# Modified sorting technique to mitigate the collateral mortality of trawled school prawns (*Metapenaeus macleayi*)

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**Abstract**—The potential for changes to onboard handling practices in order to improve the fate of juvenile school prawns (*Metapenaeus macleayi*) discarded during trawling were investigated in two Australian rivers (Clarence and Hunter) by comparing a purpose-built, water-filled sorting tray against a conventional dry tray across various conditions, including the range of typical delays before the start of sorting the catch (2 min vs. 15 min). Juvenile school prawns ($n$=5760), caught during 32 and 16 deployments in each river, were caged and sacrificed at four times: immediately ($T_0$), and at 24 ($T_{24}$), 72 ($T_{72}$), and 120 ($T_{120}$) hours after having been discarded. In both rivers, most mortalities occurred between $T_0$ and $T_{24}$ and, after adjusting for control deaths (<12%), were greatest for the 15-min conventional treatment (up to 41% at $T_{120}$). Mixed-effects logistic models revealed that in addition to the sampling time, method of sorting, and delay in sorting, the weight of the catch, salinity, and percentage cloud cover were significant predictors of mortality. Although trawling caused some mortalities and comparable stress (measured as L-lactate) in all school prawns, use of the water tray lessened the negative impacts of some of the above factors across both the 2-min and 15-min delays in sorting so that the overall discard mortality was reduced by more than a third. When used in conjunction with selective trawls, widespread application of the water tray should help to improve the sustainability of trawling for school prawns.

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Mitigating the collateral mortality from trawl fisheries is a complex issue that requires multifaceted strategies (Davis, 2002; Broadhurst et al., 2006). One option is to spatially and temporally restrict fishing to avoid known large assemblages of nontarget organisms (termed "bycatch") (Andrew and Pepperell, 1992). A broader approach involves physical modifications to gears to improve their selection of species and size of species. Such modifications are assumed to indirectly reduce mortality on the premise that the survival of escapees during fishing is generally much greater than those of organisms brought to the surface and discarded (Broadhurst et al., 2006). However, few (if any) modifications to trawls are 100% effective and therefore, despite their use in many fisheries, there remains at least some unwanted bycatch (Andrew and Pepperell, 1992; Broadhurst, 2000). A remaining ancillary strategy that has been rarely applied, but which may help to address this problem, is to refine operational and postcapture handling techniques to improve the survival of discarded bycatch (e.g., Gamito and Cabral, 2003; Macbeth et al., 2006).

Similar to attempts in many of the world's penaeid fisheries, attempts at resolving collateral mortality in the New South Wales river prawn-trawl fishery have mostly focused on the first two strategies described above. From the early 1940s until 2003, this fishery comprised over 300 small (mostly <10-m) trawlers predominantly targeting either school (*Metapenaeus macleayi*) or eastern king (*Penaeus plebejus*) prawns in five rivers and estuaries. In addition to the targeted catches, these trawlers have traditionally caught, and then discarded, large quantities of bycatch (estimated at up to 177 t/yr in some rivers and estuaries; Liggins and Kennelly, 1996; Liggins et al., 1996), often comprising juveniles of economically important species, including penaeids too small for sale (<approximately 15–17 mm carapace length [CL]). During the last 20 years, concerns over the mortality of these organisms have culminated in complete closures to fishing at some locations, and the development of, and legislation for, modifications to trawls, including bycatch reduction devices (BRDs) and square-mesh codends, for use throughout the remaining fleet (Broadhurst and Kennelly, 1996; Macbeth et al., 2007).

Effort in this fishery has now been reduced to 204 vessels distributed among three rivers; the Clarence (114 vessels), Hawkesbury (61) and Hunter (29). Although the modified gears used by the operators of these vessels are more selective than historical configurations, even under optimal conditions the relative reductions of many bycatch individuals are only between approximately 50% and 70% and therefore, at times, large numbers are still caught and discarded (Broadhurst and Kennelly, 1996). Recent work with trawlers in the Clarence River indicates that simply deploying trawls for shorter durations (30 rather than 60 min) and sorting catches in water can minimize the negative impacts to some of these discards (Uhlmann and Broadhurst, 2007; Broadhurst et al., 2008).

In particular, Broadhurst et al. (2008) described a purpose-built, onboard water-sorting system (termed a "water tray") designed to facilitate the separation of prawns and fish, and then prawns into retained and discarded categories, while minimizing their exposure to air. This system was examined for its utility in reducing the mortality of fish after both immediate and delayed discarding from trawls deployed for the shortest commercially viable period (30 min). Although the mechanical interactions associated with trawling meant that the mortalities of many fish remained high, there were significant reductions in fatalities when the water tray was used during longer delays in starting sorting.

No work has been done to assess whether the water tray similarly reduces the mortality of discarded juvenile prawns, although two relevant pilot studies support the application of this modification (Macbeth et al., 2006; Broadhurst and Uhlmann, 2007). Specifically, during four deployments at one location in the Clarence River, Macbeth et al. (2006) observed that the short-term (three days) mortality of juvenile school prawns was reduced from approximately 35% during conventional sorting to about 16%, simply by holding them in water-filled containers. However, irrespective of their handling, all surviving school prawns showed similar elevated stress responses (measured as $_{\text{L}}$-lactate) over the monitoring period, which may have increased their susceptibility to other types of mortality (e.g., through infection or predation). By contrast, using comparable replication, Broadhurst and Uhlmann (2007) observed that regardless of their handling (including maximum and minimum gear deployments and subsequent air exposure), school prawns appeared resilient to both seine- and trawl-induced impacts, which manifested as total mortalities of <15%. The lack of impacts was further reflected by a return of elevated $_{\text{L}}$-lactate concentrations immediately to baseline levels within 24 hours after the prawns had been discarded.

At least some of the observed discrepancies between the two studies above probably reflect their limited replication in space (one location) and time (one day of fishing). Other studies have demonstrated that a range of technical (e.g., gear design, deployment duration, and speed), biological (e.g., species, physiology, size, and catch volume and composition) and environmental (e.g., temperature, hypoxia, sea state, and light) factors can have complex interacting effects on the fate of discards during trawling (Davis, 2002; Broadhurst et al., 2006). It seems appropriate, therefore, that during any study that seeks to assess the utility of modifications to reduce collateral mortality, adequate information is collected on these factors across a range of commercial conditions. We sought to use this approach to assess the water tray for reducing the mortality of discarded school prawns in the Clarence and Hunter rivers.

## Materials and methods

### Trawlers and the water tray

Separate experiments were undertaken in the Clarence River (29°27′S, 153°09′E) between March and April 2007 and in the Hunter River (32°53′S, 151°45′E) between February and April 2008. A commercial prawn trawler (<14 m in length) rigged with standard twin trawls was used in the Clarence River and a commercial prawn trawler (<14 m) rigged with a single trawl was used in the Hunter River. All trawls were attached to square-mesh codends (27-mm mesh). The Hunter River trawler was equipped with a large horizontal canvas awning that covered most of the back deck (and catch sorting area). The Clarence River trawler had a much smaller, obliquely orientated, and less effective cover made from loose-weave polyvinyl chloride (PVC).

Before starting the experiments, the conventional sorting trays were removed from both vessels and replaced with a modified design (comparable in price to conventional trays), termed the "water tray" which was scaled to fit, and measured 1800×1500×300 mm (Clarence River trawler) and 1200×1190×300 mm (Hunter River trawler) (Fig. 1 and Broadhurst et al., 2008). Irrespective of overall dimensions, the design of the water tray remained similar and included a V-shaped bottom, designed to concentrate the catch towards its center and below a vertically orientated, variable opening (Fig. 1). A pump provided flow-through water from the river at 30 L/min to the water tray through a 50-mm diameter inlet located in one side. For the Clarence River trawler, a metal screen (50-mm mesh size) was positioned horizontally above the bottom of the water tray to allow school prawns to filter through onto the V-shaped bottom, separating them from any larger fish (Fig. 1). This metal screen was removed from the water tray that was used on the Hunter River trawler. During the sorting process in each water tray, nonpenaeid bycatch was either removed by hand, or directed out of the variable opening along with water and collected in a 35-L container. Once the bycatch was removed, school prawns were washed out with the remaining water and passed over a riddler (made from hexagonal mesh; Fig. 1), which separated unwanted and retained individuals into two 35-L containers (see also Macbeth et al., 2006 for details).

### Monitoring sites

Two 3000-L polyethylene holding tanks were positioned at one location on the banks of each river. All tanks

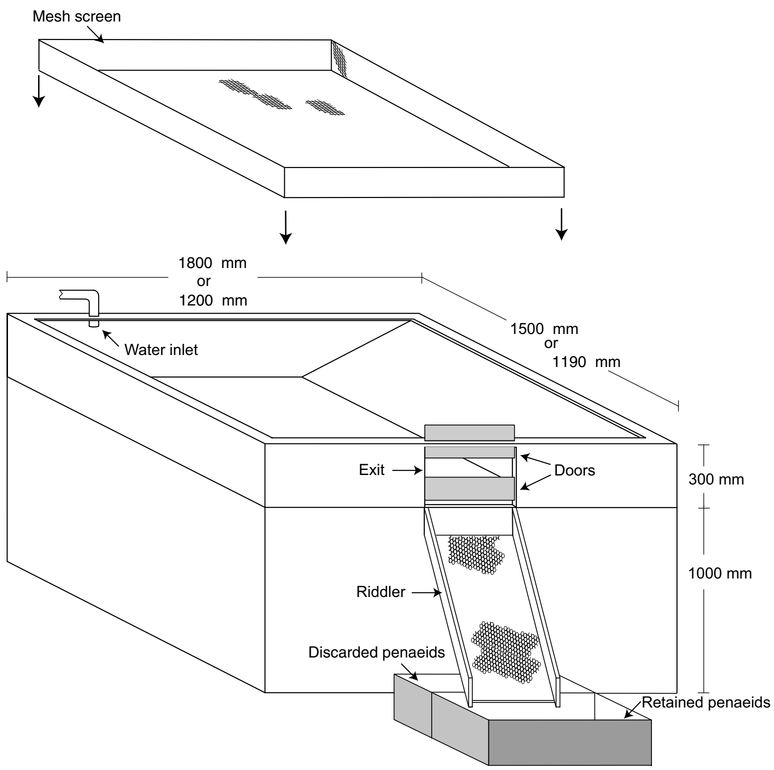


**Figure 1**

Schematic diagram of the water tray and mechanism by which school prawns (*Metapenaeus macleayi*) were riddled into discarded and retained categories in the Clarence and Hunter rivers during 2007 and 2008.

were supplied with local flow-through seawater (at a maximum rate of 63 L/min) and aerated by stone diffusers. At two sites (termed "monitoring sites") within the limits of trawling in each river, several 10-mm diameter ropes (50 m in length) were attached horizontally at a level corresponding with the average low tide to 2.5 m stanchions or existing pylons (fixed to the river bed). The rope configurations were designed to secure up to 90 portable cylindrical cages (0.3-m diameter × 0.4-m depth), each made from a modified 35-L bucket and comprising one top and three lateral openings that were covered by 6-mm PVC mesh (each <230 $cm^2$) and a solid base filled with locally collected sediment to a depth of about 6 cm (see also Broadhurst and Uhlmann, 2007 for details). Clips were attached to the tops of each cage so that they could be suspended along the 10-mm diameter rope. The cages were designed so that two could fit into in 75-L aerated water-filled PVC containers located on a dory, enabling them to be transported between the fishing and monitoring sites.

### Experimental design

In both rivers, between seven and five days before starting each experiment, approximately 1000 school prawns were collected in <5-min trawls rigged with a fine-meshed knotless polyamide, 10-mm mesh codend towed slowly in shallow water. At the end of each deployment, the codend was emptied into a water-filled container. Live and active juvenile school prawns were quickly removed, placed in tanks supplied with oxygen and transported to the two holding tanks on the river bank. The captive school prawns were fed chopped pilchard (*Sardinops neopilchardus*) at a rate of 5% biomass/24 hr and left to recover for at least five days, after which surviving, intact individuals were used as controls in the experiments described below.

Four treatment groups associated with trawling and discarding and one control group were examined in each river. The four treatments were chosen to represent the temporal limits of the conventional (i.e., dry tray) and modified (i.e., water tray) onboard handling of catches. All treatments comprised a 30-min deployment of the trawl, followed by the sorting of unwanted school prawns that was started after one of the following treatments: 1) a 2-min delay in a dry tray (termed the "2-min conventional-tray" treatment); 2) a 2-min delay in the water tray ("2-min water-tray" treatment); 3) a 15-min delay in the dry tray ("15-min conventional-tray" treatment); or 4) a 15-min delay in the water tray

("15-min water-tray" treatment). The conventional-tray treatments involved leaving the water tray empty of water and removing the mesh-separating screen. The 35-L container for the riddled, unwanted school prawns was filled with water during the water-tray treatments but was left dry for the conventional-tray treatments. Two replicates of each treatment were completed on each of four days of fishing in the Clarence River and two days of fishing in the Hunter River.

For each treatment, immediately after the unwanted school prawns were separated by the riddler into either a dry (conventional-tray treatments) or water-filled (water-tray treatments) 35-L container (Fig. 1), the transport dory was positioned alongside the trawler and 120 individuals were randomly selected and "discarded" into groups of 10 into 12 cages submerged in the water-filled 75-L PVC containers. Three of these cages were sampled immediately (termed $T_0$—see below), before the remaining nine were transported to the closest monitoring site and attached to the 10-mm rope within 20 min, and without exposing any of the school prawns to air. During transfer, all caged school prawns were held in aerated water and the water quality was checked with an Horiba U10 meter (Horiba, Irvine, CA) and maintained (via exchange) at the same levels as that recorded at the surface of the deployment site.

Within six hours of the first treatment deployment, 240 school prawns were removed from the holding tanks by scoop nets and placed in groups of 10 into 24 cages submerged in the water-filled 75-L PVC containers onboard the dory (i.e., the same number of prawns as that for the two replicate deployments of each treatment). Six cages were sampled immediately ($T_0$—see below), while the remaining 18 cages were transferred to the same monitoring sites as those housing the treatment school prawns and used as balanced controls in each experiment. For each replicate of the control and treatment groups on each day of fishing, school prawns in three of the cages were sacrificed and sampled at three times: 24 ($T_{24}$), 72 ($T_{72}$), and 120 ($T_{120}$) hours after $T_0$.

### Data collected

The following data were collected during each deployment in both experiments: towing speed (m/s); fishing depth (m); duration of air exposure of the catch (min); air temperature (°C); percent cloud cover; and the numbers and weights (kg) of retained and discarded catches. The Horiba U10 was used to record replicate measures of water temperature (°C), dissolved oxygen (mg/L), and salinity (psu) in the water tray. An EC 350 Greenspan Smart Sensor (Tyco Environmental Systems, Lakewood, NJ) was attached to the trawl to provide replicate measures of the conductivity ($\mu$S/cm) and the temperature of the river once each minute during each deployment (except on the first day of fishing in the Clarence River). An algorithm was used to convert the normalized conductivity readings to salinities. Means of these readings were used to provide a datum for the salinity and for the temperature at the surface and bottom for each deployment.

At each sampling time, the three cages from the two replicates of the control and each of the four treatment groups from each day of fishing were removed from the monitoring site. The sediments from the cages were emptied onto a tray. The numbers of alive and dead school prawns were recorded, and, if possible, they were measured to the nearest 1-mm CL. During the Hunter River experiment, the binary molt status (hard or soft) of school prawns was also noted by the rigidity of their carapace. This was not done during the Clarence River experiment because all school prawns were clearly intermolts (i.e., hard). For one randomly selected fishing day during the Clarence River experiment, two live school prawns were immediately selected from two of the cages for each replicate of the treatment and control groups at the $T_0$, $T_{72}$, and $T_{120}$ sampling times and secured in aluminum satchels before being placed in liquid nitrogen. These frozen samples were later analyzed for $_L$-lactate ($\mu$mol/g) to provide an indication of the severity of anaerobic stress and subsequent recovery, by following the methods described by Broadhurst et al. (2002).

### Statistical analyses

The data collected from each experiment were analyzed separately. Appropriate environmental, technical, and biological data collected from the gear deployments were treated as either fixed, categorical, or continuous variables. Where there was sufficient replication, these variables were considered with the fixed factors of primary interest: "method of sorting" (conventional vs. water tray); delay in sorting" (2 min vs. 15 min); and sampling time ($T_0$, $T_{24}$, $T_{72}$ or $T_{120}$); and the random factors of fishing days, deployments, and cages in mixed-effects logistic models were fitted to the dichotomous status (dead vs. alive) of the trawled-and-discarded caged school prawns.

For each experiment, three separate models were used for trawled-and-discarded school prawns and comprised data from 1) all deployments, 2) the water-tray deployments, and 3) the conventional-tray deployments only. A fourth model was fitted to control, caged school prawns, and was restricted to the above random factors and the fixed effect of sampling time. All models were fitted by using the lmer function in the R statistical software (The R Foundation for Statistical Computing, Vienna, Austria). A stepwise variable search algorithm was employed with the most parsimonious fit based on the lowest Akaike's information criterion. The total mortalities of school prawns subjected to the four handling treatments of interest were eventually adjusted for deaths to the controls.

A balanced four-factor analysis of variance (ANOVA) was used to examine differences among treatment and control groups for the levels of $_L$-lactate ($\mu$mol/g) in school prawns from one fishing day in the Clarence River experiment. The model used the following fac-

**Table 1**

Summary of mean (±standard deviation) key technical, environmental, and biological variables collected during the deployments of trawls to assess the discard mortality of school prawns (*Metapenaeus macleayi*) in the Clarence and Hunter rivers during 2007 and 2008. The number of replicate deployments is in parenthesis.

| Variable | Clarence River | Hunter River |
|---|---|---|
| Technical | | |
| Deployment | | |
| Speed (m/s) | 1.4 ±0.2 (32) | 1.3 ±0.1 (16) |
| Depth (m) | 7.3 ±1.8 (32) | 6.3 ±1.7 (16) |
| Environmental | | |
| River temperature (°C) | | |
| Surface | 23.9 ±1.1 (32) | 22.5 ±0.8 (16) |
| Bottom | 23.8 ±1.1 (24) | 22.8 ±0.3 (16) |
| River salinity (psu) | | |
| Surface | 3.7 ±2.3 (32) | 4.3 ±1.8 (16) |
| Bottom | 5.4 ±1.9 (24) | 10.2 ±5.8 (16) |
| Cloud cover (%) | 42.9 ±38.8 (32) | 3.8 ±6.2 (16) |
| Air temperature (°C) | 22.7 ±3.3 (32) | 22.6 ±4.5 (16) |
| Water tray | | |
| Dissolved oxygen (mg/L) | 5.8 ±1.0 (16) | 3.8 ±0.8 (8) |
| Temperature (°C) | 24.4 ±1.6 (16) | 22.0 ±1.6 (8) |
| Salinity (psu) | 2.5 ±1.5 (16) | 4.6 ±2.3 (8) |
| Catch air exposure (min) | | |
| 2-min conventional tray | 13.8 ±5.1 (8) | 6.3 ±1.9 (4) |
| 15-min conventional tray | 23.5 ±6.0 (8) | 20.0 ±2.7 (4) |
| 2-min water tray | 2.0 ±1.0 (8) | 1.0 ±0.0 (4) |
| 15-min water tray | 1.6 ±0.7 (8) | 1.3 ±0.5 (4) |
| Biological | | |
| Weight of catch (kg) | | |
| Total | 11.8 ±7.4 (32) | 19.4 ±16.1 (16) |
| School prawns | 9.7 ±6.6 (32) | 18.0 ±15.7 (16) |
| Carapace length (mm) of trawled-and-monitored school prawns: | 15.3 ±2.6 (32) | 15.1 ±3.8 (16) |

tors: treatment of prawns (four trawling and one control group); sample times ($T_0$, $T_{24}$, $T_{120}$ and $T_{120}$); deployments ($n$=2); and cages ($n$=3). The factors "sampling time" and "treatment of prawns" were considered orthogonal to each other and fixed. Deployments were random and nested in the treatment of prawns, whereas cages were nested in all factors. Data were transformed as required and tested for homogeneity of variances by using Cochran's test. Any missing replicates were replaced with the cell mean and the residual degrees of freedom were adjusted accordingly. Significant $F$-ratios of interest were examined with Student-Newman-Keuls multiple comparisons of means tests.

## Results

School prawns represented more than 82% of the total catch from the Clarence River and 93% of the total catch from the Hunter River, and although their mean catches per 30-min deployment were quite variable, were still within the ranges typically experienced in the fishery (Table 1). Bycatches were comparatively low in both experiments and, in addition to juvenile school prawns (approximately 9% of the total school prawn catch in each river), mostly comprised fish <200 mm total length, such as yellowfin bream (*Acanthopagrus australis*), southern herring (*Herklotsichthys castelnaui*), silver biddy (*Gerres subfasciatus*), and narrow-banded sole (*Aseraggodes macleayanus*).

Many of the technical and environmental variables were comparable between experiments and except for salinity and cloud cover, remained fairly consistent among replicate deployments (Table 1). In both rivers, there was evidence of a salinity gradient between the surface and bottom (Table 1). Catches were subjected to similar mean durations of air exposure during the 15-min conventional-tray (>20 min) and all water-tray (<2 min) treatments during both experiments. By contrast, and although highly variable, the mean duration of air exposure for catches handled during the 2-min conventional-tray treatment in the Clarence

River (approximately 14 minutes) was greater than that in the Hunter River (approximately 6 minutes; Table 1).

The first mixed-effects model that was applied to all of the data for the trawled-and-discarded school prawns in both experiments included the fixed factors of sorting method (conventional vs. water tray), delay in sorting (2 minutes vs. 15 minutes), and their interaction, sample time, and the weight of total catch, and salinity at the bottom of the river during fishing. The second and third models were applied to the water-tray and conventional-tray deployments. Both models included sorting method (conventional vs. water tray), delay in sorting (2 minutes vs. 15 minutes), and their interaction, sampling time, and the weight of total catch. Water tray salinity and dissolved oxygen were also included in the second model, and air temperature and cloud cover were used in the third model. The fourth model was applied to the control data with sampling time as the only the fixed effect. The stage of molt was not included in any of the models for the Hunter River data because it was not possible to quantify the condition of all deceased individuals. In any case, only 13.0% of all school prawns sampled at $T_0$ had soft exoskeletons. Similarly, it was not possible to measure the CL of all dead school prawns at $T_{24}$, $T_{72}$, and $T_{120}$, and therefore size could not be considered in the analyses.

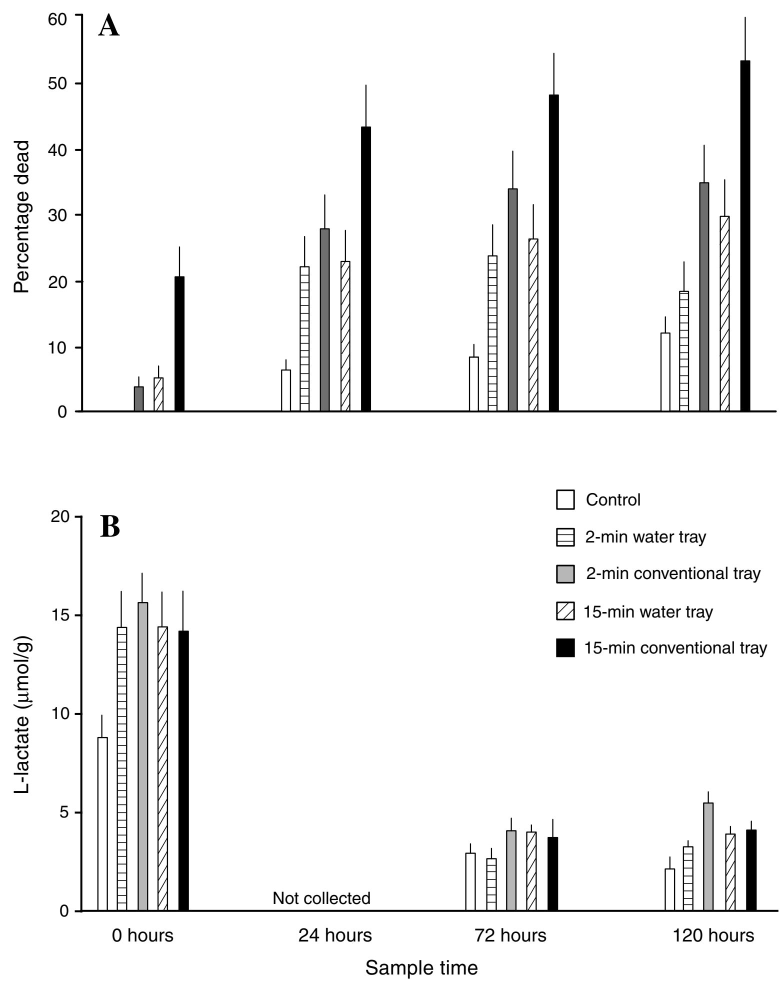


**Figure 2**

Differences in mean (± standard error) for (**A**) predicted percent mortality and for (**B**) concentrations of $_{\text{L}}$-lactate for school prawns (*Metapenaeus macleayi*) between the onboard sorting treatments and control for each of the relevant sample times in the Clarence River during 2007. No data were collected for $_{\text{L}}$-lactate at $T_{24}$.

### Clarence River experiment

A total of 4800 school prawns were caged during the experiment, of which 240 individuals were in each of the control and four treatment groups at each of the four sampling times. Seventy school prawns escaped (as a result of faulty lids on their cages) before being sampled; they escaped from one cage for the 15-min conventional-tray treatment at each of $T_{24}$ and $T_{72}$, two cages for the 15-min conventional-tray treatment at $T_{120}$, one cage for the 2-min water-tray treatment at $T_{24}$, and two cages of controls at $T_{72}$. Up to 12.0% of the control school prawns were dead at each sampling time (attributed to handling during transfer, being caged, or natural causes, Fig. 2A), providing adjusted temporal mortalities of up to 41.4% and 18.2% for the 15-min conventional and water-tray treatments, respectively (Table 2).

Irrespective of the four mixed-effects models fitted to the various data sets, or the treatment of school prawns, there was a strong significant impact of sampling time on mortality that was largely attributable to the death of most individuals during their first 24 hours of caging, after which the rate of attrition stabilized (Tables 2 and 3 , Fig. 2A , $P<0.01$). All three analyses of the trawled-and-discarded school prawns also showed a significant impact of the delay in the start of sorting, with an overall predicted (and unadjusted) mean ±standard error (SE) of 31.6 ±2.4% after 15 min, compared to only 21.2 ±1.9% after 2 min (Table 2, $P<0.05$).

In addition to the main effects of delay in sorting and sampling time, sorting method had a significant impact across all deployments, and there were consistently greater mortalities to those individuals discarded after sorting in the conventional tray (predicted unadjusted mean of 33.5 ±2.4%) than in the water tray (19.3 ±1.8%), and especially after a 15-min delay (predicted unadjusted mean ±SE of up to 53.4 ±6.5%; Tables 2 and 3, Fig. 2A, $P<0.05$). This clear trend in deaths precluded any interaction between sorting method and delay, although these means are presented in Fig. 2A for ease of interpretation (Table 3, $P>0.1$). The first model also detected a significant negative relationship between mortality and salinity at the bottom of the river (Table 3, $P<0.01$). The same significant negative relationship with mortality was observed for salinity in the water tray in the second model (Table 3, $P<0.01$). The third model identified total catch weight as having a significant positive relationship with the mortality of conventionally handled school prawns, whereas cloud cover had a negative relationship (Table 3, $P<0.05$).

ANOVA returned significant $F$-ratios for the treatment of prawns and sampling times for the levels of L-lactate in surviving school prawns from one randomly selected fishing day (Table 4 , $P<0.01$). There was no interaction between these factors ($P>0.05$), but the corresponding means are presented for clarity (Table 4, Fig. 2B). Student-Newman-Keuls tests revealed that the overall mean ±SE concentration of L-lactate in control school prawns (4.63 ±0.76 µmol/g) was significantly lower than all other treatments; which remained similar at between 6.77 ±1.28 and 8.40 ±1.21 µmol/g ($P<0.05$). Irrespective of the treatment of school prawns, all prawns had significantly greater concentrations of L-lactate at $T_0$ (13.49 ±0.81 µmol/g) than at $T_{72}$ (3.48 ±0.28 µmol/g) and $T_{120}$ (3.78 ±0.27 µmol/g) (Fig. 2B, $P<0.05$).

**Table 2**

Percentage of total mortalities of trawled-and-discarded school prawns (*Metapenaeus macleayi*) adjusted for deaths to the controls for the sorting treatments of interest (2-min and 15-min delays in the conventional and water trays) at the four sampling times (immediately [$T_0$], and after 24 hr [$T_{24}$], 72 hr [$T_{72}$], and 120 hr [$T_{120}$]) in the Clarence and Hunter rivers during 2007 and 2008.

| | Conventional tray | | Water tray | |
|---|---|---|---|---|
| | 2-min delay | 15-min delay | 2-min delay | 15-min delay |
| Clarence River | | | | |
| $T_0$ | 3.8 | 20.7 | 0.0 | 5.2 |
| $T_{24}$ | 21.4 | 37.0 | 15.7 | 16.6 |
| $T_{72}$ | 25.8 | 40.0 | 15.5 | 18.2 |
| $T_{120}$ | 22.8 | 41.4 | 6.3 | 17.8 |
| Hunter River | | | | |
| $T_0$ | 5.7 | 15.7 | 0.0 | 3.0 |
| $T_{24}$ | 29.8 | 29.0 | 13.6 | 18.1 |
| $T_{72}$ | 26.4 | 35.7 | 20.2 | 21.5 |
| $T_{120}$ | 20.6 | 34.8 | 18.6 | 8.9 |

### Hunter River experiment

A total of 2400 school prawns were caged across the control and four treatment groups; of which 10 (in one cage from the 15-min conventional-tray treatment) escaped prior to their designated sampling time ($T_{120}$). Similar to the Clarence River experiment, control deaths ranged between predicted means of 0.0% and 11.7%, providing adjusted total mortalities of up to 35.7% and 21.5% for the 15-min conventional- and water-tray treatments, respectively (Table 2, Fig. 3).

**Table 3**

Summary of variables tested in mixed-effects logistic models for their independence of the mortality of trawled-and-discarded school prawns (*Metapenaeus macleayi*) in the Clarence and Hunter rivers during 2007 and 2008. Four separate models were applied: the first to all of the available data for trawled-and-discarded individuals (All); the second and third to only those discarded from the water tray (WT) and conventional tray (CT) treatments, respectively; and the fourth to the data for the controls (C). ○ $P>0.1$; ● $P<0.1$; *$P<0.05$; **$P<0.01$; --, term not considered in the model.

| | Clarence River | | | | Hunter River | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | All | WT | CT | C | All | WT | CT | C |
| Sampling time | ** | ** | ** | ** | ** | ** | ** | ** |
| Sorting method (M) | ** | -- | -- | -- | ** | -- | -- | -- |
| Sorting delay (S) | ** | * | ** | -- | ○ | ○ | ** | -- |
| $M \times S$ | ○ | -- | -- | -- | ○ | -- | -- | -- |
| Total weight of catch | ● | ○ | ** | -- | ** | ** | ○ | -- |
| Salinity | | | | | | | | |
| bottom | ** | -- | ○ | -- | ○ | ○ | ○ | -- |
| surface (water tray) | -- | ** | -- | -- | -- | ○ | -- | -- |
| Dissolved oxygen (water tray) | -- | ○ | -- | -- | -- | ○ | -- | -- |
| Air temperature | -- | -- | ○ | -- | -- | -- | ○ | -- |
| Cloud cover | -- | -- | * | -- | -- | -- | ○ | -- |

As with the Clarence River analyses, there was a significant effect of sampling time detected in all four mixed-effects models that was largely due to proportionally more deaths to school prawns during the first 24 hours, irrespective of their treatment (Table 3, Fig. 3, $P<0.01$). The method of sorting was also significant in the first model applied across all treatment deployments, with relatively greater deaths after discarding from the conventional tray (overall unadjusted predicted mean ±SE of 29.3 ±2.0%), than from the water tray (17.6 ±1.6%) (Table 3, Fig. 3, $P<0.01$). Sorting delay had no impact on the mortality of school prawns discarded across all deployments, or from the water tray, but was significant for those that were conventionally sorted (mortalities of 25.8 ±2.5% for the 2-min delay, and 32.9 ±2.8% for the 15-min delay; Table 3, $P<0.01$).

The only remaining significant main effect in any of the models was the total weight of catch, identified as having a positive relationship with mortality across all deployments, and those restricted to sorting in the water tray (Table 3, $P<0.01$). For the water-tray deployments, individuals caught during the largest catch weights (47 kg) were more than 2.5 times as likely to be dead at each sampling time than those from the smallest catches (4 kg, Fig. 4). For both the $T_{72}$ and $T_{120}$ sampling times, the absolute probabilities of mortality during the largest and smallest catch weights were approximately 43% vs. 16% (Fig. 4).

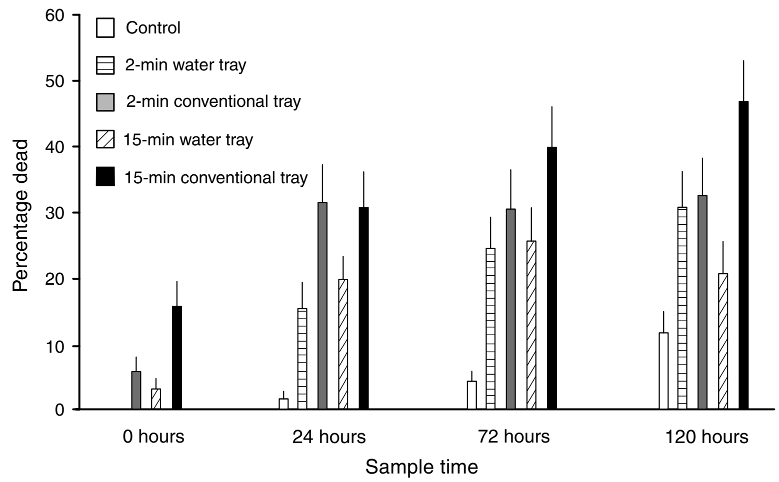


**Figure 3**

Differences in mean (± standard error) predicted percent mortality of school prawns (*Metapenaeus macleayi*) between the onboard sorting treatments and the controls for each of the sampling times in the Hunter River during 2008.

**Table 4**

Summary of model terms, *F*-ratios, and degrees of freedom (df) for ANOVA used to investigate L-lactate among trawled-and-discarded (2- and 15-min conventional- and water-tray treatments) and control school prawns (*Metapenaeus macleayi*) in the Clarence River during one day of fishing in 2007. Data were $\ln(x+1)$ transformed. Three replicates were missing, and therefore the cell means were used and the df was adjusted accordingly. $^{**}P<0.01$.

| Variable | *F*-ratio | df |
|---|---|---|
| Treatment of prawns | 14.09** | 4, 5 |
| Deployments (treatment of prawns) | 0.58 | 5, 30 |
| Sampling times | 93.41** | 2, 10 |
| Treatment of prawns × sampling times | 0.73 | 8, 10 |
| Sampling times × deployment (treatment of prawns) | 1.55 | 10, 30 |
| Cages (treatment of prawns × sampling times × deployments) | 0.95 | 30, 57 |

## Discussion

The mortalities of school prawns after being trawled, conventionally discarded, and adjusted for control fatalities were consistent between experiments and encompassed the range of earlier estimates by Macbeth et al. (2006). Further, the unadjusted mortalities were comparable to those recorded for several other similarly treated decapods monitored without controls, including caridians (1–30%, Wassenberg and Hill, 1989; Cabral et al., 2002), brachyurans (0–50%, Hill and Wassenberg, 1990; Wassenberg and Hill, 1993; Kaiser and Spencer, 1995) and anomurans (0–19%, Kaiser and Spencer, 1995). These rates of death are considerably lower than those typically observed for many trawled-and-discarded fish and mollusks and further support the resilience of school prawns, and crustaceans in general, for withstanding a range of trawl-induced impacts (Broadhurst et al., 2006).

Irrespective of apparent broad phyla-specific differences among collateral trawl mortalities, as is the case for several locally caught fish (Broadhurst et al., 2008), use of the water tray significantly reduced the short-term mortality of school prawns in both experiments. The extent of these reductions can be explained by attempting to partition mortality, along with the various significant predictors, into those fatalities caused 1) by the trawling process, and 2) after onboard handling.

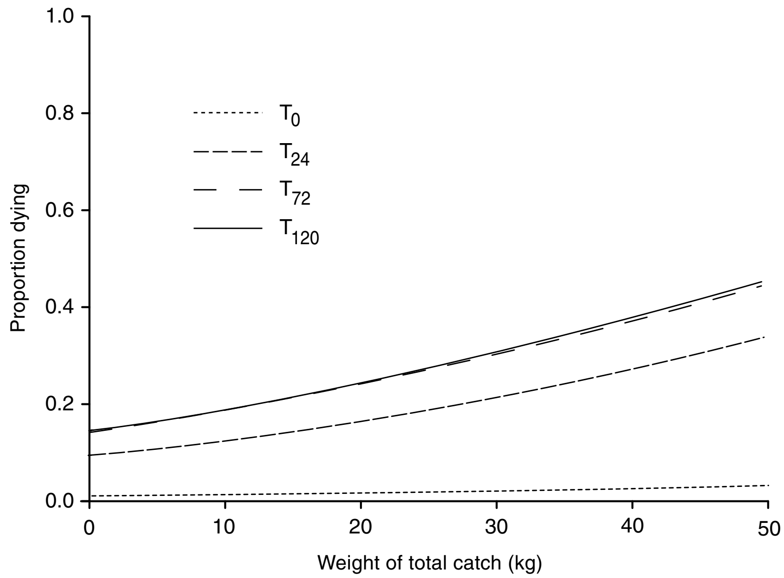


**Figure 4**

Logistic regression between catch weight and the expected proportion of school prawns (*Metapenaeus macleayi*) dying after being trawled in the Hunter River, sorted in the water tray, discarded into cages and sampled at four different times (immediately [$T_0$], and after 24 hours [$T_{24}$], 72 hours [$T_{72}$], and 120 hours [$T_{120}$]) in 2008.

When they initially contact the anterior sections of a trawl, prawns and other crustaceans with extended abdomens (e.g., Norway lobster *Nephrops norvegicus*) typically respond by contracting their tail muscle ventrally, effectively propelling themselves backwards into the top netting panels (Watson, 1976; Newland and Chapman, 1989). This behavior may be repeated several times, until an individual becomes fatigued, after which they often attempt to orientate towards the seabed using their swimmerets (Watson, 1989). Such activity is ineffective against the speed of the trawl, and therefore prawns are quickly forced against the meshes into the posterior trawl body and directed into the codend where they accumulate along with the rest of the catch.

The physiological responses supporting the above activity include anaerobic respiration and the rapid depletion of arginine phosphate in the tail muscle (Onnen and Zebe, 1983; Paterson et al., 1995). An end product of this exertion is lactic acid, which is removed during aerobic metabolism (Head and Balwin, 1986). In the present study, the concentrations of $_L$-lactate in live school prawns immediately sampled (i.e., at $T_0$) after being discarded from the various treatments in the Clarence River were elevated to mean levels between 14.2 ±2.0 and 15.6 ±1.5 μmol/g, that were greater than those previously observed for this species after exercise (typically <12 μmol/g), indicating that these individuals had been heavily exercising. Although some of the observed lactate accumulation could be attributed to onboard handling and associated anoxia (Hill et al., 1991), especially during the conventional procedures, the similar rate of accumulation across all treatments supports a strong, uniform, negative impact of the trawling process.

For some individuals, the physiological damage described above may have been sufficient to result in their immediate death, while for others the cumulative impacts of significant covariates, such as the weight of catch and salinity, would have contributed toward their more protracted (over 24 hours) trawl-related mortalities. In particular, as the catch accumulated, at least some school prawns probably sustained fatal injuries, including wounding and blood loss, due to pressure and abrasion. Also, the ongoing stimuli associated with repetitive contact among conspecifics and other organisms may have triggered additional bursts of anaerobic exercise, and further compromised their physiological condition. These density-dependant effects were more obvious in the Hunter than in the Clarence River, probably reflecting the considerably greater mean size of catch (19.4 kg [Hunter River]; 11.8 kg [Clarence River]), but also perhaps the slightly smaller mean size of school prawns (Table 1) and the presence of some soft individuals (i.e., 13% at $T_0$). Both of these latter factors have previously been demonstrated to increase the vulnerability of organisms to the impacts associated with discarding (Broadhurst et al., 2006).

Salinity also appeared to contribute towards mortality during trawling in the Clarence River. As with other penaeids (e.g., western king prawns [*Penaeus latisulcatus*] [Sang and Fotedar, 2004] and fleshy prawns [*P. chinensis*] [Chen et al., 1995]), Maguire and Allan (1985) observed that although juvenile school prawns tolerate a range of salinities (from 1 to 30 psu), the mortality of captive individuals (in grow-out ponds) was negatively associated with salinities between 10 and 30 psu. On average, the salinities observed in the Clarence River were much lower than those of the Hunter River (5.4 vs. 10.2 psu) and possibly below the optimal range for osmoregulation. Although not necessarily fatal in the absence of other stressors, low salinities would require school prawns to maintain a comparatively greater metabolic rate to achieve osmotic balance, thereby increasing their susceptibility to other trawl-related impacts. Further, an abrupt reduction to even lower salinities during the retrieval of the trawl to the surface (as a consequence of the observed halocline) would require some readjustment of osmotic concentration to regulate tissue water. A similar transition through haloclines has been identified as a factor contributing towards mortality in other species, including Norway lobster (Harris and Ulmestrand, 2004), and probably had a cumulative impact on the stress, and ultimately mortality, of some school prawns.

It is difficult to accurately quantify the cumulative impact of all trawl-related stressors on total mortality, especially since the death of some control school prawns indicates the potential for natural mortality (which was assumed to be constant across all treatments). However, after monitoring the fate of individuals collected immediately after the codend was emptied (individuals that had minimal air exposure before being sorted), Macbeth et al. (2006) estimated a short-term (over three days) mortality of 16% directly attributable to 60-min trawls, which was only slightly greater than that determined for individuals escaping through codend meshes during trawling (11%, Broadhurst et al., 2002). The results from the present study support these estimates, with an adjusted, protracted mortality in the 2-min water tray (arguably the mildest treatment) of less than 21% for both rivers.

Assuming comparable trawl-induced mortalities across treatments, the remaining differences in fatalities can be attributed to the use of the water tray for minimizing some of the negative impacts associated with onboard handling, and especially with air exposure. Most likely, by facilitating aerobic respiration, the water tray would have allowed some school prawns to recover and restore argine phosphate levels and acid-base regulation (Taylor and Spicer, 1988), which probably helped to limit further physiological damage and mortality.

In addition to limiting air exposure, the water tray maintained temperature homeostasis. Although there was no significant effect of air temperature in the models applied to the conventional-tray treatments in either experiment, there was a significant negative relationship between cloud cover and mortality in the Clarence River ($P<0.05$). This association probably reflects the greater convection, heating, and subsequent desiccation of school prawns in direct sunlight on the dry tray. Gamito and Cabral (2003) observed similar effects of heating on the mortality of brown shrimp (*Crangon crangon*) and suggested that this could be reduced by using light-colored sorting containers and avoiding trawling during the hottest time of the day. Sorting in the water tray is probably a more effective alternative in New South Wales, although the lack of any impacts of cloud cover in the Hunter River, combined with the similar range of temperatures between the two rivers also illustrates the utility of shading the conventional sorting tray with an appropriate cover.

The only obvious limiting factor of the water tray was its size for the trawler working in the Hunter River. Vessels in the Hunter River typically catch fewer school prawns than those in the Clarence River, and therefore a smaller water tray was used in the Hunter River . It is possible that, in addition to the trawling-related impacts discussed above, large catches in the sorting tray on the Hunter River trawler contributed towards mortality as a consequence of their greater biological load. Although there was no significant impact of dissolved oxygen on mortality in the water tray, the mean dissolved oxygen recorded during the Clarence River deployments was higher than that in the Hunter (5.8 mg/L vs. 3.8 mg/L). Further, during one catch of 47 kg in the Hunter River, the dissolved oxygen in the water tray after 15 minutes of sorting was 2.4 mg/L. The potential for any negative effects associated with low dissolved oxygen could be simply reduced by increasing the water exchange or volume of the water tray, or both.

Although the results from this study indicate a significant reduction in discard mortality associated with using the water tray, it is important to remember that the discarded school prawns were protected in cages and therefore other collateral mortalities were not quantified. The levels of $_{L}$-lactate at $T_0$ indicated that alive, discarded school prawns were fatigued and, during conventional fishing, these individuals could be more susceptible to predation during their descent to the bottom (Lancaster and Frid, 2002). Further, because of the temporal increase in mortality, some school prawns may have maintained their vulnerability, particularly during the first 24 hours after having been discarded. The potential for these effects could be mitigated by subtle modifications to the water tray. In particular, because low (e.g., <15°C) water temperatures have been demonstrated to reduce metabolic activity in penaeids (Paterson, 1993), cooling the water tray may reduce some of the ancillary stressors identified above and help school prawns to recover more quickly. The concomitant use of a covered guiding panel that directs the discarded school prawns into the water behind the trawler could reduce predation.

Notwithstanding the need for some refinements, it is clear that using the water tray would eliminate most of the short-term mortalities associated with onboard handling, which would translate to a total reduction in discard mortality of school prawns of more than a third. When combined with other selective mechanisms, such as square-mesh codends that reduce the catches of school prawns of nontarget sizes, the water tray should contribute towards the sustainability of trawling in New South Wales rivers.

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## Literature cited

Andrew, N. L., and J. G. Pepperell.
1992. The by-catch of shrimp trawl fisheries. Oceanogr. Mar. Biol. Annu. Rev. 30:527–565.

Broadhurst, M. K.
2000. Modifications to reduce bycatch in prawn trawls: A review and framework for development. Rev. Fish Biol. Fish. 10:27–60.

Broadhurst, M. K., D. T. Barker, B. D. Paterson, and S. J. Kennelly.
2002. Fate of juvenile school prawns, *Metapenaeus macleayi* after simulated capture and escape from trawls. Mar. Freshw. Res. 53:1189–1196.

Broadhurst, M. K., and S. J. Kennelly.
1996. Rigid and flexible separator-panels in trawls that reduce the by-catch of small fish in the Clarence River prawn-trawl fishery, Australia. Mar. Freshw. Res. 47:991–998.

Broadhurst, M. K., P. Suuronen, and A. Hulme.
2006. Estimating collateral mortality from towed fishing gear. Fish Fish. 7:180–218.

Broadhurst, M. K., and S. S. Uhlmann.
2007. Short-term stress and mortality of juvenile school prawns, *Metapenaeus macleayi*, discarded from seines and trawls. Fish. Manag. Ecol. 14:353–363.

Broadhurst, M. K., S. S. Uhlmann, and R. B. Millar.
2008. Reducing discard mortality in an estuarine trawl fishery. J. Exp. Mar. Biol. Ecol. 364: 54–61.

Cabral, H. N., C. M. Teixeira, R. Gamito, and M. J. Costa.
2002. Importance of discards of a beam trawl fishery as input of organic matter into nursery areas within the Tagus estuary. Hydrobiologia 475/476:449–455.

Chen, J-C., M-N. Lin, Y-Y. Ting, and J-N. Lin.
1995. Survival, haemolymph osmolality and tissue water of *Penaeus chinensis* juveniles acclimated to different salinity and temperature levels. Comp. Biochem. Physiol. 110A(3):253–258.

Davis, M. W.
2002. Key principles for understanding fish bycatch discard mortality. Can. J. Fish. Aquat. Sci. 59:1834–1843.

Gamito, R., and H. Cabral.
2003. Mortality of brown-shrimp discards from the beam trawl fishery in the Tagus estuary, Portugal. Fish. Res. 63:423–427.

Harris, R. R., and M. Ulmestrand.
2004. Discarding Norway lobster (*Nephrops norvegicus* L.) through low salinity layers—mortality and damage seen in simulation experiments. ICES J. Mar. Sci. 61:127–139.

Head, G., and J. Baldwin.
1986. Energy metabolism and the fate of lactate during recovery from exercise in the Australian freshwater crayfish *Cherax destructor.* Aust. J. Mar. Freshw. Res. 37:641–646.

Hill, A. D., A. C. Taylor, and R. H. C. Strang.
1991. Physiological and metabolic responses of the shore crab *Carcinus maenas* (L.) during environmental anoxia and subsequent recovery. J. Exp. Mar. Biol. Ecol. 150:31–50.

Hill, B. J., and T. J. Wassenberg.
1990. Fate of discards from prawn trawlers in Torres Strait. Aust. J. Mar. Freshw. Res. 41:53–64.

Kaiser, M. J., and B. E. Spencer.
1995. Survival of bycatch from a beam trawl. Mar. Ecol. Progr. 126:31–38.

Lancaster, J., and C. L. J. Frid.
2002. The fate of discarded juvenile brown shrimps (*Crangon crangon*) in the Solway Firth UK fishery. Fish. Res. 58:95–107.

Liggins, G. W., and S. J. Kennelly.
1996. By-catch from prawn trawling in the Clarence River estuary, New South Wales, Australia. Fish. Res. 25:347–367.

Liggins, G. W., S. J. Kennelly, and M. K. Broadhurst.
1996. Observer-based survey of by-catch from prawn trawling in Botany Bay and Port Jackson, New South Wales. Mar. Freshw. Res. 47:877–888.

Macbeth, W. G., M. K. Broadhurst, B. D. Paterson, and M. E. L. Wooden.
2006. Reducing the short-term mortality of juvenile school prawns (*Metapenaeus macleayi*) discarded during trawling. ICES J. Mar. Sci. 63:831–839.

Macbeth, W. G., R. B. Millar, M. K. Broadhurst, C. W. Hewitt, and M. E. L. Wooden.
2007. Intra-fleet variability in the size selectivity of a square-mesh trawl codend for school prawns (*Metapenaeus macleayi*). Fish. Res. 86:92–98.

Maguire, G. B., and G. Allan.
1985. *Development of methods for growing juvenile school prawns, Metapenaeus macleayi in estuarine ponds. In* Second Australian National Prawn Seminar (P. C. Rothlisberg, B. J. Hill, and D. J. Staples, eds.) p. 337–351. Second National Prawn Seminar, Queensland, Australia.

Newland, P. L., and C. J. Chapman.
1989. The swimming and orientation behaviour of Norway lobster, *Nephrops norvegicus* (L.), in relation to trawling. Fish. Res. 8:63–80.

Onnen, T., and E. Zebe.
1983. Energy metabolism in the tail muscles of the shrimp *Crangon crangon* during work and subsequent recovery. Comp. Biochem. Physiol. 74A:833–838.

Paterson, B. D.
1993. Respiration rate of the kuruma prawn, *Penaeus japonicus* Bate, is not increased by handling at low temperature (12°C). Aquaculture 114:229–235.

Paterson, B. D., G. B. Goodrick, and S. G. Grauf.
1995. Inosine monophosphate (IMP) concentration in shrimp flesh cannot be used as an index of "freshness" when comparing shrimp that have been harvested in different ways. J. Aquat. Food Prod. Tech. 4(3):59–74.

Sang, H. M., and R. Fotedar.
2004. Growth, survival, haemolymph osmolatity and organosomatic indices of the western king prawn (*Penaeus latisulcatus* Kishinouye, 1896) reared at different salinities. Aquaculture 234:601–614.

Taylor, A. C., and J. I. Spicer.
1988. Functional significance of a partial-emersion response in the intertidal prawn *Palaemon elegans* (Crustacea: Palaemonidae) during environmental hypoxia. Mar. Ecol. Progr. 44:141–147.

Uhlmann, S. S., and M. K. Broadhurst.
2007. Damage and partitioned mortality of teleosts discarded from two Australian penaeid fishing gears. Dis. Aquat. Org. 76:173–186.

Wassenberg, T. J., and B. J. Hill.
1989. The effect of trawling and subsequent handling on the survival rates of the by-catch of prawn trawlers in Moreton Bay, Australia. Fish. Res. 7:99–110.
1993. Selection of the appropriate duration of experiments to measure the survival of animals discarded from trawlers. Fish. Res. 17:343–352.

Watson, J. W.
1976. Electrical shrimp trawl catch efficiency for *Penaeus duorarum* and *Penaeus aztecus*. Tran. Am. Fish. Soc. 105:135–148.
1989. Fish behaviour and trawl design: potential for selective trawl development. *In* Proceedings of the world symposium on fishing gear and fishing vessels (Campbell, C. M., ed.), p. 25–29. Marine Institute, St Johns, Newfoundland.