

# The effect of dredge capture on the escape response of the great scallop, *Pecten maximus* (L.): implications for the survival of undersized discards

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## Abstract

The effect of simulated dredge capture on the swimming escape response of the great scallop, *Pecten maximus*, was assessed in order to determine the potential for mortality in undersized discards. Three experiments were carried out: firstly, to determine how the effect of simulated dredging on the escape response varied with season and scallop size; secondly, to assess the time taken for scallops to recover following simulated dredging; and thirdly, to determine the interactive effects of dredging, exposure to air and recovery time. In all experiments, simulated dredging caused a significant increase in the response time of scallops and a significant decrease in the number of valve adductions performed. The negative effects of dredging occurred irrespective of season (spring versus autumn) and scallop size. Exposure to air also had a negative effect on the escape response, which was evident in both dredged and nondredged scallops. Determination of the period taken to recover showed that although some recovery was evident after 1 h, the negative effects of simulated dredge capture were still apparent after a period of 24 h. These results suggest that there is a potential for high levels of mortality in undersized discarded scallops, and scallops which encounter dredges but are not captured. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Dredging; Escape response; Fishing impacts; *Pecten maximus*; Scallop; Swimming

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## 1. Introduction

The capture and discard of nontarget species and undersized target species has always occurred in fisheries worldwide, and regulations to reduce this by-catch have formed a part of fisheries management techniques since the early 20th century (Alverson and

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Hughes, 1996). Over the past decade, as fisheries have expanded and the potential environmental damage of commercial fishing has been realised (see Dayton et al., 1995; Jennings and Kaiser, 1998; Auster and Langton, 1999 for reviews), the assessment and control of by-catch has become a major issue. In most fisheries, a proportion of the captured target species will be discarded because of their small size. These individuals may be unmarketable, either for economic or regulatory reasons. Where size selectivity of gear is poor, discard mortality may exceed catch mortality (Alverson et al., 1994), although in most cases mortality of discards can only be estimated. Many studies have shown that damage, resulting from capture or encounter with fishing gear, can cause high levels of mortality (see Chopin and Arimoto, 1995 for review). However, the effects of stress or slight damage caused by encounter with gear on survival rates are not at all clear.

In common with many types of fishing gear, scallop dredges typically catch large numbers of undersized individuals of the target species. For example, in the Irish Sea, 'Newhaven' spring toothed scallop dredges catch an average of 35% of scallops under the minimum legal landing size of 110 mm shell length (Jenkins, unpublished data). On some fishing grounds, up to 75% of the catch can be comprised of undersized scallops. Given the large percentages of catches that are discarded, it is clear that the fate of undersized discards when returned to the sea bed is of obvious importance to the long-term sustainability of exploited populations.

Discarded scallops returned to the seabed may die as a direct result of physical damage incurred during the capture and sorting process (e.g. Medcof and Bourne, 1964) or indirectly due to predators or disease (McLoughlin et al., 1991). A number of studies have quantified dredge-induced damage in both captured (Medcof and Bourne, 1964; Jenkins et al., 2001) and noncaptured (Caddy, 1973; Butcher et al., 1981; Shepard and Auster, 1991) scallops. Although it is likely that physical damage results in significant levels of mortality, the majority of scallops that encounter dredges are apparently undamaged (Medcof and Bourne, 1964; Shepard and Auster, 1991; Jenkins et al., 2001). This is particularly true for the great scallop, *Pecten maximus*. Jenkins et al. (2001) found that less than 10% of scallops encountering dredges showed any signs of external physical damage on a scallop fishing ground in the north Irish Sea. The effect of capture on survival rate, growth and reproduction in undamaged scallop discards is unknown. Undamaged *P. maximus*, captured using dredges, show low levels (< 5%) of mortality in the laboratory (Jenkins unpublished data). However, such observations ignore the potential effects of predators and longer-term effects of stress.

Animals which are disturbed or damaged by demersal fishing gear on the seabed, and those which are captured and subsequently discarded, attract mobile predators and scavengers (Kaiser and Spencer, 1994, 1996). It is likely, therefore, that undamaged scallops, discarded along with large quantities of damaged invertebrate by-catch (Veale et al., 2001), will be subjected to high levels of predator activity. Scallops show a characteristic escape response to predators (see Brand, 1991 for review), reacting by either closing the shell, jumping or swimming (Thomas and Gruffydd, 1971). Jumping or swimming is brought about by the powerful ejection of water from the mantle cavity by rapid adduction of the shell valves. During jumping, water is ejected from the ventral mantle margins by valve adductions, which recur at low frequencies, typically only 1–3

adductions (Brand, 1991). When swimming, the scallop moves ventral edge first, propelled by water ejected dorsally on either side of the hinge in a series of adductions, which recur in rapid succession. Shepard and Auster (1991) speculated that the swimming ability of scallops may be impaired by the passage of a dredge, either by stress caused by physical impact, or by exhaustion following swimming induced by the approaching dredge. A reduction in the scallop's ability to escape predators has important implications for survival of undersized discards.

We focused on assessing the effect of simulated dredging on the timing and magnitude of the swimming escape response in the great scallop, *P. maximus*. Dredging was simulated by agitating a mixture of scallops and rocks in seawater for a period of time representative of a typical tow length in the north Irish Sea scallop fishery. Scallops were stimulated to escape by applying the tube feet of *Asterias rubens*, a known predator of *P. maximus*, to the scallop's mantle margin. A number of response variables were measured, including the time taken to respond to stimulation and the total number of adductions made before exhaustion. In this way, the general hypothesis that dredging has a deleterious effect on the ability of *P. maximus* to escape from predators was tested. Experiments were conducted during a period of minimum and maximum seawater temperatures to determine how the effect of dredging varied seasonally. In addition, the time taken to recover from any potential reduction in swimming ability, following dredging, was assessed by testing scallops at set periods of time after simulated dredging.

Captured scallops undergo two distinct forms of stress before being returned to the seabed: the dredging process itself and subsequent exposure to air on board the fishing vessel. Scallops are known to survive for long periods out of water (e.g. Maguire et al., 1999). We hypothesised that the relatively short period of exposure to air, typical in undersized discards caught on fishing boats in the north Irish Sea, would cause no further reduction in swimming ability.

## 2. Methods

### 2.1. Collection and maintenance in the laboratory

Scallops beneath the minimum legal landing size of 110-mm shell length were collected using spring toothed scallop dredges from fishing grounds off the Isle of Man, British Isles. They were collected from two locations, the 'Chickens' scallop ground (53°59'N 4°53'W) and the Laxey Bay scallop ground (53°14'N 4°21'W). After sorting on deck, scallops were placed in seawater and transported to Port Erin Marine Laboratory, where they were maintained indoors in tanks (1 × 1 × 0.4 m) with fresh running seawater. The animals were not given supplementary food but were used in experiments within 3 weeks of collection. All scallops were given at least 10 days to recover from the dredging process before use in experiments.

### 2.2. Assessment of swimming ability

A preliminary experiment was carried out to determine the relationship between the number of valve adductions and the distance travelled by *P. maximus* (size range

90–110 mm) during swimming. A single scallop was placed in the centre of a large circular tank (depth 0.9 m, diameter 2.8 m) and stimulated to swim by touching the tube feet of a single arm of the starfish *A. rubens* onto the scallop's mantle edge. The distance moved in a single bout of swimming from the tank centre was measured and the number of valve adductions counted. The scallop was placed back in the centre of the tank and stimulated to swim again. Scallops were used in this way until swimming responses ceased. At least six observations of each adduction number, between 1 and 14, were made.

### 2.3. General experimental procedure

In order to assess the effect of dredge disturbance on the swimming escape response of scallops, we took the same approach as in previous studies of scallop swimming (e.g. Thomas and Gruffydd, 1971; Stephens and Boyle, 1978). The lower (right) valve of each scallop was attached to the substratum to prevent movement of the animal whilst performing valve adductions. This was achieved by gluing a nylon nut to the lower valve of each scallop using Araldite Rapid™ adhesive. During the gluing procedure, scallops were exposed to the air for a maximum of 10 min. The head of a nylon bolt was glued to a brick so that the scallop could be quickly and easily screwed to the bolt and immobilised. Scallops were given at least 3 days to recover after the gluing procedure.

A system of six circular experimental tanks (diameter 0.38 m × depth 0.28 m), each with a brick and bolt for immobilising a single scallop, was set up with running seawater. The experimental procedure consisted of removing a set of scallops from the storage tanks, subjecting them to the appropriate treatment (see below) and then quickly screwing them to the single brick in each experimental tank. This could be achieved underwater to avoid additional stress. Once immobilised in the experimental tanks, all scallops, whatever the experimental treatment, were given 15 min to recover from the handling process. This time was chosen as it allowed even the most stressed scallops time to open their valves. After 15 min, scallops were stimulated to 'escape' using the predator *A. rubens*. A number of individuals of this species, of similar size (15–18-cm diameter), were maintained in seawater tanks, and a different individual used for each set of scallops. To stimulate an escape response, a starfish was introduced to a scallop, so that the tube feet of a single arm touched the mantle edge. Care was taken to avoid creating shadows and displacing water, which could cause the scallop to close its valves before the starfish could be applied. The starfish arm was left in place until a response was initiated. The time from the first stimulation until an escape response was performed was recorded using a stopwatch, and the number of valve adductions counted. After valve adductions had ceased, the scallop was again stimulated in the same way, and the number of adductions counted. This was continued until the valves closed firmly or until there was no response after 60 s.

In this way, a single response time (the time from the first stimulation until an escape response was performed) was recorded, plus a series of adductions. Adductions were either in the form of single valve claps, or rapidly repeated valve claps. Preliminary observations on swimming, described above, showed that a high total number of adductions could be made, either in the form of a few bouts of sustained valve claps (swimming), or by numerous single adductions (jumping). It is known that the jumping

response occurs in bouts of between 1 and 3 valve claps (Brand, 1991). In order to differentiate between the swimming response and the jumping response, the percentage of the total number of valve claps that occurred in bouts of 4 or more was calculated. This separation between 3 and 4 valve adductions was justified by the results of the preliminary swimming experiment which showed a doubling in the distance travelled, from 20 to 40 cm, in scallops which exhibited 4 valve claps compared with 3 (Fig. 1).

#### 2.4. Simulation of dredging

In order to simulate the effects of dredging on scallops caught in a typical dredge used in the Irish Sea, a nylon mesh bag (30 × 50 cm) was prepared containing an assortment of stones varying in diameter from 6 to 12 cm and with a total weight of 7 kg. Between four and seven scallops (depending on the experiment) were placed in the bag, which was then placed in a 60-l tank of seawater containing a thin layer of sand. The bag was attached via two overhead pulleys to a 22-cm arm attached to the axle of an electric motor, which turned at the rate of 38 times per minute. Action of the motor caused the arm to turn, which caused the bag of scallops and stones to lift approximately 10 cm and to fall under its own weight onto the base of the tank. Throughout the process the scallops were continuously submerged. For all experiments, scallops were ‘dredged’ for 40 min. This time period represents the lower end of the range of tow durations for scallop fishing boats in the north Irish Sea.

#### 2.5. Experiment 1: effect of dredging in different seasons and on different sized scallops

Scallops were collected from the ‘Chickens’ scallop ground on March 15th, 2000, and September 12th, 2000. These dates occur during periods of minimum and maximum

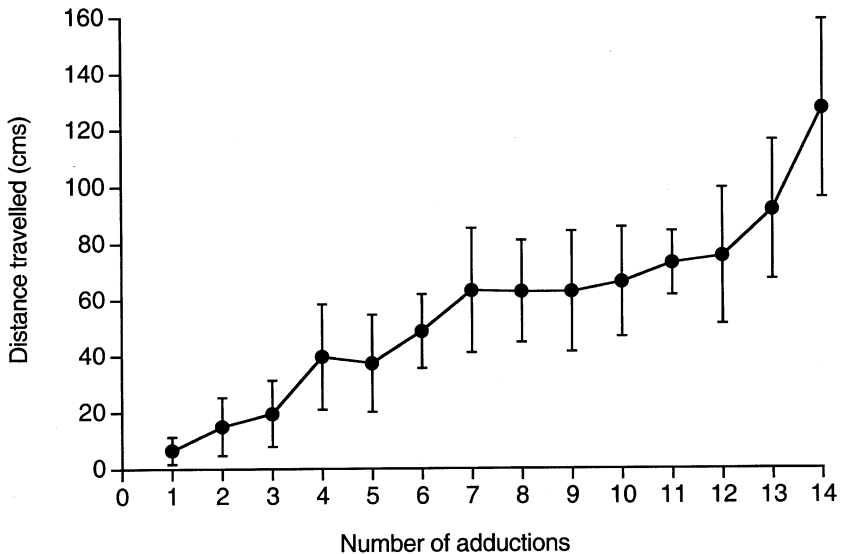


Fig. 1. The relationship between the number of consecutive valve adductions performed by *P. maximus* during an ‘escape response’ and the distance travelled over the ground. Error bars =  $\pm 1$  SD.

water temperatures in the north Irish Sea. The mean temperature of the water in laboratory tanks at the time of experimentation was 8 °C (range: 7.4–10 °C) in the spring and 15 °C (range 15–16 °C) in the autumn. Two size classes of undersized scallops were collected, 80–95-mm and 105–110-mm shell length. For each size class of scallop there were two treatments, nondredged and dredged, with each size class–treatment combination replicated five times. Each replicate consisted of four scallops which were treated as sub-samples and averaged to give a single value.

### *2.6. Experiment 2: determination of the time taken for scallops to recover following dredging*

Undersized scallops (80–110 mm) were collected from the ‘Chickens’ scallop ground on April 28th, 2000. The experiment consisted of seven experimental treatments and one control. Scallops underwent simulated dredging for 40 min and were then left to recover in holding tanks with running seawater for varying lengths of time: 0, 1, 2, 4, 6, 8, and 24 h. In addition, there was a single control treatment in which no dredging took place. For each of the eight treatments, four replicates were used, with each replicate consisting of seven scallops.

### *2.7. Experiment 3: determination of the interactive effects of dredging, exposure to air and recovery time*

Undersized scallops (80–110-mm shell length) were collected from Laxey Bay on November 2nd, 2000. A three-way factorial experiment was designed to investigate the interactive effects of dredging, exposure to air (hereafter termed desiccation) and recovery time. All three factors had two levels, presence and absence, resulting in eight orthogonal treatments which were replicated four times. Five scallops were used for each replicate. Simulated dredging was undertaken for 40 min, whilst scallops were exposed to the air for 20 min at a temperature of 10–13 °C. The recovery period was either 0 or 1 h.

### *2.8. Data analysis*

Data were analysed using ANOVA. Prior to using ANOVA, Cochran’s test was used to test for heterogeneity of variance. Multiple comparisons of levels within significant factors were made using Student Newman Keuls (SNK) tests.

## **3. Results**

### *3.1. General observations of swimming and adduction patterns*

There was a large degree of variability in the swimming response of scallops within a single treatment. For example, in control individuals the total number of adductions

performed ranged from 1 to 38, whilst the response time ranged from 1 to 58 s. The total number of valve adductions performed in one bout ranged from 1 to a maximum of 25. In dredged scallops, although the swimming response was typically very low, some scallops performed very well, with a maximum of 18 adductions in total. Dredged scallops frequently took long periods to respond at each stimulation, and the adductions were often relatively weak, with a shallow gape and slow valve movements. Adductions that were judged to be too weak to move the scallop were ignored.

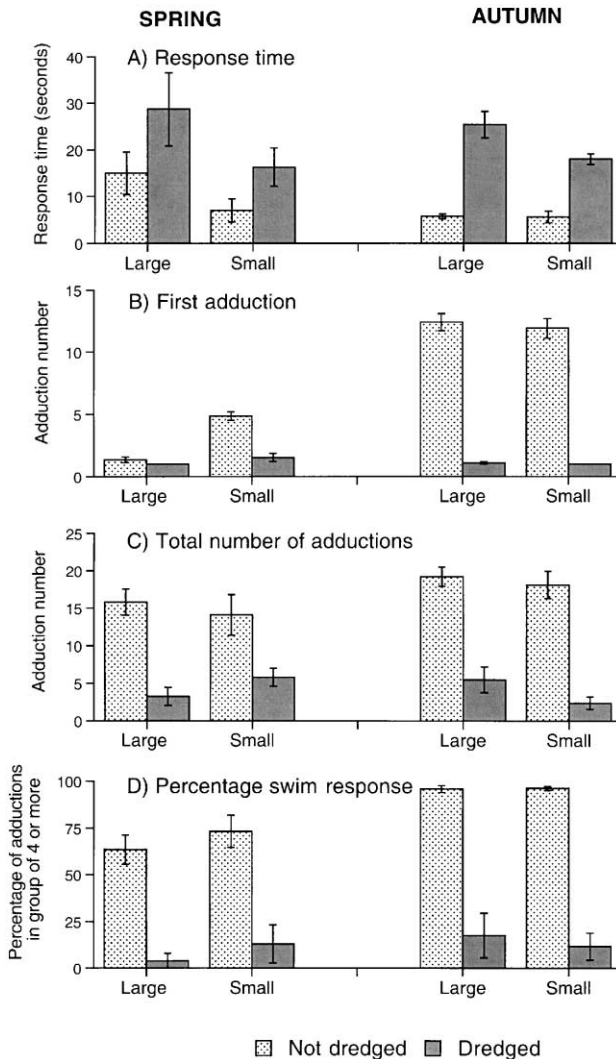


Fig. 2. The effect of dredge simulation on the responses of 'large' (105–110-mm shell length) and 'small' (80–95-mm shell length) *P. maximus* following stimulation by the predatory starfish *A. rubens* in spring and autumn 2000. Error bars =  $\pm 1$  SE.

Table 1  
ANOVA of four response variables in experiment 1 carried out in spring and autumn 2000

| Source                 | Response time (transformation: $(\sqrt{(x+1)})$ ;<br>$C = 0.3079$ $P > 0.05$ ) |       |          |         | First adduction (transformation: $(\sqrt{(x+1)})$ ;<br>$C = 0.2866$ $P > 0.05$ ) |          |         |
|------------------------|--|-------|----------|---------|--|----------|---------|
|                        | <i>df</i>  | MS    | <i>F</i> | P       | MS   | <i>F</i> | P       |
| Dredge                 | 1  | 31.71 | 38.22    | < 0.001 | 17.78  | 645.79   | < 0.001 |
| Season                 | 1  | 1.06  | 1.27     | > 0.25  | 6.27   | 227.80   | < 0.001 |
| Size                   | 1  | 6.59  | 7.94     | < 0.01  | 0.57   | 20.64    | < 0.001 |
| Dredge × season        | 1  | 1.58  | 1.91     | > 0.15  | 7.34   | 266.83   | < 0.001 |
| Dredge × size          | 1  | 0.42  | 0.51     | > 0.4   | 0.29   | 10.90    | < 0.01  |
| Season × size          | 1  | 1.65  | 1.99     | > 0.15  | 0.84   | 30.39    | < 0.001 |
| Dredge × season × size | 1  | 0.21  | 0.25     | > 0.6   | 0.36   | 13.21    | < 0.001 |
| Residual               | 32   | 0.83  |          |         | 0.03   |          |         |

| Source                 | Total adductions (transformation: none;<br>$C = 0.3416$ $P > 0.05$ ) |         |          |         | % Swim response (transformation: none;<br>$C = 0.3218$ $P > 0.05$ ) |          |         |
|------------------------|--|---------|----------|---------|---|----------|---------|
|                        | <i>df</i>  | MS      | <i>F</i> | P       | MS  | <i>F</i> | P       |
| Dredge                 | 1  | 1565.63 | 114.54   | < 0.001 | 49799.06  | 174.77   | < 0.001 |
| Season                 | 1  | 24.94   | 1.82     | > 0.15  | 2872.25   | 10.08    | < 0.01  |
| Size                   | 1  | 6.88    | 0.50     | > 0.4   | 112.02  | 0.39     | > 0.5   |
| Dredge × season        | 1  | 45.33   | 3.32     | > 0.05  | 1164.77   | 4.09     | > 0.05  |
| Dredge × size          | 1  | 2.80    | 0.21     | > 0.6   | 30.38   | 0.11     | > 0.7   |
| Season × size          | 1  | 15.52   | 1.14     | > 0.25  | 368.41  | 1.29     | > 0.25  |
| Dredge × season × size | 1  | 24.15   | 1.77     | > 0.15  | 19.10   | 0.07     | > 0.7   |
| Residual               | 32   | 13.67   |          |         | 0.83  |          |         |



### 3.2. Experiment 1

Simulated dredging caused a significant increase in the time taken for scallops to respond to the predator stimulus for both large and small scallops, in both spring and autumn (Fig. 2, Table 1). The average response time for all scallops tested was 8 s in

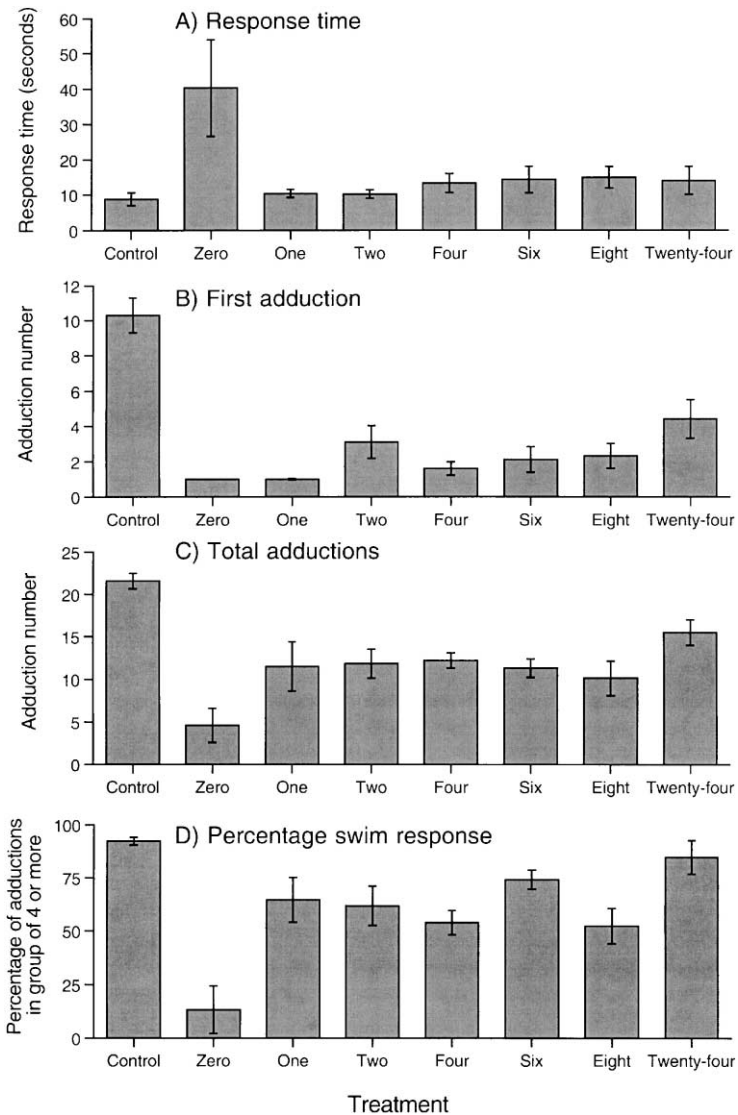


Fig. 3. The time taken to recover the 'escape response' in *P. maximus* following simulated dredging. All treatments except the control were dredged and given differing periods of time to recover (0 to 24 h) before stimulation with the predatory starfish *A. rubens*. Error bars =  $\pm 1$  SE.

nondredged scallops, compared with 22 s in dredged scallops. There was a significant effect of the factor size, with large scallops (105–110 mm) being slower to respond than small scallops (80–95 mm) (Fig. 2, Table 1).

The effect of simulated dredging on the number of adductions shown after the first stimulation by *A. rubens* ('first adduction') was dependent on both scallop size and season, as shown by the significant three-way interaction (Table 1). Adduction number was significantly reduced for all treatments, except in large scallops in the spring. In all dredged scallops only 3 individuals out of 80 showed more than one adduction in their first response. There was a clear difference in the number of adductions between seasons in control scallops, with a significantly higher number in the autumn (Fig. 2).

The total number of adductions was significantly lower in scallops that had undergone simulated dredging (Fig. 2, Table 1). This was true irrespective of size or season. The mean number of adductions was 17 in controls, compared with only 4 in dredged animals. There was no difference in adduction number between seasons or sizes. The percentage of the total number of adductions which occurred as a swim response (in bouts greater than three valve claps) was significantly lower in dredged scallops (Fig. 2, Table 1). In addition, there was a greater proportion of swimming bouts in the autumn compared with spring.

### 3.3. Experiment 2

For all four variables measured there was a significant effect of dredging; response time increased from a mean of 9 to 40 s, the mean number of adductions in the first

Table 2  
ANOVA of four response variables in experiment 2

|   | Source    | df | MS      | F     | P       |
|---|-----------|----|---------|-------|---------|
| <i>Response time</i>                                      |           |    |         |       |         |
| Transform: Ln ( $x + 1$ )                                 | Treatment | 7  | 0.66    | 3.89  | < 0.01  |
| $C = 0.2708$  | Residual  | 24 | 0.17    |       |         |
| SNK test: 0 > all other treatments                        |           |    |         |       |         |
| <i>First adduction</i>                                    |           |    |         |       |         |
| Transform: none   | Treatment | 7  | 37.29   | 17.05 | < 0.001 |
| $C = 0.2950$  | Residual  | 24 | 2.19    |       |         |
| SNK test: control > all other treatments; 0 and 1 < 24    |           |    |         |       |         |
| <i>Total adductions</i>                                   |           |    |         |       |         |
| Transform: none   | Treatment | 7  | 93.16   | 7.48  | < 0.001 |
| $C = 0.3458$  | Residual  | 24 | 12.45   |       |         |
| SNK test: control > all other treatments; 0 < 1, 6, 8, 24 |           |    |         |       |         |
| <i>% Swim</i>   |           |    |         |       |         |
| Transform: none   | Treatment | 7  | 2355.65 | 9.33  | < 0.001 |
| $C = 0.2436$  | Residual  | 24 | 252.36  |       |         |
| SNK test: 0 < all other treatments                        |           |    |         |       |         |

The factor treatment refers to comparison between the control and seven dredged treatments with differing periods of recovery.

response decreased from 10.3 to 1, the total number of adductions declined from 21.6 to 4.6, whilst the percentage of adductions which occurred as a swim response declined from 92% to 13% (Fig. 3). The rate of recovery after simulated dredging varied depending on the response variable. Both the response time and the percentage of adductions performed as a swim response showed no significant difference to control levels after only 1 h (Fig. 3, Table 2). However, both the number of adductions in the first response and the total number of adductions were still lower than control levels after 24 h of recovery. The total number of adductions showed a clear pattern, with a partial recovery after only 1 h, but no further recovery over the following 23 h (Fig. 3, Table 2). The number of adductions in the first response showed no recovery 8 h after

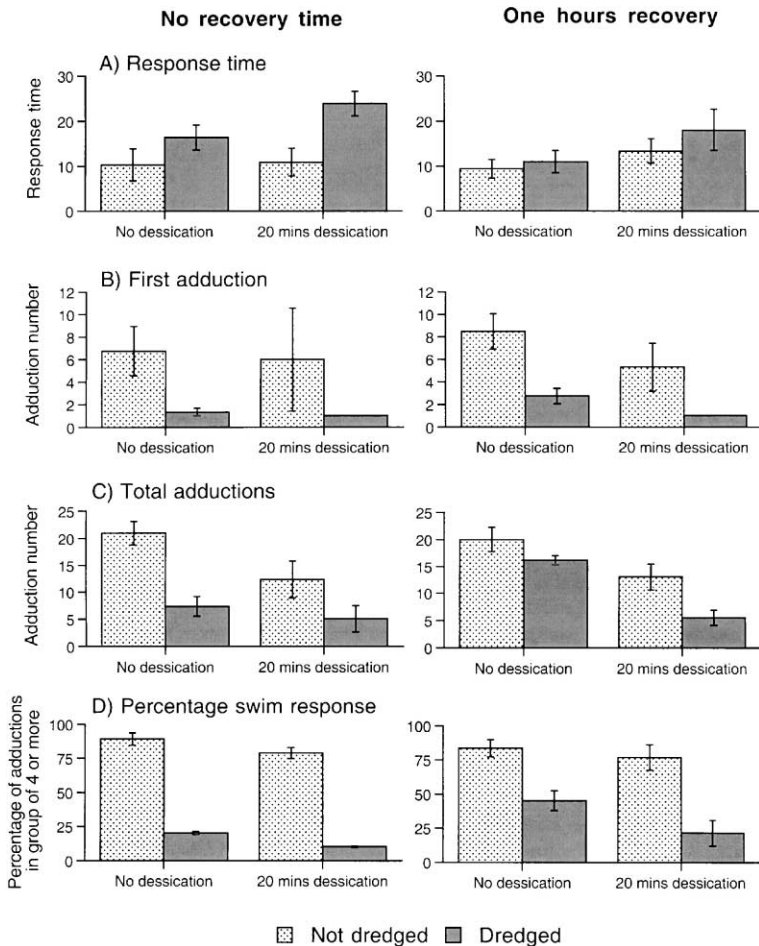


Fig. 4. The effect of dredge simulation and exposure to air on the responses of *P. maximus* following stimulation by the predatory starfish *A. rubens*. *P. maximus* was given both 0 and 1 h recovery time before stimulation. Error bars =  $\pm 1$  SE.

Table 3  
ANOVA of four response variables in experiment 3

| Source                      | Response time (transformation: none;<br>$C = 0.2726$ $P > 0.050$ ) |        |          |        | First adduction (transformation: $\ln(x)$ ;<br>$C = 0.4208$ $P > 0.05$ ) |          |         |
|-----------------------------|--|--------|----------|--------|--|----------|---------|
|                             | <i>df</i>  | MS     | <i>F</i> | P      | MS   | <i>F</i> | P       |
| Dredge                      | 1  | 322.47 | 8.44     | < 0.01 | 12.14  | 20.67    | < 0.001 |
| Desiccation                 | 1  | 182.49 | 4.78     | < 0.05 | 3.13   | 5.33     | < 0.05  |
| Time                        | 1  | 50.54  | 1.32     | > 0.25 | 1.14   | 1.94     | > 0.15  |
| Dredge × desiccation        | 1  | 49.96  | 1.31     | > 0.25 | 0.05   | 0.08     | > 0.75  |
| Dredge × time               | 1  | 81.87  | 2.14     | > 0.15 | 0.14   | 0.02     | > 0.85  |
| Time × desiccation          | 1  | 4.49   | 0.12     | > 0.7  | 0.26   | 0.44     | > 0.5   |
| Dredge × desiccation × time | 1  | 7.59   | 0.20     | > 0.6  | 0.19   | 0.33     | > 0.55  |
| Residual                    | 24   | 38.21  |          |        | 0.59   |          |         |

|                             | Total adductions (transformation: none;<br>$C = 0.2989$ $P > 0.05$ ) |        |          |         | % Swim response (transformation: none;<br>$C = 0.1911$ $P > 0.05$ ) |          |         |
|-----------------------------|--|--------|----------|---------|---|----------|---------|
|                             | <i>df</i>  | MS     | <i>F</i> | P       | MS  | <i>F</i> | P       |
| Dredge                      | 1  | 525.82 | 26.75    | < 0.001 | 26694.55  | 96.88    | < 0.001 |
| Desiccation                 | 1  | 411.72 | 20.95    | < 0.001 | 1285.97   | 4.67     | < 0.05  |
| Time                        | 1  | 40.46  | 2.06     | > 0.15  | 419.40  | 1.52     | > 0.2   |
| Dredge × desiccation        | 1  | 3.39   | 0.17     | > 0.6   | 138.19  | 0.50     | > 0.45  |
| Dredge × time               | 1  | 45.56  | 2.32     | > 0.1   | 947.84  | 3.44     | > 0.05  |
| Time × desiccation          | 1  | 22.92  | 1.17     | > 0.25  | 51.40   | 0.19     | > 0.65  |
| Dredge × desiccation × time | 1  | 51.21  | 2.61     | > 0.1   | 149.72  | 0.54     | > 0.45  |
| Residual                    | 24   | 19.66  |          |         | 275.54  |          |         |

dredging. After 24 h the number of adductions was significantly greater than at 0 h but was still lower than the control scallops.

### 3.4. Experiment 3

The escape response of scallops was tested immediately (0 h) and 1 h after experimental treatments. Scallops showed a similar response to the effect of simulated dredging and exposure to air at both times, indicated by the nonsignificant dredge  $\times$  time and desiccation  $\times$  time interactions (Fig. 4, Table 3). Thus, after 1 h, scallops were still negatively affected by the treatments. Simulated dredging had a significant negative effect on all four response variables (Fig. 4, Table 3). Exposure to air had a negative effect on all response variables except the number of adductions in the first response. We had hypothesised that there would be no effect of exposure to air in dredged scallops. This would be expressed as a significant dredge  $\times$  desiccation interaction. However, this interaction was nonsignificant; there was a negative effect of desiccation for both dredged and nondredged scallops. For all response variables, at both 0 and 1 h, those scallops subject to both dredging and exposure to air were the most negatively affected (Fig. 4).

## 4. Discussion

Scallops have a number of natural predators, the most important of which are usually starfish (e.g. Olsen, 1955; Barbeau and Scheibling, 1994; Lake and McFarlane, 1994), crabs (Lake et al., 1987; Minchin, 1991) and gastropod molluscs (Ordzie and Garofalo, 1980). High predator-induced mortality in scallop populations has been observed, both in natural populations (Olsen, 1955; Dickie and Medcof, 1963), and in areas seeded for aquaculture (Caddy, 1988; Minchin, 1991). The swimming escape response is an important defence against mortality from all types of predator, although it seems likely that it is most important in providing protection from those which are less mobile, such as starfish and gastropod molluscs. In the north Irish Sea, the predominant predators of *P. maximus* are the starfish *A. rubens* and the crab *Cancer pagurus* (Brand et al., 1991). Both species are abundant and are attracted to high scallop densities, for example, in areas of juvenile reseedling (Wilson, 1994), and to simulated by-catch discards (Veale et al., 2000). The results of numerous studies, investigating attraction of scavengers and predators to recently trawled or dredged areas (e.g. Kaiser and Spencer, 1994, 1996), or to by-catch discards (e.g. Ramsay et al., 1997; Veale et al., 2000), strongly suggest that undamaged scallops, discarded along with large quantities of damaged invertebrate by-catch (Veale et al., 2001), will be subjected to high levels of predator activity.

Simulated dredging clearly reduced the ability of *P. maximus* to escape from an introduced predator. Ramsay and Kaiser (1998) subjected the whelk *Buccinum undatum* to disturbance which simulated the effects of demersal fishing gear. They showed a reduction in the ability of whelks to right themselves and perform an escape response from *A. rubens*. Coffen-Smout and Rees (1999) demonstrated a delay in the reburrowing response of the cockle *Cerastoderma edule* L. following simulated fishing disturbance. Such studies rely on adequate simulation of fishing disturbance. The method we

used to simulate dredging does not replicate exactly the type of movement and physical impacts that captured scallops undergo. However, it was hoped that the method used would give an approximation of these stresses. Stones were used within a size range observed in the catches of dredges around the Isle of Man and the degree of vertical movement was similar to that observed in videos of dredges in action. It should be noted that the simulated dredging in the laboratory was the second period of disturbance experienced by these scallops over a period of 10 to 21 days. We made the assumption, which was not tested, that scallops had totally recovered from the negative effects of dredge capture. This could be tested in future studies by comparing diver and dredge captured scallops, or determining the escape response in the laboratory at increasing time periods after dredge capture.

In *P. maximus*, both the increase in response time and the reduction in swimming ability after dredging suggest an increase in vulnerability to predation, particularly from slow moving predators such as starfish and gastropod molluscs. *A. rubens* uses tube feet to grasp the shell of bivalve prey (Jangoux, 1982) and can generate sufficient force to open the valves of large *P. maximus*. Thus, once held by the arms of *A. rubens*, it seems unlikely that the swimming escape response will be effective. Any increase in the time taken to respond to a predator will also reduce the likelihood of the swimming escape response being successful. The number of adductions in the scallop's first response to a predator will dictate the distance travelled from the point of initial stimulation. Movement over a large distance may mean the end of the predation threat in the short term. Nearly all dredged scallops responded initially by performing only one adduction. This 'jumping' response may cause the scallop to prevent attachment of an attacking starfish (Brand, 1991) but will not separate predator and prey by any significant distance. In contrast, the mean number of adductions in the first response of control scallops over all experiments was 8 adductions. Our data suggest this will result in a distance travelled of over 0.6 m. The propensity for dredged scallops to exhibit single valve adductions, rather than sustained swimming, was shown not only in the first response but throughout the period of stimulation until exhaustion. Some dredged scallops performed a relatively high total number of adductions, but these were performed as single valve adductions suggesting they had lost the ability (at least in the short term) of sustained swimming activity. The total number of adductions which a scallop is capable of performing with repeated stimulation is of obvious relevance to the probability of survival in an area of high predator density such as is likely to occur at discard sites. Our method of repeated stimulation by *A. rubens* was not designed to replicate exactly the predator-prey interactions on the seabed, but to provide an estimate of the ability of differently treated scallops to escape frequent attacks before exhaustion. Simulated dredging caused a substantial reduction in the total number of adductions which scallops are capable of performing.

There are numerous factors associated with dredge capture which may cause stress to scallops and a subsequent reduction in swimming ability. The physical impact of dredge teeth at the point of capture, physical impact with rocks during the period within the dredge bag and exposure to high suspended sediment levels are all potential causative factors. Alternatively, scallops may simply be exhausted by attempting to swim whilst in the dredge itself. The swimming escape response of scallops is energetically very

demanding (Thompson et al., 1980); clapping of valves results in an accelerated heart rate, a decrease in blood  $P_{O_2}$  and invoking of anaerobic metabolism (de Zwaan, 1977). Physiological functions take several hours to return to normal values (Thompson et al., 1980). Exposure to air also had a negative effect on scallop swimming. Aerial exposure is an obvious cause of stress in a subtidal marine invertebrate. Maguire et al. (1999) showed high levels of stress (measured as the reduction in adenylic energetic charge) in juvenile *P. maximus* after 4 h of exposure to air, although mortality as a direct result of such exposure was low even after 12 h of exposure. We showed that exposure to air for only 20 min caused a significant decline in subsequent swimming ability in both dredged and nondredged scallops.

The experiment to determine recovery time in *P. maximus* clearly showed that a scallop's ability to escape a predator is at its lowest immediately after dredging. A limited recovery was shown after 1 h in experiment 2 but at this stage, and for the following 23 h, scallops were still negatively affected by dredge disturbance. The implications of recovery time to a scallop's chance of survival when returned to the seabed depend on the time taken for predators to aggregate to discarded material. The rate of aggregation will depend on an individual species sensory abilities, mobility and behaviour. Highly mobile predators such as fish may arrive at dredge and trawl tracks or discards within 30 min after disturbance (Kaiser and Spencer 1996), but less mobile invertebrate predators such as whelks and starfish may take a number of hours to arrive. Experiments to simulate the supply of damaged discards to the sea bed, conducted in the Irish Sea, have shown that the predatory starfish *A. rubens* starts to increase in density after approximately 5 h and numbers peak at around 20 h (Kaiser and Spencer, 1996; Veale et al., 2000). Thus, it is likely that discarded scallops will be subjected to elevated levels of predatory starfish activity within the period during which we have shown a reduction in the ability to escape. In addition, *A. rubens* is relatively resilient to the effects of demersal trawls (Kaiser and Spencer, 1995) and dredges (Veale et al., 2001). Thus, high numbers of starfish, discarded with undersized scallops, may be able to prey on *P. maximus* immediately on return to the seabed.

We have investigated the effect of dredging on captured scallops, which are subsequently discarded. However, dredges are notoriously inefficient at capturing the target organism (e.g. Caddy, 1968; Chapman et al., 1977; Dare et al., 1993) and the majority of scallops which encounter dredges remain on the seabed. For example, Dare et al. (1993) estimated the capture efficiency of spring toothed scallop dredges varied from 6% to 41% (scallops > 90 mm) depending on ground type. Jenkins et al. (2001) showed that the levels of damage to organisms left on the seabed (including *P. maximus*) following the passage of spring toothed scallop dredges, were similar and in some cases higher than in the organisms captured. These observations indicate that scallops which encounter the dredge, but are not captured, may show the same levels of stress and reduction in swimming ability as undersized discards.

In conclusion, we have demonstrated a reduction in swimming ability in captured undersized scallops. These data, together with numerous studies of predator aggregation to discarded material, indicate that there is a potential for high levels of mortality in undersized discards of *P. maximus* and in impacted but uncaptured individuals. A number of studies have assessed the probability of survival in stressed and damaged

invertebrates and fish following capture (De Veen et al., 1975; van Beek et al., 1990; Evans et al., 1994; Kaiser and Spencer, 1995). However, these studies have invariably assessed direct mortality and ignored the indirect effects of predators and disease. There is a need to carry out realistic field-based tests of survival of stressed and damaged organisms impacted by demersal fishing.

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