Survival of decapod crustaceans discarded in the *Nephrops* fishery of the Clyde Sea area, Scotland

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The Clyde Sea *Nephrops* fishery produces large amounts of invertebrate discards. Of these, as much as 89% are decapod crustaceans, including the swimming crab *Liocarcinus depurator* (Linnaeus, 1758), the squat lobster *Munida rugosa* (Fabricius, 1775) and the hermit crab *Pagurus bernhardus* (Linnaeus, 1758). The short-term mortality of these species was assessed following trawling and periods of aerial exposure on deck (16–90 min), and ranged from 2–25%, with *Pagurus bernhardus* showing the lowest mortality. Two experiments were performed to determine the longer-term survival of trawled decapods compared to those with experimentally ablated appendages. Deliberately damaged decapods had a significantly lower longer-term survival (ca. 30%) than controls (72–83%). Survival of trawled *Liocarcinus depurator* that had been induced to autotomize two appendages was slightly lower (74%) compared with intact creel-caught animals (92%). Mortality rates stabilised about 10 d after trawling. Our results suggest that post-trawling mortality of discarded decapod crustaceans has been underestimated in the past, owing to inadequate monitoring periods.

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Introduction

In recent years, the ecological effects of fishing have become a global environmental concern resulting in a large number of studies that were reviewed by Jennings and Kaiser (1998); Hall (1999) and Moore and Jennings (2000). Commercial fishing has been estimated to produce 27 million t yr^{-1} discards world-wide (Alverson *et al.*, 1994). "Discards" is a term used for non-target species and undersized commercial animals that are rejected from the catch.

The Norway lobster (*Nephrops norvegicus*, hereafter referred to by genus alone) is the most valuable shellfish in Scottish waters. It lives on muddy substrata and is mainly fished by otter-trawling. In the Clyde Sea area (ca. 40°00′N 05°00′W) *Nephrops* trawls (mesh size ≥70 mm) disturb wide areas of the sea bed and benthic fauna as weighted ground lines and heavy otter doors are dragged across the sediment (Marrs *et al.*, 2000; Coggan *et al.*, 2000) and 50–90% of the catch (by volume) is discarded (Bergmann *et al.*, 2001a). Invertebrates account for up to 90% of the number of animals discarded, with up to 89% of these being decapod Crustacea. However, little is known about the fate of this important component of the catch. Swimming crabs (*Liocarcinus depurator*) and squat lobsters (*Munida rugosa*) are the most abundant decapod species discarded in the Clyde Sea area, concurring with findings from the Adriatic Sea (*inter alia*: Gramitto and Froglia, 1998; Wieczorek *et al.*, 1999).

Whilst various aspects of the biology of *L. depurator* have been studied (e.g. Abelló, 1989; Hall *et al.*, 1990; Freire, 1996; Muiño *et al.*, 1999; Spicer and Baden, 2000), information on squat lobsters has focused on other members of the Galatheidae (Zimmermann, 1913; Nicol, 1932; Rice and de Saint-Laurent, 1986; Hartnoll

et al., 1992; Gramitto and Froglia, 1998) than *M. rugosa* (but see Howard, 1981; Zainal *et al.*, 1992).

Almost 50% and 60% of *L. depurator* and *M. rugosa*, respectively, caught by commercial trawls in the Clyde Sea area show signs of recent injury such as loss of appendages (Bergmann *et al.*, 2001b). Such losses may be caused by physical contact with the fishing gear, other species in the catch, or by handling. Alternatively, appendages can be autotomized deliberately in attempts to escape or in order to reduce damage and haemolymph loss after injury has occurred (Wood and Wood, 1932; Goss, 1969; McVean, 1982; Juanes and Smith, 1995). Thus, the manner of appendage loss (i.e. involuntary or voluntary) could have an effect on subsequent survival rates. Previous studies on the fate of discards have dealt chiefly with undersized *Nephrops* and commercial fish (Symonds and Simpson, 1971; Evans *et al.*, 1994; Wileman *et al.*, 1999) or other undersized commercially important decapods (e.g. Bennett, 1973; Davis, 1981; Reilly, 1983; Simonson and Hochberg, 1986; Vermeer, 1987; Kennelly *et al.*, 1990; Stevens, 1990; Potter *et al.*, 1991). Fewer studies have dealt with the post-trawling survival of non-target crustaceans (Wassenberg and Hill, 1989, 1993; Craeymeersch, 1994; Fonds, 1994; Kaiser and Spencer, 1995; Bergman *et al.*, 1998).

Post-fishing survival is affected by a range of factors. First, trawling characteristics such as tow duration, towing speed, fishing depth, substratum, catch size and composition are likely to affect damage and mortality (Bergman *et al.*, 1998; Wileman *et al.*, 1999). Second, once the catch is on deck, mortality may be enhanced as animals endure hypoxia (Spicer *et al.*, 1990), temperature changes (Zainal *et al.*, 1992), high light intensities (Chapman *et al.*, 2000) and physical damage due to handling and compression by the weight of the catch (Stevens, 1990; Wileman *et al.*, 1999). Catch sorting times vary between 10–280 min on commercial Scottish *Nephrops* trawlers, depending on catch size and composition, sediment type and number of crew (Chapman *et al.*, 2000). Sorting times on Clyde fishing boats range from 45–300 min with a median of 90 min (M. Bergmann, pers. obs.).

The object of the present study was to assess short- and longer-term survival of ecologically important decapod species from the Clyde Sea *Nephrops* fishery, with respect to the effects of injury and autotomy.

Materials and methods

Three experiments (including both field and laboratory-based trials) were carried out to investigate the short and longer-term rates of mortality in three species of decapod crustaceans that are routinely discarded in high numbers during commercial fishing for *Nephrops* in the Clyde Sea area, i.e. *L. depurator*, *M. rugosa* and *Pagurus bernhardus*.

Experiment 1: short-term mortality

Short-term mortality was assessed after trawl-caught decapods had been separated from commercial species, exposed to air on deck for 16–90 min (to simulate commercial practice) then transferred into standard fish boxes (75 cm × 40 cm) supplied with running seawater (25 cm water depth). Counts were made of the numbers of dead and live animals, with individuals considered dead if there was no reaction to mechanical stimuli or their maxillipeds had ceased to move.

Experiment 2: longer-term survival of trawled and experimentally damaged decapods

Previous work in the Clyde Sea area has shown that up to 50% and 60% of *L. depurator* and *M. rugosa*, respectively, caught in *Nephrops* trawls were physically damaged during the fishing process (Bergmann *et al.*, 2001b). In this experiment, the degree of damage to test organisms was manipulated to quantify its effect on survival. In September 1999, RV "Aora" (15 m, 260 hp) conducted a two hour tow at 2.5 knots and 45 m depth in Fintray Bay (ca. 57°47′N 04°58′W) using a commercial rockhopper otter-trawl with 70-mm diamond-shaped mesh, reflecting local fishing practice (see Strange, 1981). The volume of the catch was measured using baskets (44 l) as the catch was sorted and the two most common decapod species (*M. rugosa* and *L. depurator*) were collected to monitor post-trawling survival. Since discards often remain on deck for 90 min on commercial Clyde trawlers, the selected test animals were exposed to air for 90 min before placing them in fish boxes supplied with running sea water. Intact *M. rugosa* and *L. depurator* captured in *Nephrops* creels (see Strange, 1981) baited with mackerel were collected from Fintray Bay over a period of 14 d prior to trawling and used as controls for the effects of trawling and on-deck damage. Aerial exposure of the creel-caught animals was minimised (<15 min) while they were carefully transferred into cages. As a second treatment, the survival of intact, trawled individuals was monitored in creels following 90 min aerial exposure. In a third treatment, one cheliped and one second pereiopod were removed by hand from intact, trawled, air-exposed animals to simulate the type of physical injury frequently encountered in trawled animals (Bergmann *et al.*, 2001b). All animals were measured, sexed, transferred into individual plastic mesh containers (1.3-cm square mesh, Figure 1) and placed in creels modified to prevent the entry of large epibenthic predators. The creels were deployed at 40 m depth in Fintray Bay where the survival was monitored twice a week over the following three weeks. The median survival time in different treatments was determined using a Kruskal–Wallis test and subsequent pairwise Mann–Whitney U tests. In order to allow for multiple
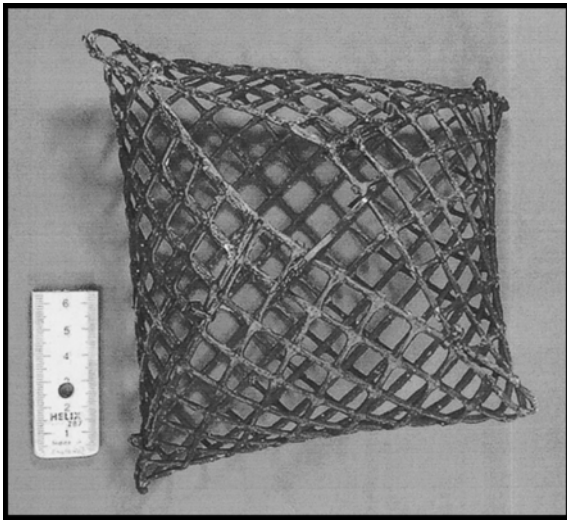
Figure 1. Plastic mesh containers employed to house individual decapods. Containers measured ca. 20 cm × 15 cm and were made from 1.3-cm square mesh plastic netting.

comparisons and increase the robustness of the test, the significance level (α=0.05) was divided by the number of comparisons (M. Carr, pers. comm.).

Experiment 3: longer-term survival after trawl damage and induced autotomy

A third experiment was carried out to distinguish between the effects of injury and autotomy on survival of *M. rugosa* and *L. depurator*. Crustaceans were captured in a 2-h trawl tow at a speed of 2.5–3.0 knots in January 2000 by RV Aora in Fintray Bay at 46–48 m depth. As in the previous experiment, the catch volume was measured and the animals were exposed to air for 90 min before being stored in running sea water. On return to the laboratory, *M. rugosa* and *L. depurator* were measured and subjected to one of the three treatments described below. The survival of intact, trawled individuals was recorded following a 90 min period of aerial exposure. In a second treatment, one cheliped and one second pereiopod were removed from originally intact, trawled and air-exposed animals to simulate physical injury due to trawling. A third treatment attempted to distinguish between the effect of injury and autotomy on post-trawling survival. Following trawling and 90 min aerial exposure, autotomy of one cheliped and one second pereiopod was induced by exerting pressure on the propodus with hand-held pliers. Intact creel-caught animals (controls) were not captured until a week after trawling but were nevertheless monitored over a three week period. *Liocarcinus depurator* were held within seawater tanks in individual floating plastic mesh containers (Figure 1) along with haphazardly collected trawled and creel-caught (controls) *P.*

bernhardus to prevent interactions. Since mortality of control *M. rugosa* in Experiment 2 had been high, these squat lobsters were held in larger plastic mesh compartments on this occasion (15 cm × 17 cm). The outdoor holding tanks (325 cm × 100 cm, water depth 30 cm) were supplied with running sea water at 7–8°C, similar to the *in situ* temperature in Fintray Bay. The survival of each group was recorded daily over a period of three weeks. As before, the median survival time in different treatments was analysed using a Kruskal–Wallis test and subsequent pairwise Mann–Whitney U tests dividing the significance level (α=0.05) by the number of comparisons.

Overall mortality

Total mortality of decapods was estimated as the sum of the mean percentage short-term and the percentage longer-term mortality recorded in Experiment 3, based on the observation that 57% and 47% of all trawled *M. rugosa* and *L. depurator*, respectively, sustain damage (Bergmann *et al*., 2001b). As it is difficult to distinguish on-deck loss of appendages due to autotomy from loss due to mechanical damage, estimates of overall mortality can only be given as a range. The upper mortality limit assumes that all individuals with missing limbs had undergone autotomy and the lower limit assumes that all individuals with missing limbs had suffered their forceful removal.

Results

Experiment 1: short-term mortality

The short-term mortality of decapods varied from 7–25% in *L. depurator*, 2–23% in *M. rugosa* and 6–13% in *P. bernhardus*. The mean mortality for both *L. depurator* and *M. rugosa* was 14% (Table 1). In total, 11% of *P. bernhardus* were found without a shell. Of these, 56% were dead whereas only 8% of the hermit crabs that remained in their shells died.

Experiment 2: longer-term survival of trawled and experimentally damaged decapods

The highest mortality in *M. rugosa* occurred during the first week (Table 2). The survival of damaged *M. rugosa* was significantly lower than in controls or undamaged trawled animals (Mann–Whitney U test, α<0.016). Intact control animals had a 15 % lower survival rate compared with intact trawled *M. rugosa*. Mortality of *L. depurator* was highest during the first week but continued throughout the monitoring period (Table 2). Damaged crabs had a significantly lower median survival than trawled or control crabs (Mann–Whitney U test, α<0.016). The mean size of creel-caught *M. rugosa*

Table 1. Short-term mortality of three decapod crustacean species caught by *Nephrops* otter-trawls. Each trip is shown separately as season, vessel, tow duration, average tow depth, on-deck exposure to air, temperature and the total catch varied. The proportion of dead individuals that sustained visible damage is also given (RB="FV Red Baron", Aa="RV Aora").

Species	Date	Vessel	Tow duration (min)	Depth (m)	Exposure time (min)	Air temperature (°C)	Total catch (baskets)	n	% dead animals damaged	Short-term mortality (%)
L. depurator	20/7/98	RB	97	62	16	14	14.5	107	n.a.	16
	29/9/98	Aa	90	76	60	15	8.3	100	100	13
	30/9/98	Aa	90	92	60	n.a.	10	95	57	7
	04/5/99	RB	154	46	70	12	8.5	100	80	25
	16/2/00	Aa	120	75	90	5	7	126	n.a.	10
M. rugosa	29/9/98	Aa	90	76	60	15	8.3	70	100	21
	30/9/98	Aa	90	92	60	n.a.	10	91	100	2
	04/5/99	RB	154	46	70	12	8.5	105	73	10
	16/2/00	Aa	120	75	90	5	7	61	n.a.	23
P. bernhardus	04/5/99	RB	154	46	70	12	8.5	23	n.a.	13
	16/2/00	Aa	120	75	90	5	7	85	n.a.	6
	06/6/00	Aa	120	74	90	15	n.a.	81	n.a.	4

Table 2. Longer-term survival of three decapod crustacean species. "Control" decapods were caught in creels; "trawled" decapods were intact trawl-caught animals that had been exposed to air for 90 min; "damaged" decapods were intact trawl-caught animals that had two appendages removed after exposure to air for 90 min.

Species	n	Date	Percentage survival				
			Day 2	Day 7	Day 9	Day 14	Day 21
L. depurator							
Control	54	Experiment 2	98	96	96	92	83
Trawled	50	15/09/99	96	96	94	88	86
Damaged	56		70	59	57	38	29
M. rugosa							
Control	54	Experiment 2	89	76	76	76	72
Trawled	53	15/09/99	89	89	89	89	87
Damaged	55		49	42	40	38	35
P. bernhardus							
Control	20	Experiment 3	100	95	95	95	95
Trawled	18	13/01/00	94	94	94	94	94

was significantly higher than that of trawled individuals (ANOVA, $p < 0.001$).

Experiment 3: longer-term survival after trawl damage and induced autotomy

The median survival time was lowest in damaged *L. depurator* (Mann–Whitney U test, $\alpha < 0.0083$). Survival of crabs that had autotomized appendages or were intact was lower than in controls although this was not statistically significant ($\alpha > 0.0083$). Again, mortality was highest in the first two weeks but continued throughout the experiment (Figure 2). Within six days of trawling, 50% of the *L. depurator* had died. This contrasts with the mortality in all other treatments and for the other species which never rose above 30%. The mortality of *M. rugosa* was highest during the first two weeks
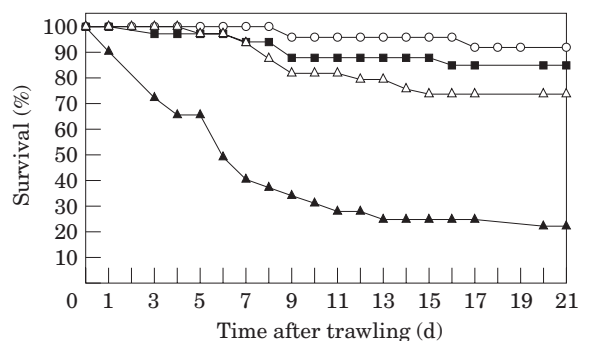

Figure 2. Post-capture survival in swimming crabs *Liocarcinus depurator* over three weeks ((○) control, n=24; (■) intact trawled, n=33; (△) two autotomized appendages, n=34; (▲) two removed appendages, n=32).
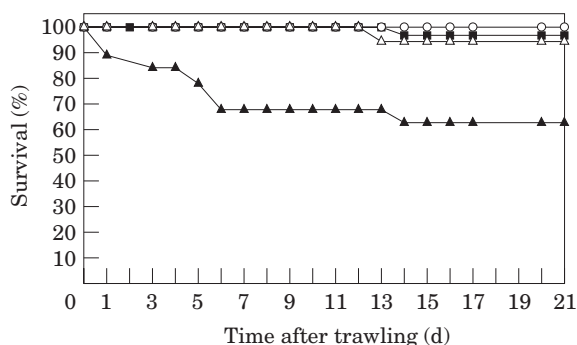
Figure 3. Post-capture survival in squat lobsters *Munida rugosa* over three weeks ((○) control, n=26; (■) intact trawled, n=34; (△) two autotomized appendages, n=19; (▲) two removed appendages; n=19).

([Figure 3]), and median survival time was significantly lower in damaged *M. rugosa* compared with all other treatments (Mann–Whitney U test, α<0.0083). The proportion of survivors in control and trawled *P.*

bernhardus was equivalent; only one hermit crab in each treatment died ([Table 2]).

Overall mortality

The overall mortality was then estimated, based on the observations that (1) on average, 14% of the catch died on deck ([Table 1]) and (2) 47% and 57% of all trawled *L. depurator* and *M. rugosa*, respectively, sustained damage ([Bergmann *et al*., 2001b]). Thus 86% of the animals brought on deck were still alive when discarded (for *M. rugosa*: 57% × 86%=49% damaged, and 43% × 86%=37% intact). The hypothetical ''best-case'' overall survival scenario for *M. rugosa*, assuming that 95% of the damaged animals survived (the survival rate of those with autotomized appendages; [Figure 3]) will therefore be 84% (49% damaged and alive × 0.95+37% intact alive *M. rugosa*). Similarly, the ''worst-case'' scenario, based on the survival of individuals with forcefully removed appendages (63%) can be estimated as 68%. Hence, the overall mortality of trawled *M. rugosa* will lie somewhere in the range of 16–32%
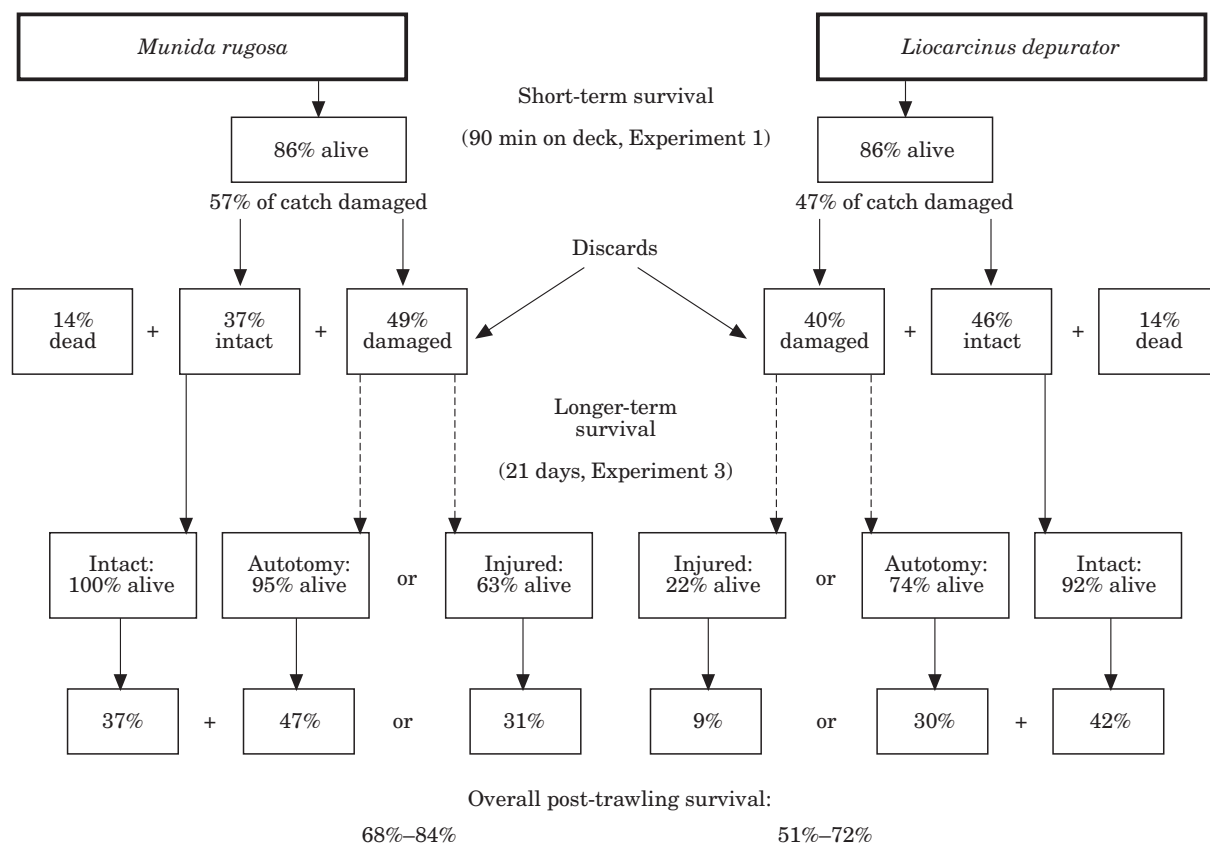

Figure 4. Diagram summarizing the overall post-trawling survival of *Liocarcinus depurator* and *Munida rugosa*.

(Figure 4). Following the same procedure for *L. depurator*, the overall mortality of trawled swimming crabs is estimated to be between 28–49% (Figure 4).

Discussion

There was considerable variation between trawl hauls with respect to season, tow duration, vessel, tow depth, air exposure, temperature, total catch volume (Table 1) and catch composition, all of which contribute to damage and mortality of captured organisms (Bergman *et al.*, 1998; Wileman *et al.*, 1999). This makes it difficult to identify any single factor as being responsible for damage and mortality. Seasonal factors also merit consideration since longer tows with larger catches in summer months will contribute to higher mortality as physical injury and physiological stresses on deck become more severe. Therefore, it is not surprising that short-term mortality varied considerably (2–25%). The highest *L. depurator* mortality coincided with the longest tow duration (Table 1), implying that long tows decrease the survival chance of swimming crabs.

Up to 100% of the individuals that died in the capture/sorting process suffered from severe damage such as torn abdomens and crushed carapaces. Such severe mechanical injuries are a major cause of death (Stevens, 1990). The mean short-term mortality in *L. depurator* (14%) reported here is in close agreement with a similar study in the Irish Sea (Kaiser and Spencer, 1995), although their tow durations were only 30 min and their crabs had not been exposed to air. However, immediate mortalities of swimming crabs found by Fonds (1994) and Bergman *et al.* (1998) in the North Sea were much higher (22–62%). This could be attributed to their use of heavier fishing gear (12-m beam trawl fitted with tickler chains) or different temperatures, which affect mortality rates considerably (Simonson and Hochberg, 1986). The short-term mortality of *P. bernhardus* (6–13%) was in the same range as that reported by Bergman *et al.* (1998), but higher than that stated by Kaiser and Spencer (1995), which again could be attributed to the shorter tow durations used by them. Fonds (1994) reported that 11% of trawled *P. bernhardus* abandoned their gastropod shell, and of those 56% were dead. Trawled hermit crabs without a shell will be prone to predation.

The survival rates obtained from *L. depurator* kept at sea (Experiment 2) and those held in laboratory tanks (Experiment 3) were comparable. Damaged *L. depurator* had the lowest longer-term survival (22% and 31%). They were the only ones to experience a 50% mortality in our trials, indicating that this species is quite vulnerable to trawling impact. Kennelly *et al.* (1990) found 100% mortality in spanner crabs (*Ranina ranina*) 8 d after the removal of two appendages, and survival after

removal of one dactylus continued to decrease for a period of 50 d. Reasons for mortality were thought to be general stress and excessive loss of haemolymph before clotting. Unlike *L. depurator* and *M. rugosa*, *R. ranina* cannot autotomize appendages, and this could have contributed to their higher mortality. Simonson and Hochberg (1986) found an increase in stone crab (*Menippe mercenaria*) mortality with severity of claw break and increasing aerial exposure. Depending on the fracture sustained, mortality after 13 d ranged from 16–88%. In our experiments, appendages were removed arbitrarily, which has probably introduced variability in the break surface and hence resultant mortality. *L. depurator* and *M. rugosa* with a break at the fracture plane are likely to survive better than those with breaks that extend into the body where the resulting wounds are wider (Davis *et al.*, 1980 cited by Simonson and Hochberg, 1986). The latter could lead to unrestricted bleeding, damage to the gills and an increased risk of predation as the odour plume from injured crustaceans provides a potent attractant for predators (Zimmer-Faust, 1993).

Survival rates for *M. rugosa* were much higher in Experiment 2 (controls=72% after 21 d, Table 2) than in Experiment 3 (controls=100% after 21 d, Figure 3). The 28% mortality of the larger control animals in Experiment 2, is suggestive of an experimental artifact. Although caught in the same area, the control *M. rugosa* were significantly larger than trawled individuals. Held in small plastic mesh containers these large-clawed animals had perforce to either fold their large chelipeds inwards or protrude them through the meshes of the container. This probably added to their stress and could have induced the appendage loss observed throughout the experimental period. The survival rate of both intact trawled *L. depurator* and *M. rugosa* was very close to the survival rate of controls suggesting that most animals soon recovered from stress due to trawling and hypoxia.

The survival of *L. depurator* with autotomized appendages was unexpectedly low compared with controls (although not statistically significantly different). Simonson and Hochberg (1986) showed an increase in break severity in stone crabs with increasing periods of aerial exposure, and Wood and Wood (1932) stated that a condition of exhaustion can attenuate the autotomy reflex. Likewise, some *L. depurator* may have exhibited sub-optimal autotomy as a result of trawling and air-exposure, giving rise to increased infection and mortality rates. In contrast, the survival of *M. rugosa* with autotomized appendages was very close to that of control and intact trawled conspecifics. Wood and Wood (1932) stated that galatheids autotomize appendages more readily than any other decapod, requiring little stimulus to induce evasive autotomy in order to escape from enemies. The higher survival rates of *M. rugosa* that underwent autotomy compared with *L. depurator* may

indicate that the autotomy reflex is more highly evolved in galatheids.

Unfortunately, it is difficult to determine in the field whether a decapod has lost appendages as a result of autotomy or of forceful removal during the trawling/handling process. We have shown that the survival rates of injured decapods differed from those that underwent autotomy. Hence it is also difficult to predict mortality based on damage assessments of trawled crustaceans. The most reasonable way to estimate overall mortality in this study is therefore to generate a range estimate rather than a single percentage (Figure 4). Superficially, the longer-term survival range of *L. depurator* (51–72%) appears similar to results from the North Sea (Craeymeersch, 1994; Fonds, 1994; Bergman *et al*., 1998) and the Irish Sea (Kaiser and Spencer, 1995). However, bearing in mind that the monitoring periods in those studies did not exceed 6 d and mortality in our experiment continued to increase by >25% from day 6–21, it can be concluded that the post-trawling mortality for *L. depurator* has been underestimated in the past. Evans *et al*. (1994) also lost ca. 15% of injured North Sea *Nephrops* during the second week after trawling. Other workers (Wassenberg and Hill, 1989, 1993; Craeymeersch, 1994; Evans *et al*., 1994; Fonds, 1994; Kaiser and Spencer, 1995; Bergman *et al*., 1998) did not include control treatments in their survival studies which could have biased their results. The levels of *M. rugosa* mortality recorded in our experiments are likely to be exceeded in commercial tows (which are up to 4–5 h duration, see Wileman *et al*., 1999) since longer tow durations increase the probability of damage to this species (Bergmann *et al*., 2001b).

Concurring with Fonds (1994); Kaiser and Spencer (1995) and Wileman *et al*. (1999), our results should be regarded as broad-brush estimates since survival in the field depends on so many factors. Live injured individuals returned to the sea may be prone to predation (Evans *et al*., 1994; Kaiser and Spencer, 1996) and are likely to be less competitive in resource acquisition. Potter *et al*. (1991) reported that the recapture rates of tagged injured or trawled sand crabs (*Portunus pelagicus*) were much lower than returns from creel-caught specimens, indicating a low survival *in situ*. Vermeer (1987) ascribed chronic behavioural changes such as reduced responsiveness to threatening stimuli and a diminished 'tail-flip' escape response in spiny lobsters due to neural damage caused by an increase in haemolymph lactate and ammonia following air exposure. Zainal *et al*. (1992) found that *M. rugosa* became torpid after periods of aerial exposure, which again can be expected to reduce survival after discarding owing to increased susceptibility to predation. Smith and Hines (1991) reported significantly lower foraging rates in blue crabs (*Callinectes sapidus*) after removal of two chelipeds. Berzins and Caldwell (1983) showed that

stomatopods missing two raptorial appendages had a reduced ability to conquer or defend home cavities. The seriousness of such handicap is increased, as is often the case, if by-catch crustaceans are discarded over unsuitable habitats (Evans *et al*., 1994; Wileman *et al*., 1999) or repeatedly caught by trawlers.

Our study has shown that the mortality of discarded decapod crustaceans has been underestimated in the past, probably as a result of brief monitoring periods. Based on our results we recommend a monitoring period of 10–14 d for more realistic survival estimates in prospective studies. Furthermore, future experiments need to be designed to address the fate of survivors returned to the seabed.

Acknowledgements

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