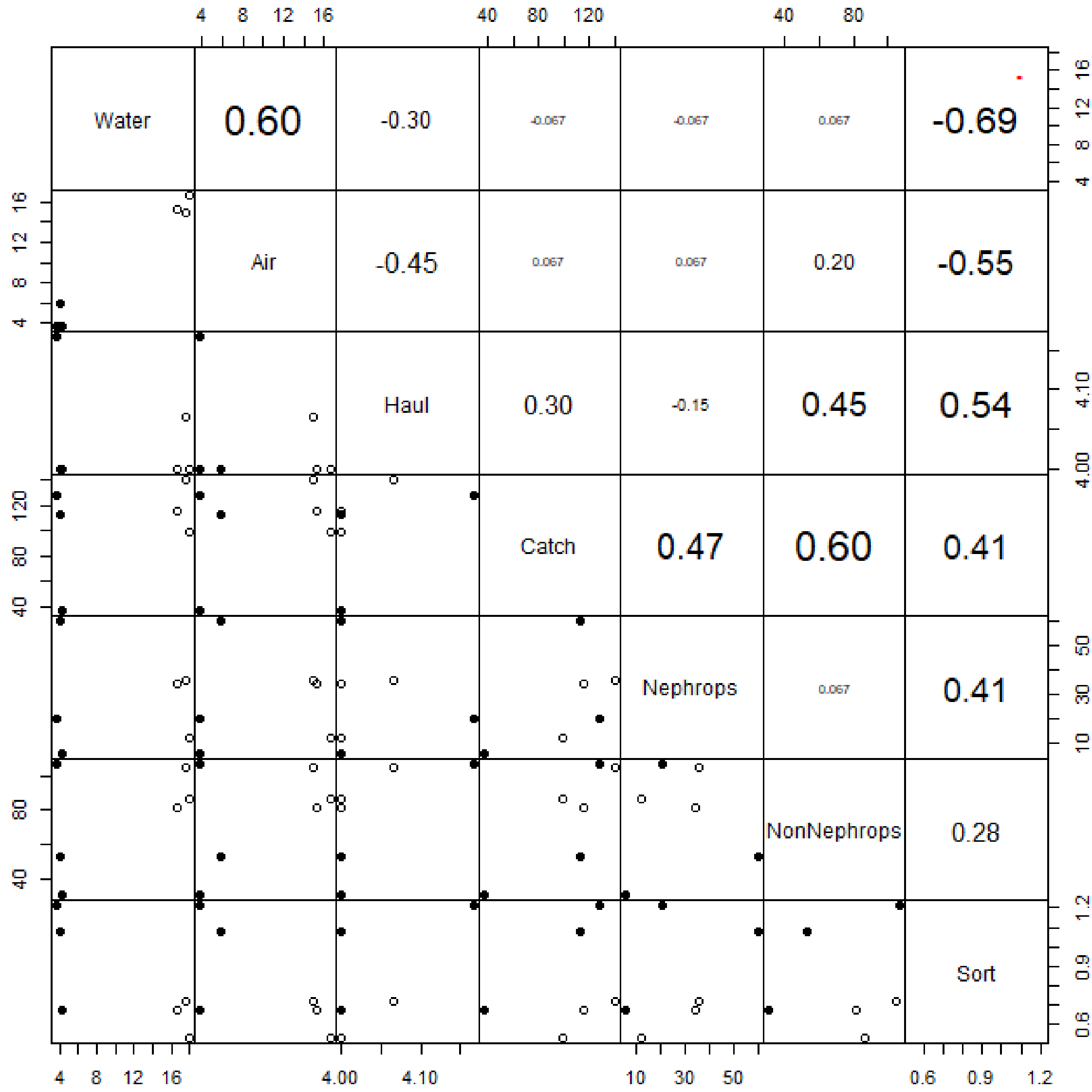


Figure S4: Pairs plot for Study 3 SweGrid trawl hauls operational co-variables. Panels above the diagonal give Kendall correlation coefficients with font size related to significance and significance (p< 0.05*> p<0.01**> p<0.001***). Symbols are solid circles — winter hauls; open circles — summer hauls. Water — sea surface temperature (ºC); Air — hopper air temperature (ºC); Haul — haul duration (h); Catch — total catch weight (kg); *Nephrops* — catch weight of *Nephrops* (kg); Non-*Nephrops* — catch weight of organisms other than *Nephrops* (kg); Sort — total sorting time (h).

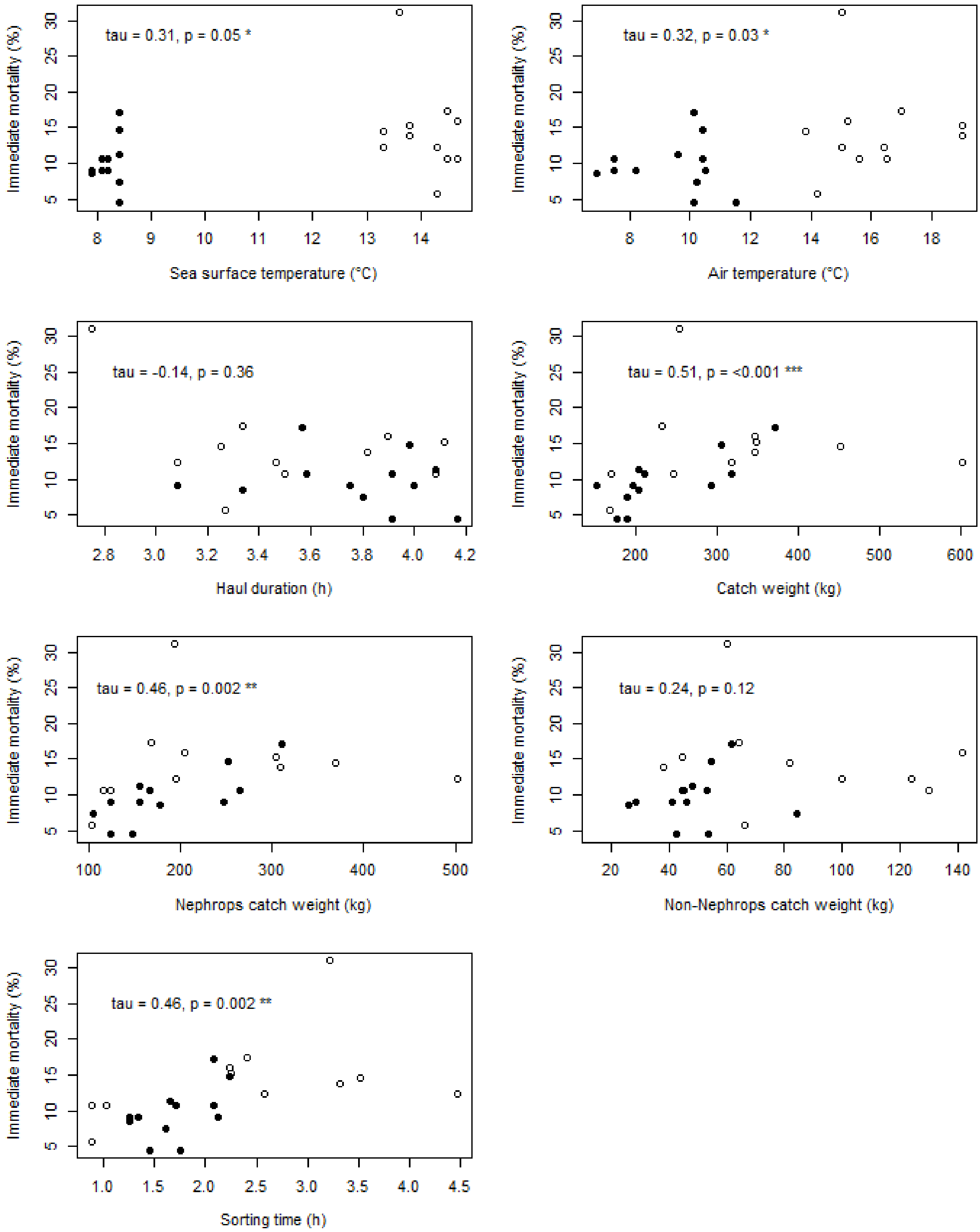


Figure S5: Scatterplots of immediate mortality against available covariates from each haul in Study 1. The Kendall tau correlation and its significance (p< 0.05*> p<0.01**> p<0.001***) are shown in each panel. Symbols are solid circles — winter hauls; open circles — summer hauls.

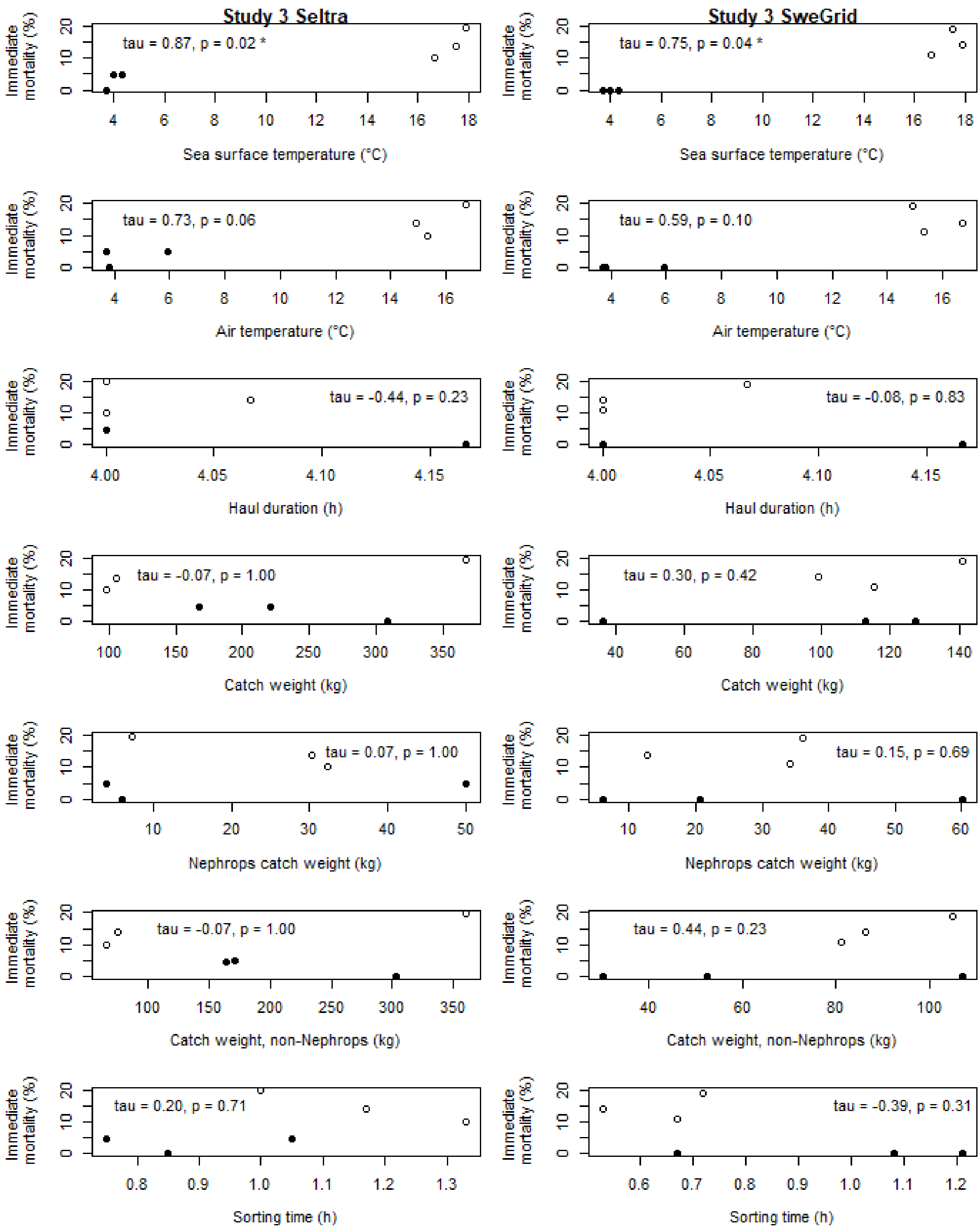


Figure S6: Scatterplots of immediate mortality against available operational covariates from each haul in Study 3 by gear (left hand column — Seltra trawl hauls; right hand column — Swedish grid trawls). The Kendall tau correlation and its significance (p< 0.05*> p<0.01**> p<0.001***) are shown in each panel. Symbols are solid circles — winter hauls; open circles — summer hauls.

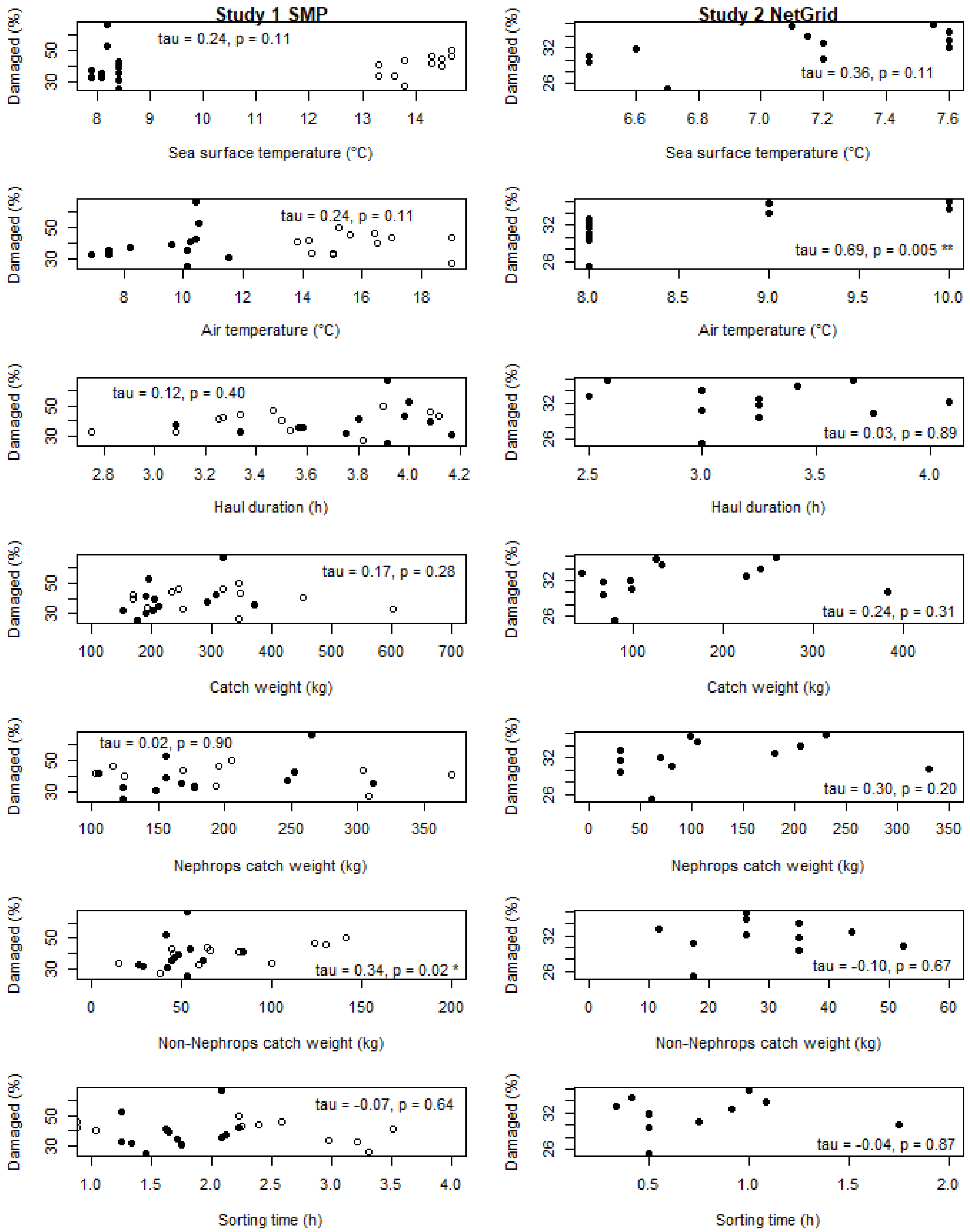


Figure S7: Scatterplots of proportion of *Nephrops* with at least one recorded physical injury during catch sorting for studies 1 (left hand column) and 2 (right hand column) against available operational covariates from each haul. The Kendall tau correlation and its significance (p< 0.05*> p<0.01**> p<0.001***) are shown in each panel. Symbols are solid circles — winter hauls; open circles — summer hauls.

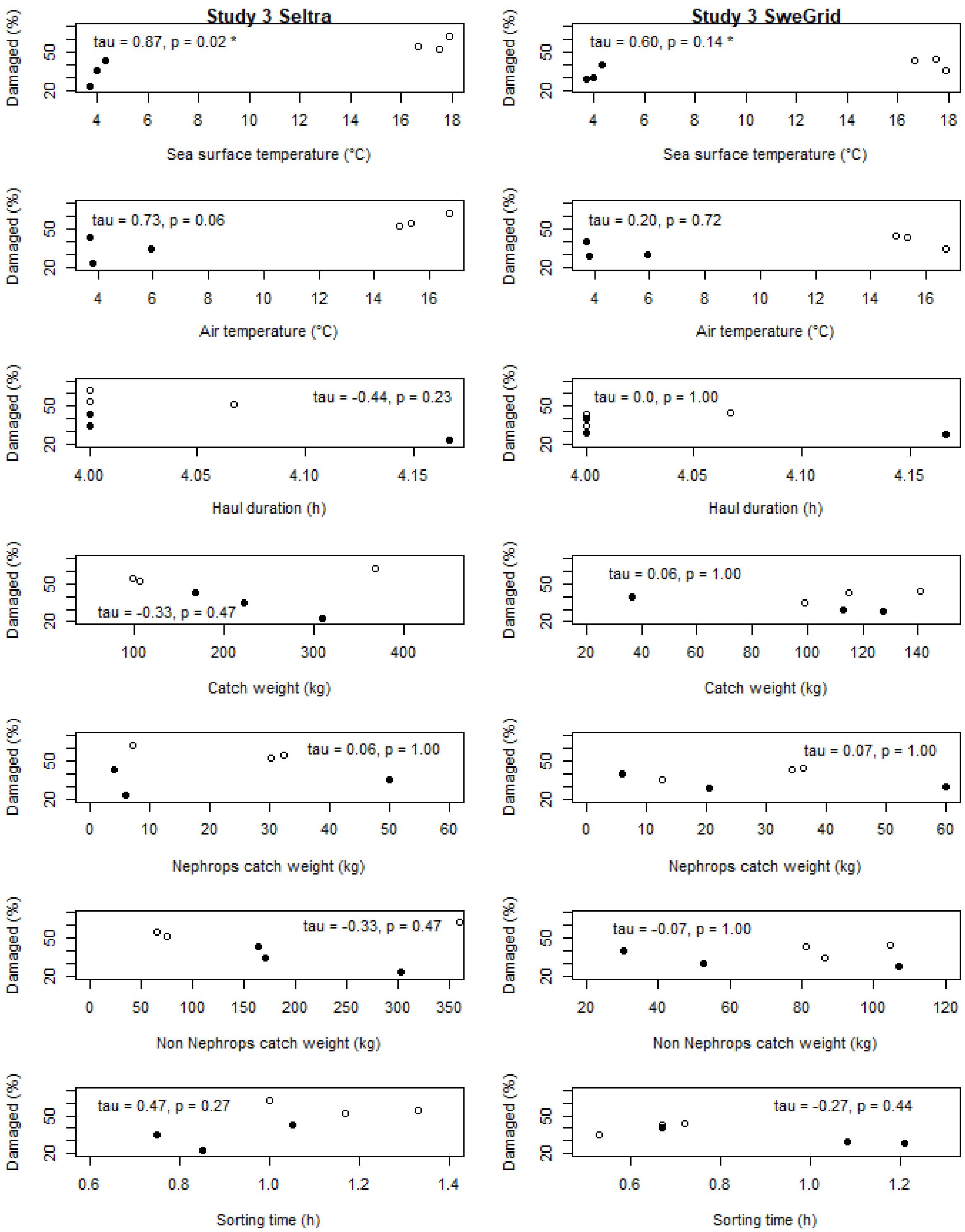


Figure S8: Scatterplots of percentage of *Nephrops* with at least one recorded physical injury during catch sorting against available operational covariates from each haul in Study 3 by gear (left hand column — Seltra trawl hauls; right hand column — Swedish grid trawls). The Kendall tau correlation and its significance (p< 0.05*> p<0.01**> p<0.001***) are shown in each panel. Symbols are solid circles — winter hauls; open circles — summer hauls.

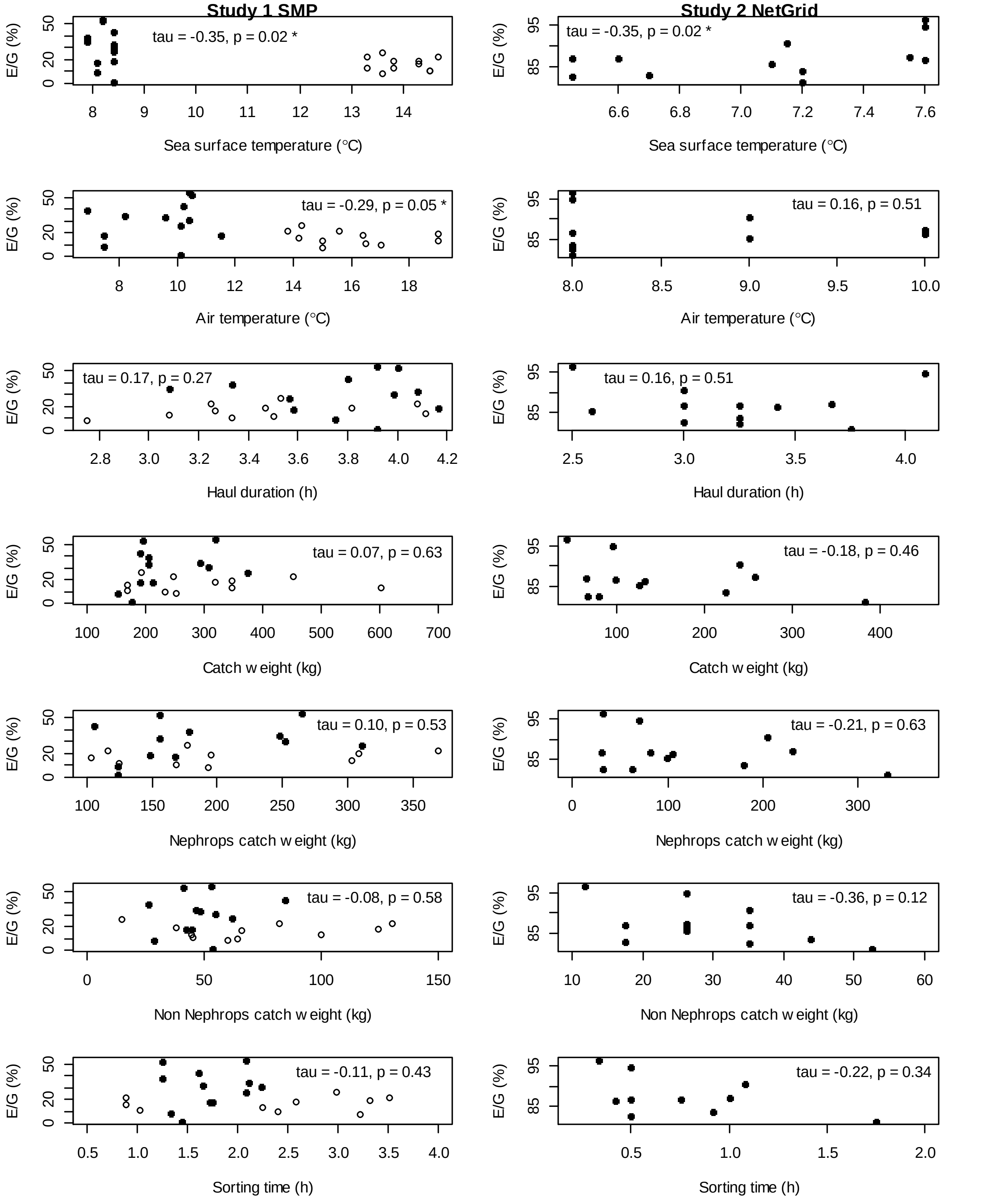


Figure S9: Scatterplots of percentage of *Nephrops* sampled for captive observation in the 'Excellent' plus 'Good' (E/G) vitality category during catch sorting for studies 1 (left hand column) and 2 (right hand column) against available operational covariates from each haul. The Kendall tau correlation and its significance ($p< 0.05$*> $p<0.01$**> $p<0.001$***) are shown in each panel. Symbols are solid circles — winter hauls; open circles — summer hauls.

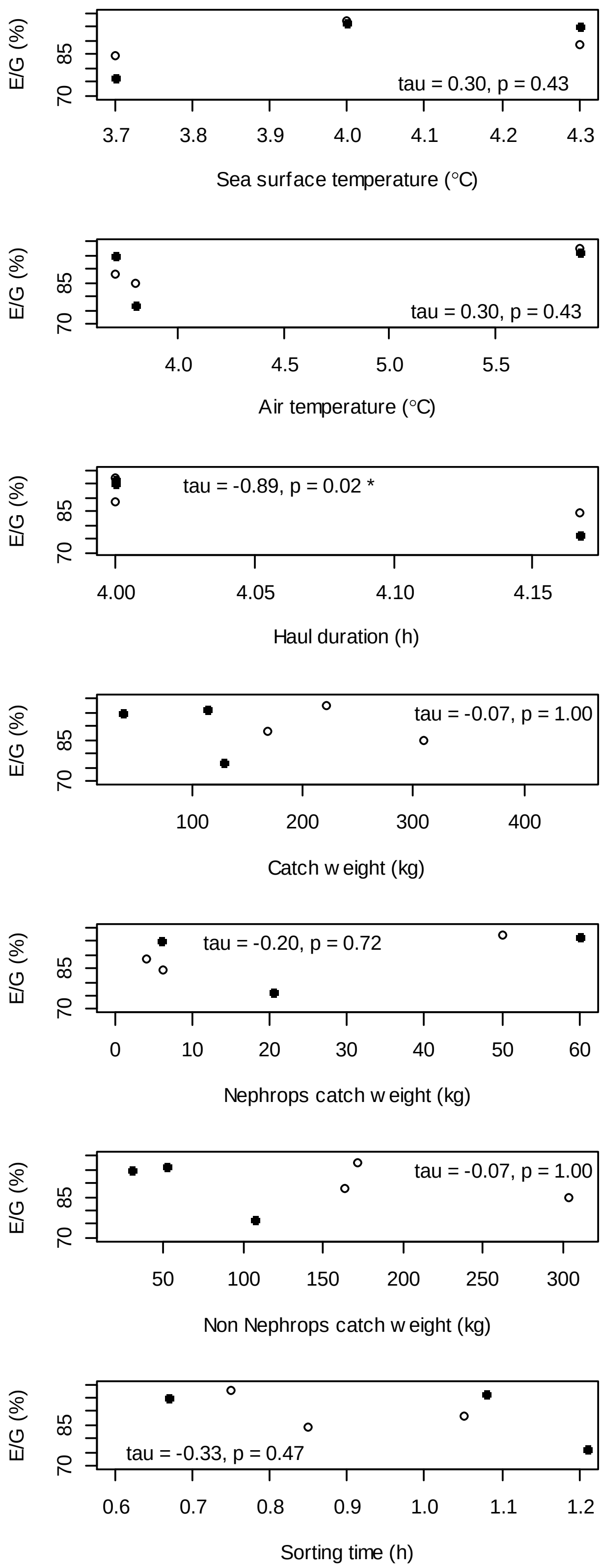


Figure S10: Scatterplots of percentage of *Nephrops* sampled for captive observation in the ‘Excellent’ plus ‘Good’ (E/G) vitality category during catch sorting for Study 2. The Kendall tau correlation and its significance (p< 0.05*> p<0.01**> p<0.001***) are shown in each panel. Vitality was not recorded for the summer tows in study 3. Symbols are open circles — winter hauls with Seltra trawl; solid circles — winter hauls with SweGrid trawl.

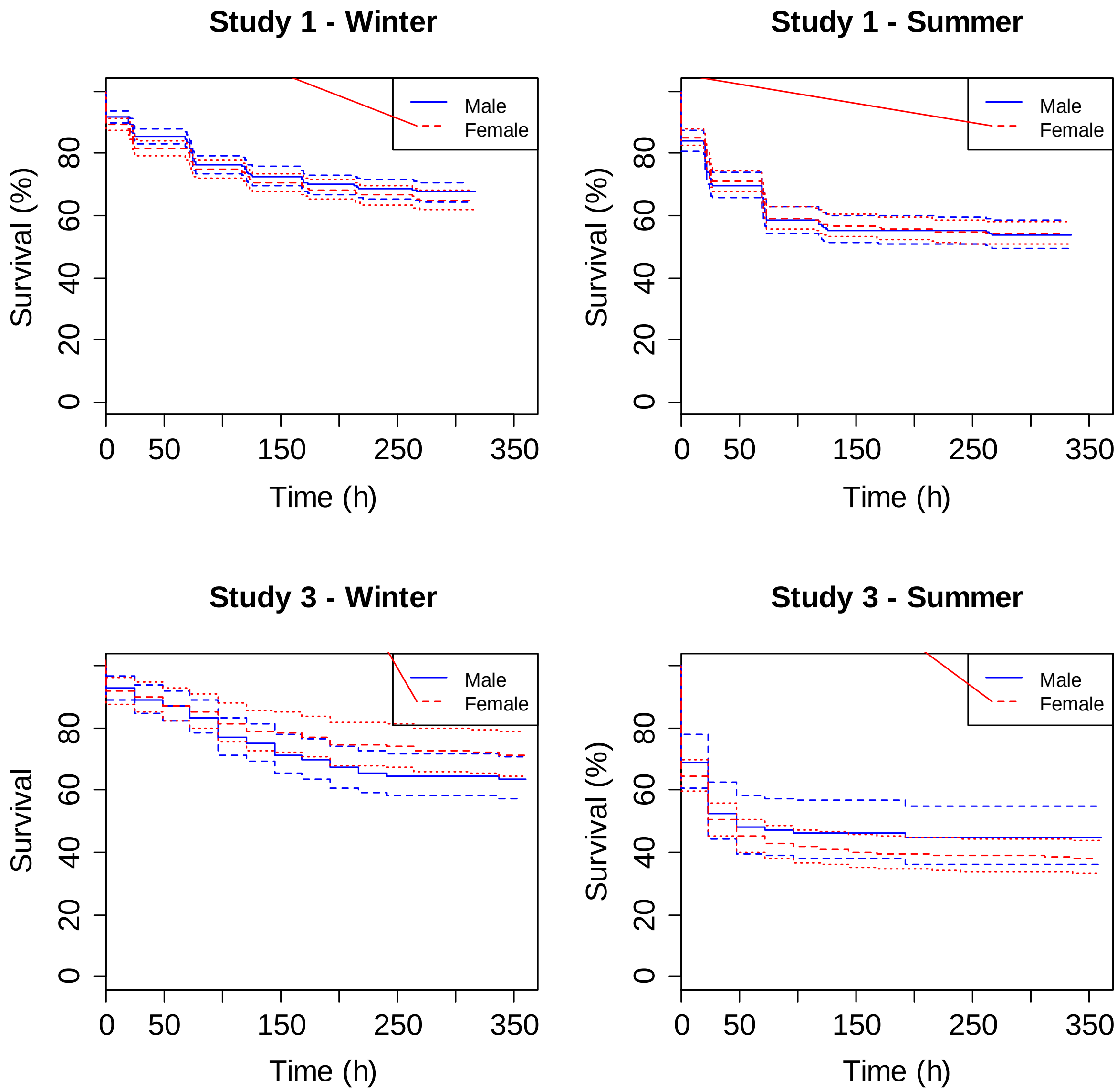


Figure S11: Kaplan-Meier survival curves relating the probability of survival of individual *Nephrops* in the observation tanks against sex for studies 1 and 3. Solid lines are the mean curves, dashed lines are the 95% confidence intervals. Note that these plots exclude immediate mortality because sex was not recorded for dead *Nephrops* during catch sorting.

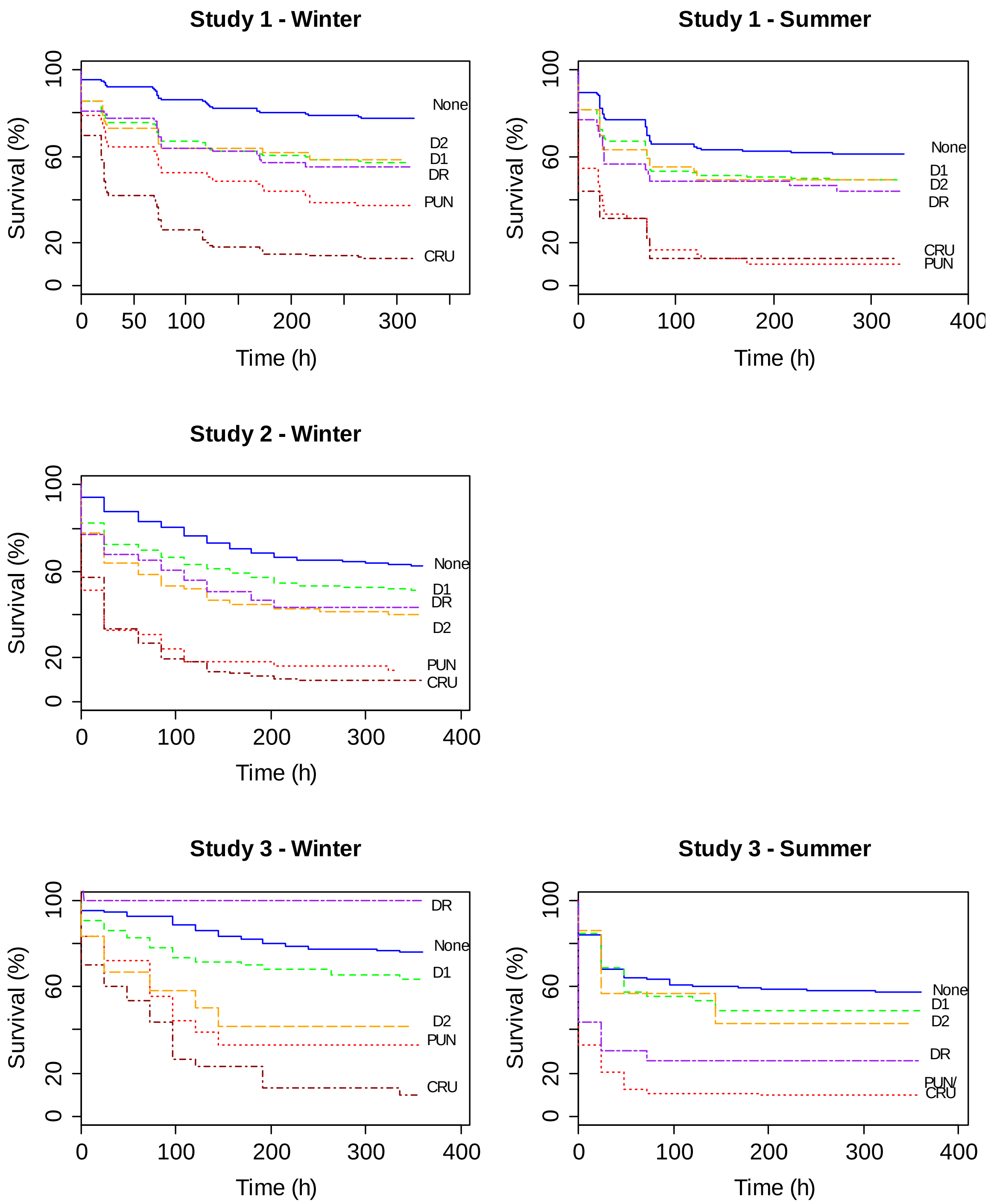


Figure S12: Kaplan-Meier survival curves for effect on survival of the presence of different physical injuries: D1 — loss of one chela; D2 — loss of 2 chelae; DR — damaged rostrum; PUN — puncture; CRU — crush. Note that individual *Nephrops* may have had more than one type of injury. For clarity, confidence intervals are omitted.

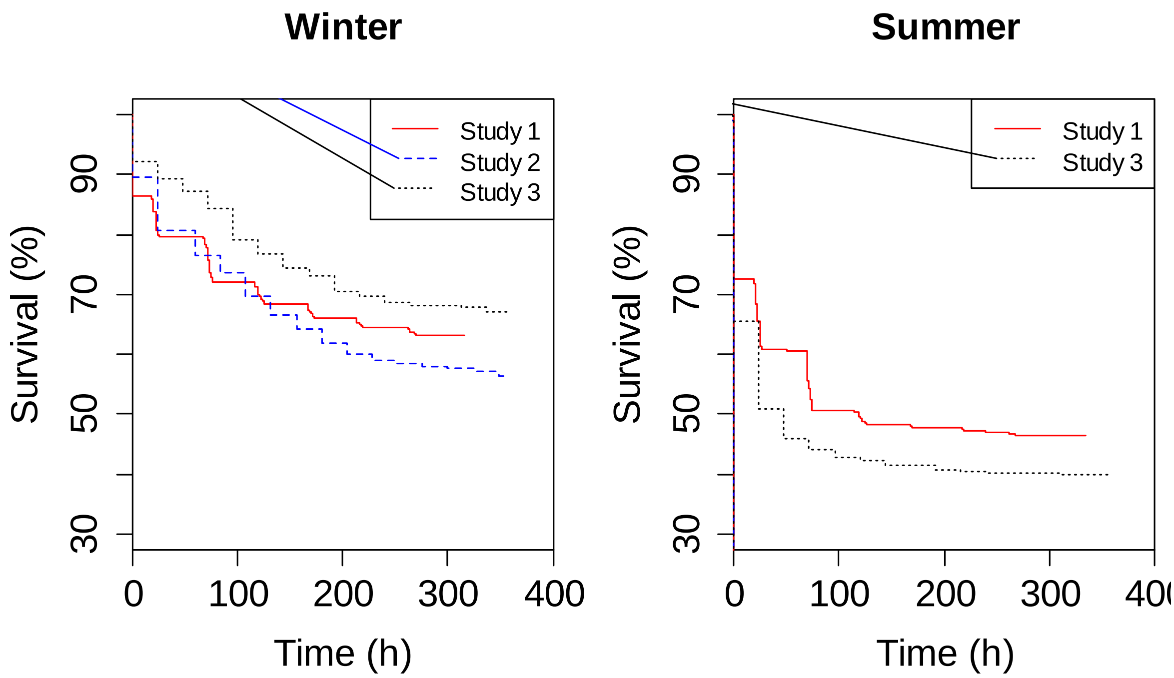


Figure S13: Kaplan-Meier survival curves for individual *Nephrops* monitored in captivity by season and study. For clarity, *c*onfidence intervals are omitted.

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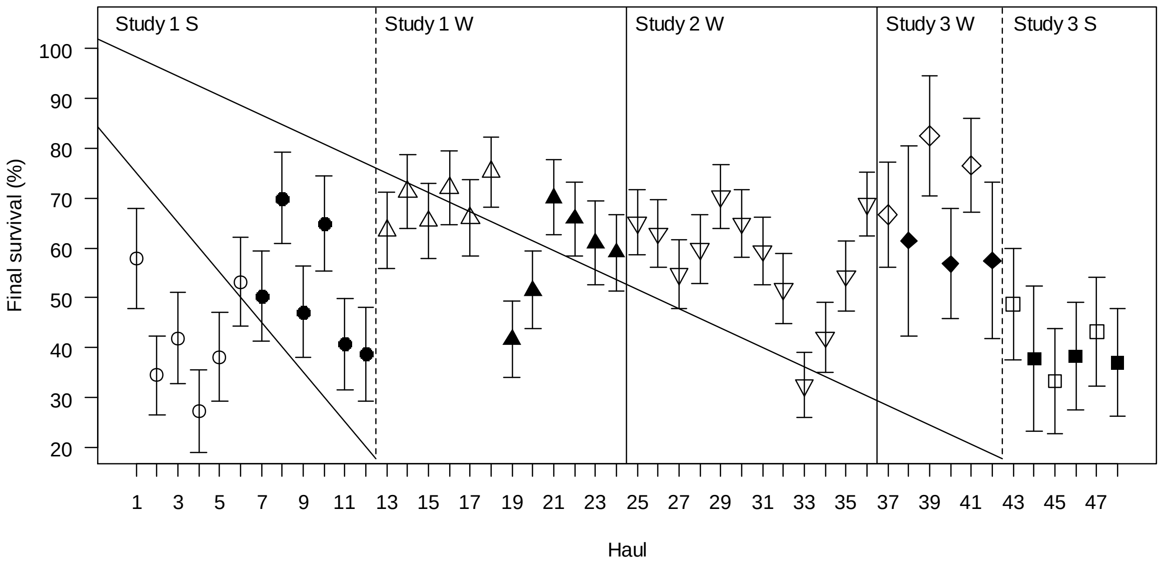

Figure S14: Kaplan-Meier estimates of final mean survival, including immediate mortality, at the time of last observation by haul. Symbols indicate the mean and the whiskers are ± 95% confidence intervals. S — summer, W — winter. By haul symbols: Open circles — Study 1 SMP 100 mm cod-end summer hauls; Filled circles — Study 1 SMP 80 mm cod-end summer hauls; Open triangles — Study 1 SMP 100 mm cod-end winter hauls; Filled triangles — Study 1 SMP 80 mm cod-end summer hauls; Open inverted triangles — Study 2 NetGrid 80 mm cod-end winter hauls; Open diamonds — Study 3 SweGrid 70 mm cod-end winter hauls; Filled diamonds — Study 3 Seltra 90 mm cod-end summer hauls; Open squares — Study 3 SweGrid 70 mm cod-end summer hauls; Filled squares — Study 3 Seltra 90 mm cod-end summer hauls.

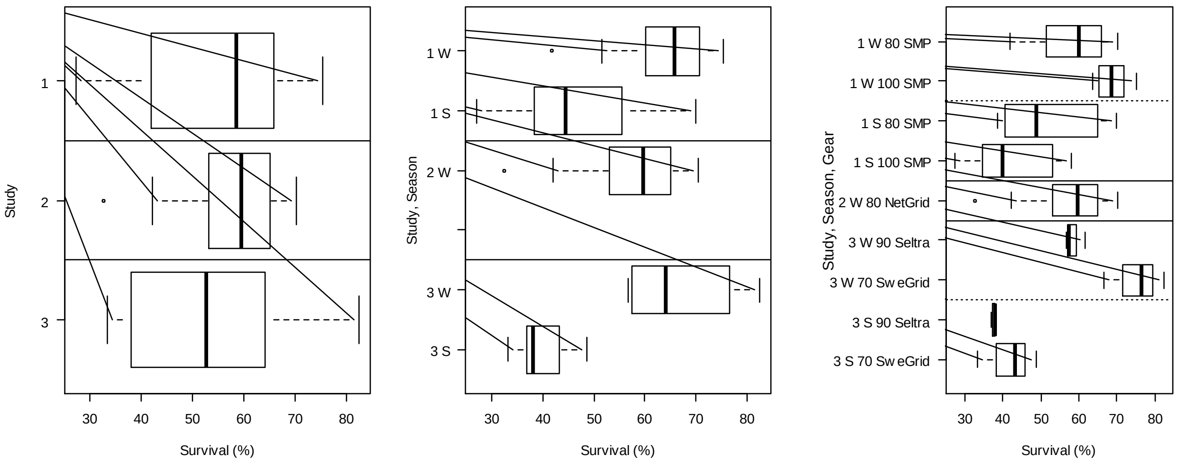

Figure S15: Boxplots of observation tank-based Kaplan-Meier final survival estimates, including immediate mortality, amalgamated by study (left panel), study and season (middle panel), and study, season and gear (right panel). Seasons labelled as W — winter, S — summer; Gears labelled as cod-end mesh size plus gear modifications as described in the text. Heavy vertical bars indicate medians and boxes inter-quartile ranges; left and right whiskers are the lower and upper quartile minus or plus 1.5 times the inter-quartile range respectively.

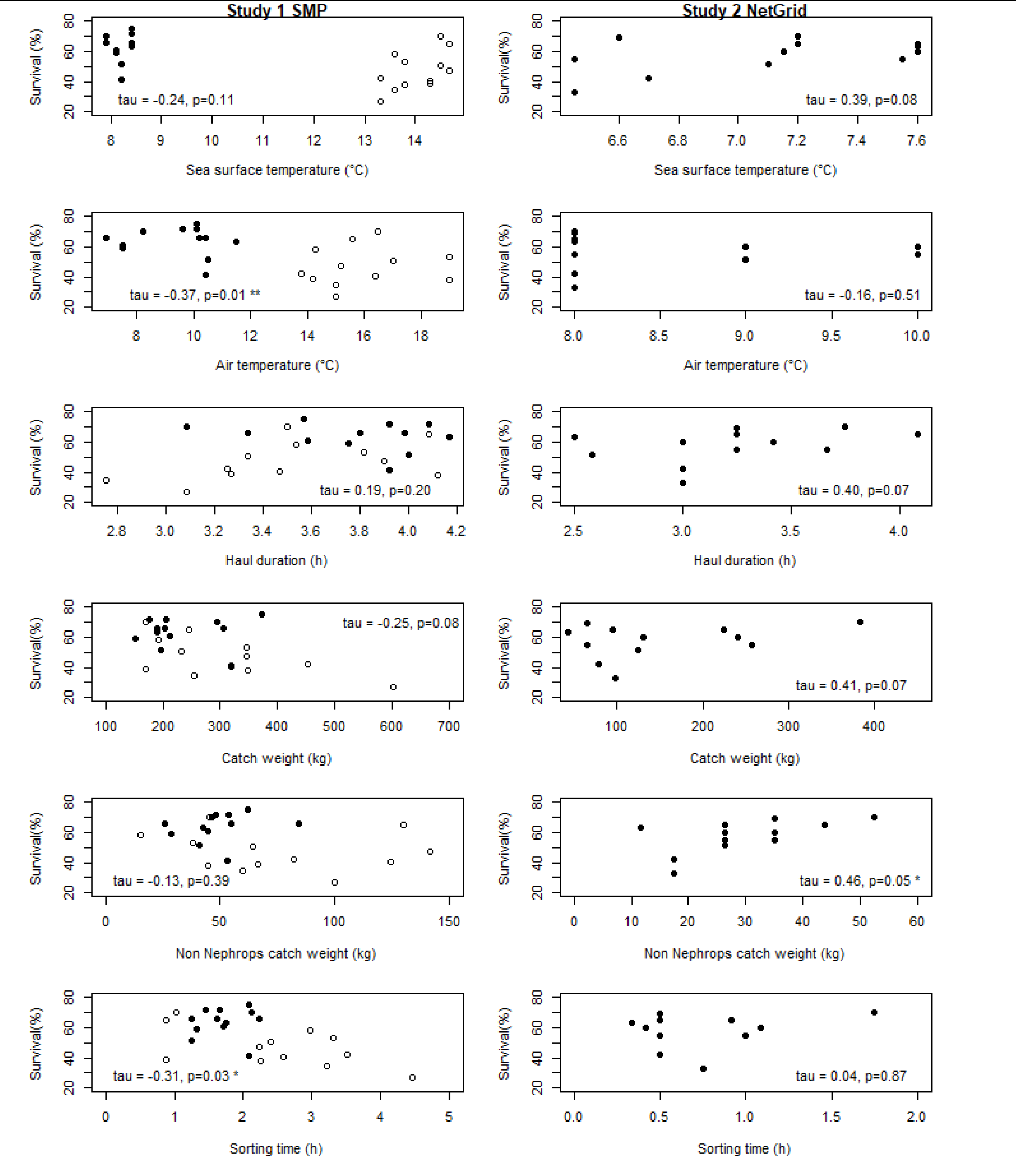

Figure S16: Scatterplots of final mean survival estimates for studies 1 (left hand column) and 2 (right hand column) against available environmental and operational covariates for studies 1 (left hand column) and 2 (right hand column). The Kendall tau correlation and its significance (p< 0.05*> p<0.01**> p<0.001***) are shown in each panel. Symbols are solid circles — winter hauls; open circles — summer hauls.

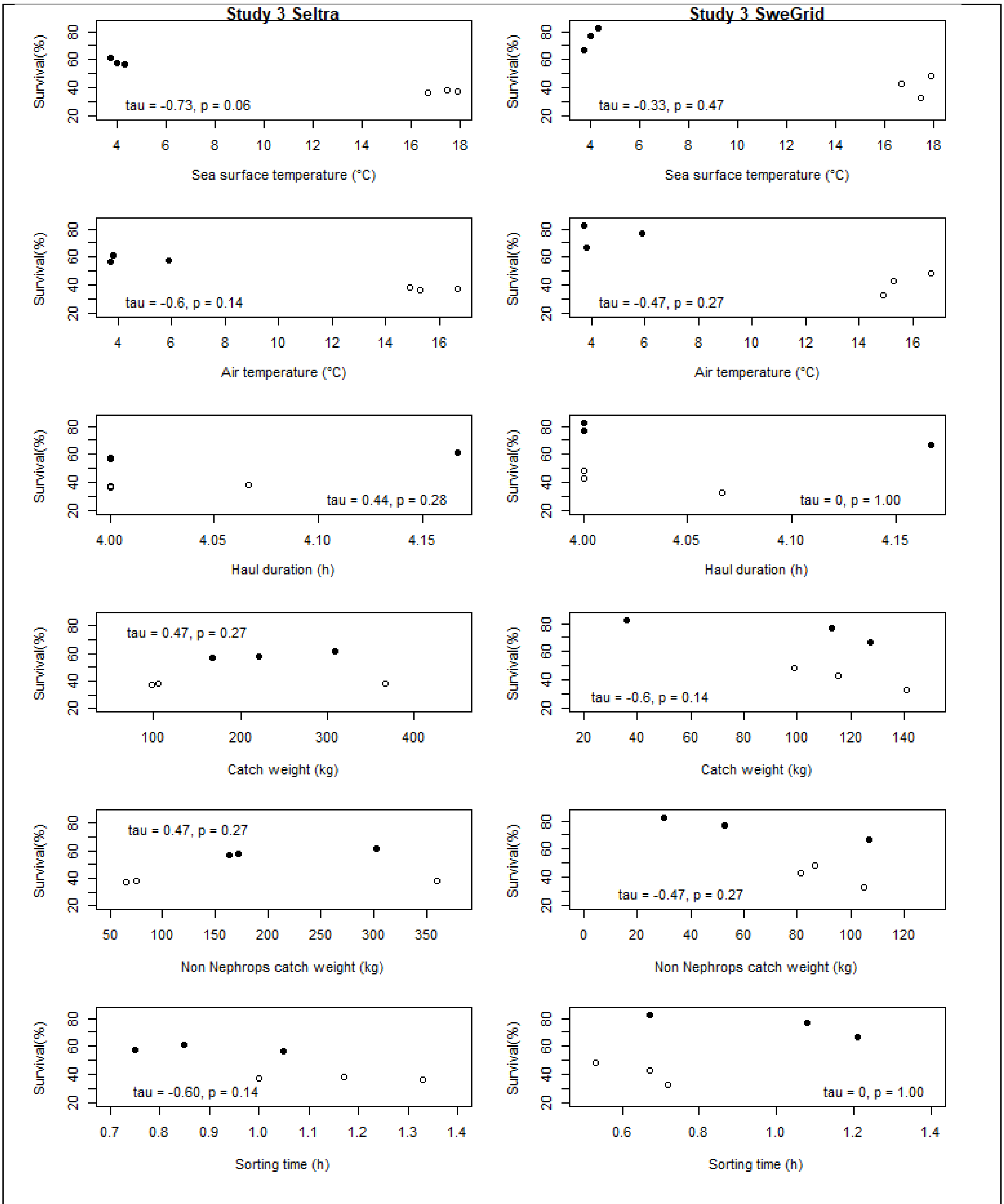

Figure S17: Scatterplots of final mean survival estimates for study 3 against available environmental and operational covariates for study 3 by gear (left hand column — Seltra trawl hauls; right hand column — Swedish grid trawls). Symbols are solid circles — winter hauls; open circles — summer hauls.

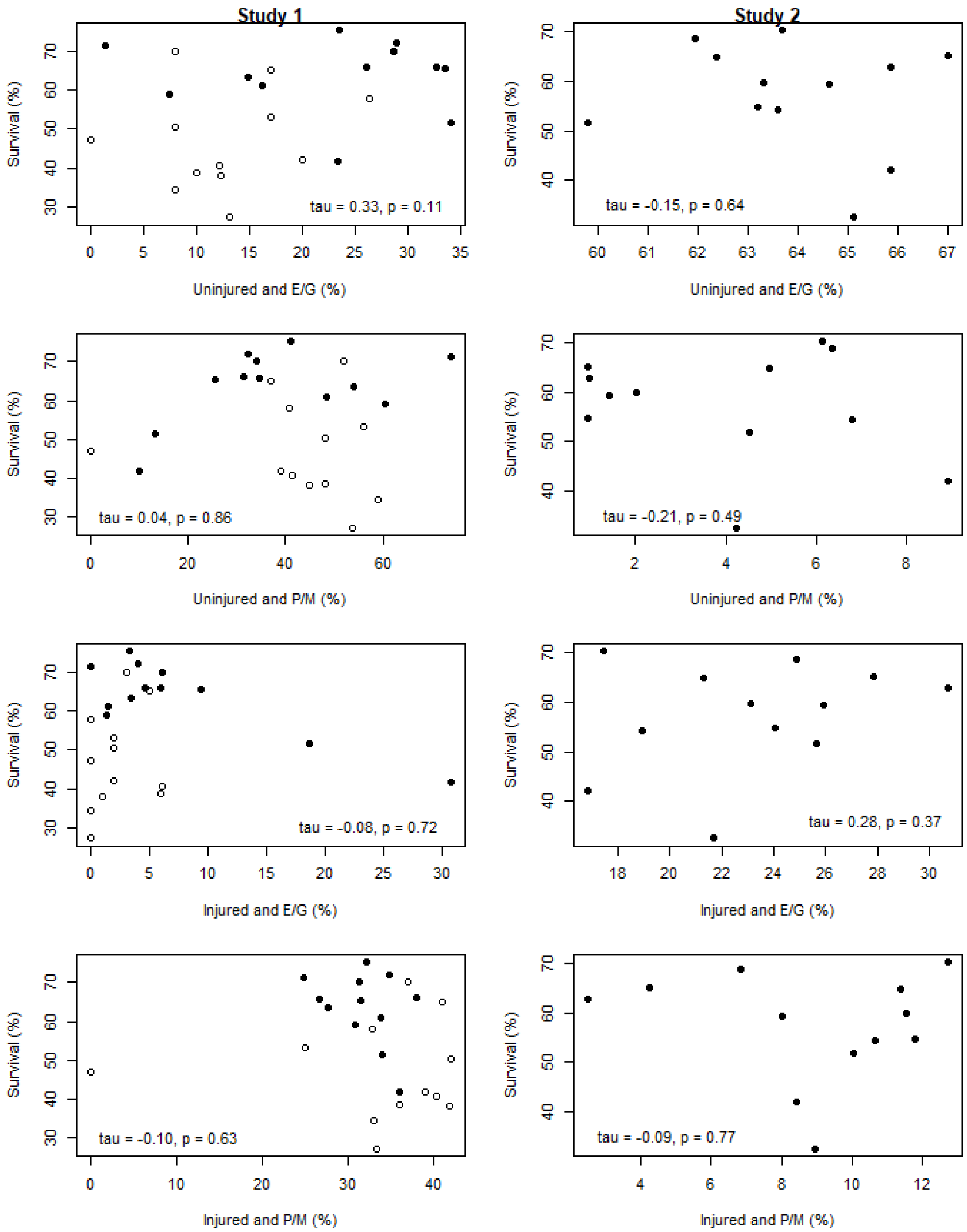

Figure S18: Scatterplots of final mean survival estimates for studies 1 (left hand column) and 2 (right hand column) against biological factor percentage of Nephrops in the four injury combined with vitality groups. The Kendall tau correlation and its significance (p< 0.05*>

p<0.01**> p<0.001***) are shown in each panel. Symbols are solid circles — winter hauls; open circles — summer hauls.

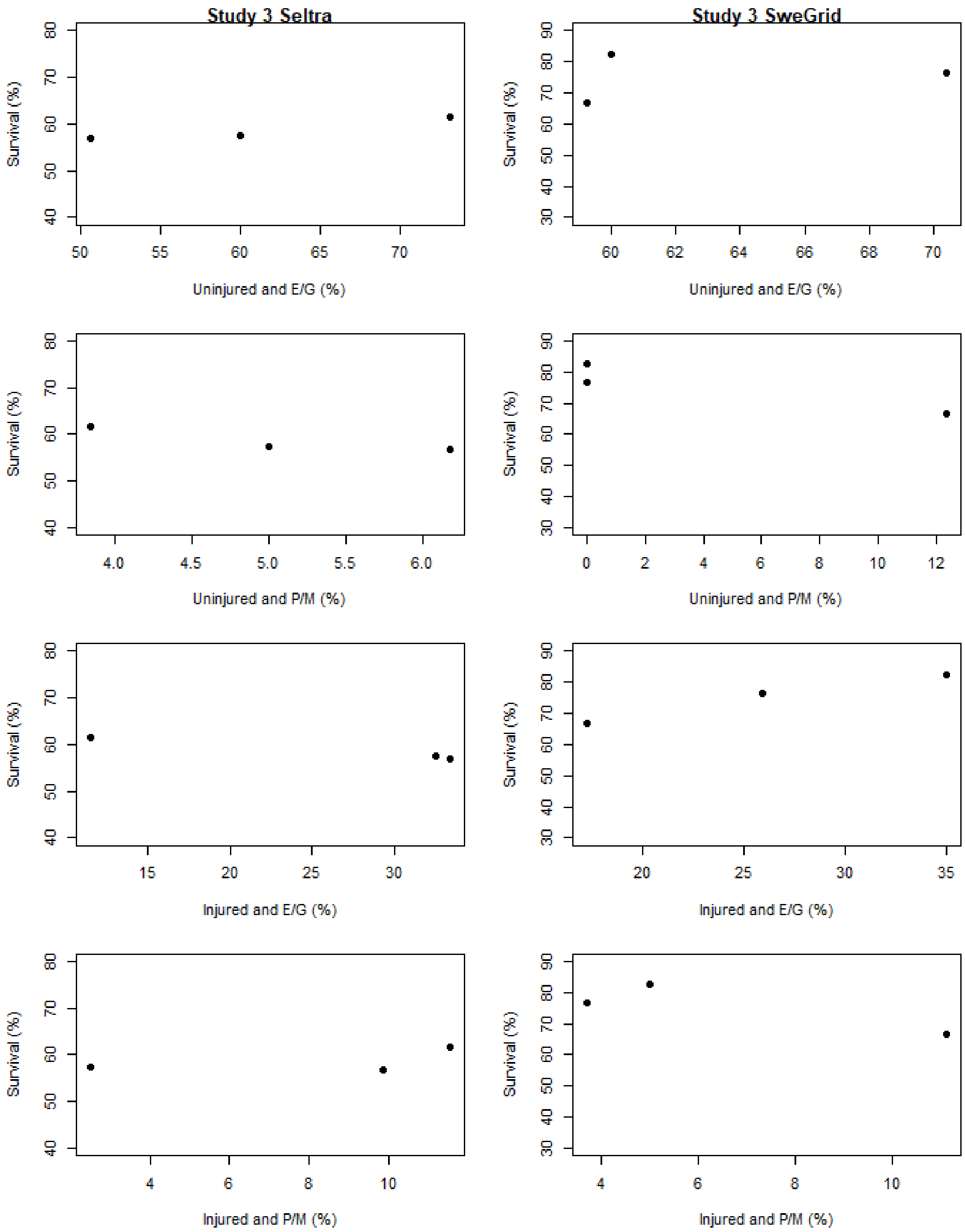

Figure S19: Scatterplots of final mean survival estimates for study 3 against biological factor proportion of *Nephrops* in the four injury combined with vitality groups by gear. Correlations were not computed due to small sample size. Symbols are solid circles — winter hauls; Note that vitality was not recorded for the summer hauls.