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Mortality of mackerel (*Scomber scombrus* L.) after pursing and slipping from a purse seine

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ABSTRACT

A new method was used to study the effect of crowding and subsequent slipping from a purse seine on the mortality of Atlantic mackerel (*Scomber scombrus* L.). Mackerel were allowed to swim from a purse seine through a transfer channel into two identical large floating net-pens. One pen was used as a control and was left floating in the sea without further treatment. The other was used to simulate crowding and slipping. The volume of the pen was gradually decreased by hoisting the bottom of the pen using a crane until the fish started to show panic reactions, and this volume was maintained for 15 min (2006) or 10 min (2007). The volume was then allowed to return to normal and the net-pens were left to drift freely in the open sea for 3–6 days. Five repeat experiments were performed, all of which showed that crowding has a major effect on survival rates. In all five experiments, mortality was higher among the crowded fish (80–100% mortality) than the controls (0.1–46% mortality), and the difference was significant ($p = 0.01$). The experiments demonstrate that excessive crowding before slipping mackerel from purse seines should be avoided, if possible, in order to avoid massive fish kills.

1. Introduction

Catch regulation by slipping the whole or parts of a catch has traditionally been used in pelagic fisheries if catches are too large, or the size and/or quality of the fish are regarded as unsatisfactory (Stratoudakis and Marçalo, 2002; Borges et al., 2008). This is particularly the case when there is a large price differential among fish sizes or qualities (high grading). Until now, little has been known about how pelagic fish are affected by contact with fishing gears, although some studies of herring (Misund and Beltestad, 1995; Suuronen et al., 1996a,b), mackerel (Misund and Beltestad, 2000) and sardine (Marçalo et al., 2006, 2007, 2010) suggest that these species are highly vulnerable to gear-inflicted injury. ICES has called attention to the fact that landed catches alone do not explain the total loss from the stock of NE Atlantic mackerel (ICES, 2007). A study by Simmonds et al. (2010), which performed detailed analyses of data from landed catches, tagging experiments and egg surveys, estimated that the total fishing related removals lies between 1.6 and 3.4 times the reported landings, with the most probable estimate being 2.4 times the catch. In addition to reported landings, real losses include unreported discards, slippage, escape mortality and undeclared landings. The relative importance of the individual fractions of the unaccounted mortality is unknown and may differ among fleet segments. The magnitude of unaccounted mortality is a key problem for marine fisheries management in terms of waste of the resource and uncertainty in estimating fishing mortality.

Lockwood et al. (1983) carried out a comprehensive small-scale study of the effects of crowding mackerel to various densities and for different durations. They observed severe mortalities when mackerel were held at densities similar to those in pursing before slipping. Although these experiments display excellent experimental data on the relationship between crowding and mortality, the fishing industry would not fully accept these results, claiming that small-scale experiments do not reflect conditions during fishing and that the experimental mortality rates cannot be considered valid for the commercial fishing fleet. The Norwegian fishing industry and fisheries managers have therefore demanded that these small-scale mortality rates be confirmed using full-scale fishing experiments in order to improve their credibility in the eyes of the industry.

The experiments described in this study are an attempt to meet these requirements. To carry out full-scale survival experiments in the field is certainly not straightforward (Suuronen, 2005), as they are extremely expensive to execute and are sensitive to a range of influences such as weather and availability of fish, while time and costs will almost inevitably limit the number of valid replicates. The sea trials in our study were carried out under conditions as close as possible to those experienced in commercial fishing operations. A new method for studying the survival of mackerel caught in a

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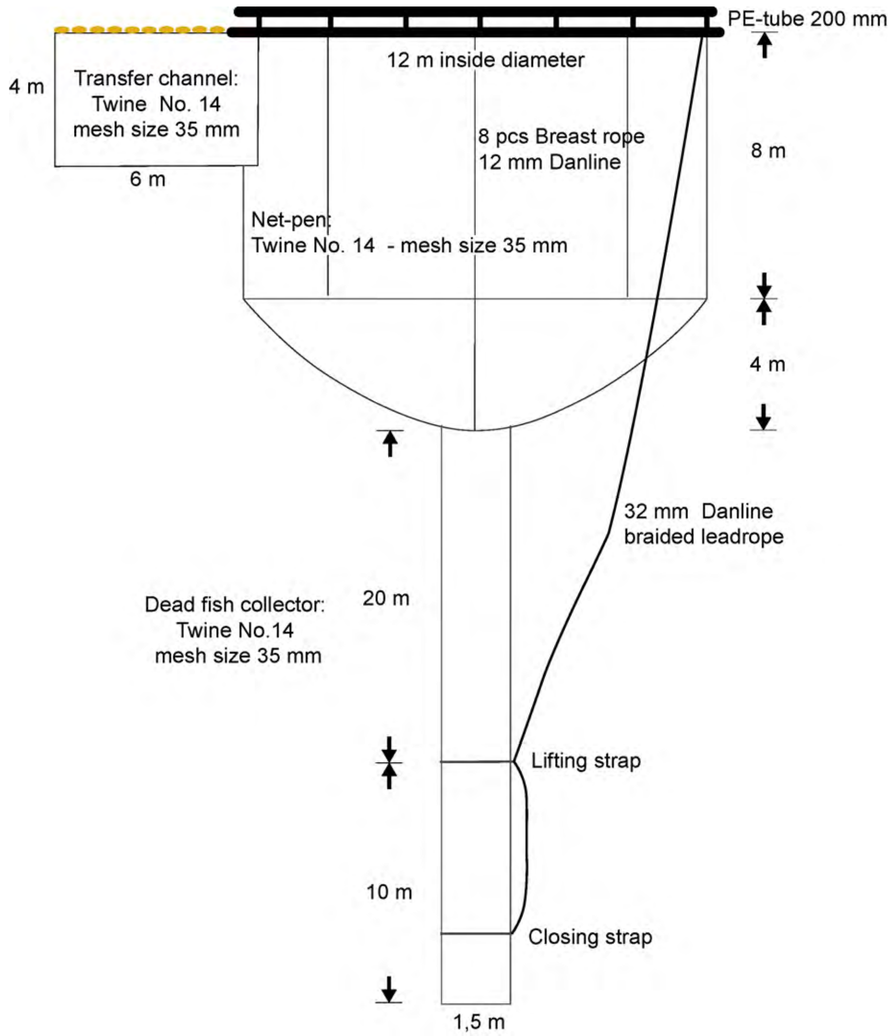

Fig. 1. Construction of net-pen with transfer channel. The dead fish collector was only used in 2007. In 2006, attempts were made to remove dead fish by pumping.

purse seine and crowded before slipping is described. The method involves minimal handling of the fish beyond that caused by the catch process itself.

2. Materials and methods

The experiments were carried out in the North Sea in August/September 2006 and 2007. Two large purse seiners were chartered for the experiments. Circular net-pens, each with an inner diameter of 12 m, were attached to a stiff frame of double (2006) or triple (2007) 200 mm polyethylene tubes (Fig. 1). The frame of large plastic tubes made it possible to work from the pens after they were deployed in the open sea. The netting material used in the pens was identical to that used in the bunt of many purse seines. An entrance channel made of the same material was attached to the pen, and an identical one was attached to the bunt of the purse seine. In 2006 the net-pens were readied for a pump system built for removal of dead fish from aquaculture net-pens (Lift Up Akva AS, Eikelandsosen, Norway). As this did not work well, in 2007 it was replaced with a 30-m-long collecting bag attached to the bottom of the cone (Fig. 1). A 30 kg weight attached to the end of the bag ensured that the pens kept their shape while drifting in the sea.

One purse seine vessel set its net on a suitable sonar record of mackerel and hauled the net carefully until about half the seine was taken onboard. A purse boat helped to keep the seine open during hauling. The other seiner was used to carry the equipment and to help with handling the large net-pens during fish transfer and crowding. The pens were deployed on the surface when the purse seine had been hauled about halfway and the presence of fish in the catch had been ascertained. The transfer channels from the net-pen and the purse seine were then joined to make an escape opening from the seine into the net-pen. The first vessel continued hauling with extreme caution until part of the school was swimming calmly (visual inspection) through the channel and into the net-pen (Fig. 2). The fish did not appear to be particularly stressed during this procedure and were swimming freely, not touching the net. They maintained their organized and polarized schooling behaviour and continued circling calmly inside the pen. As soon as about 10 tonnes of mackerel, estimated visually by a skilled fisherman, had entered the net-pen, the transfer channel was closed and parts of the seine were slackened in order to provide more space for the remaining fish.

Two net-pens were filled with mackerel from each set of the seine: one for the control and one for the experimental group. The control and experimental pens were alternately filled first in order to avoid any effect of order. Two pairs of pens were filled with fish during the 2006 experiments and three pairs during 2007. The control pens were left floating freely in the open sea without further treatment, while the experimental pens were used for the crowding experiments. In order to simulate the crowding that occurs during pursing, a rope attached at the midpoint of the conic bottom of the

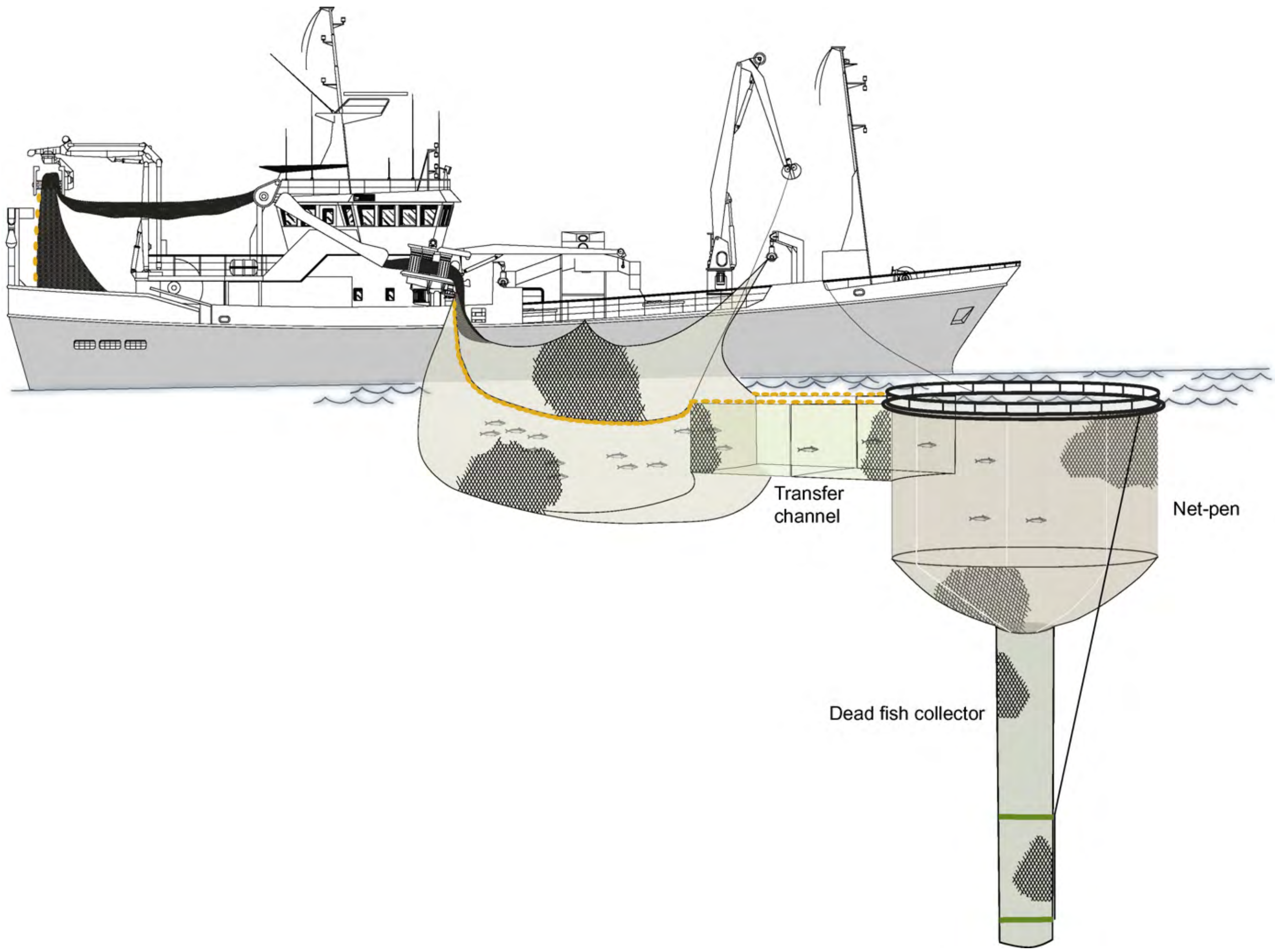

Fig. 2. The purse seine and net-pen were connected by a channel for transfer of the fish.

pen was hoisted up by the crane of the purse seiner until the mackerel started to evince a panic reaction (Misund, 1994) similar to the flash expansion behaviour described by Pitcher (1986). At this stage, organized swimming structure was lost and fish rose rapidly to the surface, where individuals could be seen moving haphazardly at high speed. The crowding time was chosen to reflect the typical duration of pursing in the fishing fleet. In 2006, the crowding density was maintained for 15 min, and in 2007, for 10 min, after which the pens were returned to their full volume and left to drift freely in the open sea. The pens would then drift at nearly the same speed as the currents, and maintain their shape even during strong winds and currents. There was one exception to this treatment: in the first experiment in 2006, the control and the experiment pen were tied together when left drifting, in order to facilitate tracking during the observation phase. In 2007, each pen was equipped with an Argos satellite transmitter (Campbell Scientific Inc., Castillo de San Marcos, FL) for positioning.

In order to observe fish behaviour in the pens during the observation phase, a colour pan and tilt UV camera or a monochrome pan camera was suspended in the middle of the pens. The pens were inspected twice a day via a video link to the fishing vessel, which enabled observations to be made at a distance of 50–100 m from the pens with minimal disturbance of the fish. The original plan was to leave the net-pens drifting in the sea for 5 days, but due to windy conditions, the first experiment had to be terminated after only 3.5 days. We also noted that the major mortality occurred during the first 2 days, and therefore decided to reduce the observation time to 3 days. However, weather conditions caused the actual observation periods to vary from 2 days and 15 h to 5 days and 23 h. At termination, the collecting bag was hoisted onboard the vessel, and the number of dead fish counted. The fish that remained in the net-pens were considered as survivors, and were pumped onboard, counted and measured.

Previous experiments have shown that the mortality of mackerel after crowding is primarily dependent on crowding density and crowding duration (Lockwood et al., 1983). In our experiments, with one exception (2006B), the fish were crowded to the point of displaying a panic reaction. Fish density at that point is difficult to estimate with any accuracy, as no equipment exists that is capable of measuring fish densities *in situ* in relatively small volumes of water. We therefore calculated the approximate water volume of the net-pen at maximum crowding retrospectively on the basis of photographs taken during the experiments. We suggest that the shape of the remaining volume of water in the net-pen during crowding, when the middle of the bottom was lifted in the crane of the vessel, had the shape of half a 'doughnut' (a semi torus). The volume (V) and net surface area (S) could then be calculated as $V = (a - b)(\pi b)^2$, and $S = 2b(a - b)\pi^2$, where a = the major radius (of the large circle) and b = the minor radius (of the circular cross-section).

In order to combine crowding duration and density, Lockwood et al. (1983) calculated a Stress Index (SI) as the product of crowding density and crowding duration, and showed that the relationship between the instantaneous mortality rate and the stress index was

Table 1
Observed mortality, length and weight measurements of individual mackerel in the experiments performed in 2006 and 2007.

Year	Experiment	Crowding duration (min)	Duration observation phase	Total no. of fish	Mortality (%)	Individual weight (kg)		Length (cm)	Comments
						Total catch	Alive	Alive	
2006	A	0	3 days 13 h	28,684	46	0.493	0.497	34.1	Pens linked together. Fish stressed by pumping
		15		71,294	100		0.477	35.4	
	B	0	3 days 1 h	17,678	0.2	0.465	0.466	35.6	
		15		10,651	27.9		0.469	36.3	Only 1/3 of the net dried up
2007	A	0	5 days 23 h	11,887	1	0.462	0.521	36.9	
		10		?					Pen torn in bad weather due to much dead fish
	B	0	4 days 20 h	15,231	0.1	0.468	0.473	36.2	
		10		19,740	83.5		0.504	36.6	
	C	0	2 days 15 h	14,543	22.2	0.495	0.457	35.8	15 min stop in hauling, seine collapsed, cork down
		10		31,234	99.2		0.405	35.1	15 min stop in hauling, seine collapsed, cork down

described by a power curve. In order to enable our data to be compared with those of Lockwood et al., their indices were recalculated from number of fish per m^3 to kg per m^3, as the fish in our experiments were substantially larger (465 g against 216 g).

3. Results

A total of five parallel experiments, each comprising one control and one experimental pen, were performed in 2006 and 2007. The number of experiments was, as so often is the case in large-scale experiments, mainly limited by the weather, but also by the capacity of the vessels to transport and monitor the large and heavy experimental equipment needed to carry out experiments in the open sea. The method required manual operations to be performed on the floating net-pens while the transfer channel was connecting the seine to the pens and during transfer of fish. Windy conditions with high waves made this operation risky at times.

In experiment 2007A, we obtained mortality estimates only from the control group (1% mortality), while the experimental pen burst in bad weather because of a heavy load of dead fish at the bottom of the pen (Table 1). Although mortality estimates from the experimental group could thus not be obtained, it was obvious that there had been massive mortality among the crowded fish, while mortality in the control group was only 1%. The other four parallel groups provided data from both the control and experimental groups (Table 1 and Fig. 3). The mortality of the crowded fish was significantly higher than that of the control groups ($p = 0.01$, Paired t-test with pooled SD), although there was considerable variation between the parallel groups. The number of valid observations was too low to give a reliable estimate of variance.

Some methodological problems influenced the mortality rates in the two parallel experiments performed during the 2006 study. The first pair of net-pens launched (2006A) was linked in order to facilitate tracking during the observation period. Dead fish rapidly accumulated at the bottom of the experimental pen. The pump system for removing dead fish turned out to be extremely inefficient. One of the fishing vessels worked for 13 h over 2 days, moored to the pen, trying to remove the dead fish. The presence of the vessel obviously stressed the fish, not only in the experimental pen but also in the attached control pen. This affected the survival rates of both groups, which reached 46% in the control group and 100% in the crowded group. In experiment 2006B, crowding was not complete because the crane on board the vessel was unable to lift the bottom of the net high enough. Only about one-third of the pen (measured as surface area) was properly dried. In this experimental run, the two pens were left drifting separately, and this method was maintained for all subsequent repeats. We also refrained from removing dead fish during the observation period in order to avoid stressing the fish. Due to the incomplete crowding, mortality was low (27.9%) in this experimental group. When this figure is compared to the mortality of the other replicates, it should be borne in mind that the crowding density was lower.

The amount of fish caught in experiment 2007C was larger than in any of the other replicates. The catch contained about 200 tonnes of mackerel, and its weight caused the cork line to be drawn below the surface during hauling. This may have further stressed the fish before transfer from the seine to the pens, and thereby raising their mortality, which was 22% in the control and 99% in the crowded group. Only one experiment (2007B) was totally without problems. In this parallel, we found a mortality rate in the control group of only 0.1% after an observation period of almost 5 days, while that of the crowded group was 85%. In spite of all methodological problems, however, there was consistently higher mortality in each experimental group than in the corresponding control groups, showing that crowding has a substantial effect on mackerel survival.

The observation period between the parallels ranged from 2.5 to almost 6 days (Table 1). This variation was not intentional, but was a result of the windy conditions during the experiment period, which prevented termination at predetermined times. The temperature in the upper water layers, where the mackerel schools were swimming before being caught and where the fish were stored during the observation phase, varied between 14.9 and 15.8 °C, which is in the upper range of the thermal preference for mackerel (Mendiola et al., 2006). Since the fish were stored at the same depth interval as their natural swimming depth, temperature is not expected to have had any detrimental effect on survival.

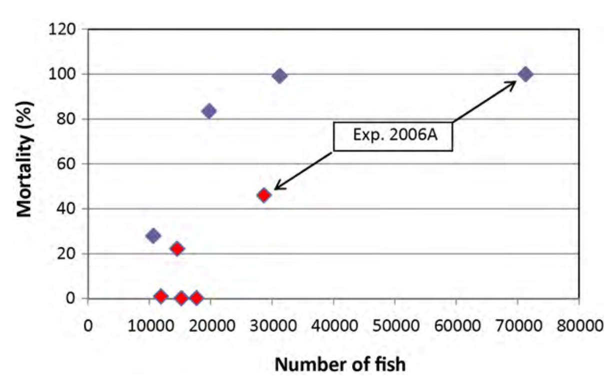

Fig. 3. Mortality as a function of fish density (number of fish in the pen) in the net-pens. Red symbols mark control groups, while blue mark experimental groups. See text for details about experiment 2006A.

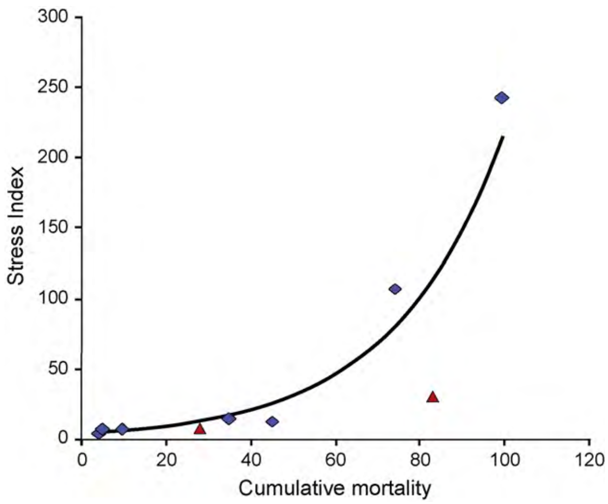

Fig. 4. Stress indices (fish density (kg m^{-1}) times crowding time) from Lockwood et al. (1983) (diamonds) and from our own experiments (triangles). The exponential line is fitted to the data from Lockwood et al.

There was some variation in the number of fish in the different pens. We tried to transfer about 10 tonnes of fish from the seine to each net-pen, but we had no other means of quantifying the biomass of fish swimming through the transfer channel than visual evaluation by an experienced fisherman. This was not an easy task, and when the fish were counted at the termination of the experiments, their numbers ranged from 10,651 to 31,234. There seem to be a tendency for higher fish densities to be related to higher mortality (Fig. 3), but it is also clear that the mortality in the control groups was consistently lower than in experimental groups with similar fish densities. It must also be borne in mind that the number of replicates is low, and that experiment 2006A, which had the highest fish densities and mortality rates, included the groups that were stressed unintentionally hard when the removal of dead fish from the experimental pen also stressed the fish in the attached control pen.

The mean individual weights of the fish from each set, as well as the mean weights and lengths of surviving mackerel from each net-pen were measured (Table 1). Due to their state of decomposition, dead fish were not measured.

The fish density during crowding in experiment 2007B, when the fish exhibited panic behaviour, was estimated to be about 400 fish or 187 kg/m^3. In experiment 2006B, when the fish were not fully crowded, fish density was 67 fish or 31 kg/m^3. The three other experiments were partly confounded by unintended sources of stress, and have therefore not been used for calculations of density. The stress indices derived from these crowding densities and the corresponding crowding times (10 and 15 min) compared to those found by Lockwood et al. (1983) are shown in Fig. 4.

4. Discussion

Our full-scale experiments onboard fishing vessels confirm what has previously been documented in small-scale experiments (Lockwood et al., 1983): that mackerel are extremely sensitive to handling stress, and even moderate handling may produce high mortality. In all five experiments in this study, mortality was significantly higher among fish that had been crowded to a density at which they displayed panic reactions for 10 or 15 min, than among unstressed control fish. Even though the number of replicates was too low (five replicates, of which four gave valid survival estimates) to give a reliable measure of variability, the evidence was clear that the process of pursing and slipping mackerel, as often practised by the purse seine fleet (Marçalo et al., 2007; Stratoudakis and Marçalo, 2002), has a substantial impact on the survival of the fish after release. The arguments for slipping may be that the encircled catch is too large, or that the species mix, size or quality is suboptimal. This practise certainly causes an unknown, but in all likelihood substantial, unaccounted mortality.

Ninety percent of Norwegian catches of mackerel, which have ranged from 120,000 to 185,000 metric tonnes per year during the last decade, is caught by purse seine. No systematic data have been collected on the frequency of slipping, but anecdotal information indicates that crowding and slipping occur frequently on the fishing grounds, particularly when the price differential between size groups is large or schooling densities are high. Norwegian newspapers have often reported that bottom trawlers operating in the same areas as the purse seine fleet, catch dead and decomposed mackerel, and routine ROV inspections along pipelines crossing the mackerel fishing grounds have observed dead mackerel scattered on the bottom. A more thorough understanding of the magnitude of slipping mortality caused by the purse seine fleet will depend on quantitative studies being performed, although these would not be easy.

Our experiments show that the survival of mackerel after crowding and slipping is highly dependent on how they are handled during the capture process. If the fish are kept in the seine for too long, or if they are prevented from swimming freely and synchronously out of the seine, high mortality can be expected. Similar findings were found for another pelagic species, *Sardinops sagax*, after a catch was forced over the headline of a purse seine (Mitchell et al., 2002). This should be taken into account when regulations for purse seine fisheries for pelagic species are being formulated. Reducing the unaccounted mortality caused by slipping will require the development both of methods for the determination of the quantity, size and quality of pelagic fish schools prior to setting, and of net designs that permit the rapid release of any unwanted catch.

Lockwood et al. (1983) observed high mortalities at densities of 130 fish or 30 kg/m^3 or more. This is in line with our density estimates, where a mortality of 28% was found after crowding to 31 kg/m^3, but the duration of crowding is also important for fish mortality, and Lockwood et al. showed that mortality correlated with the product of crowding duration and density (Stress Index). The crowding duration in our trials was set to 15 min in 2006 and 10 min in 2007. This duration was chosen on the basis of video documentation of commercial purse seining provided by the Norwegian coast guard. Our experiments showed that a crowding duration of only 10 min may be fatal to mackerel.

One important factor that affects mortality is fish size (Davis, 2002; Suuronen et al., 1996a). Small fish are usually more sensitive than larger ones; they are more easily fatigued and do not have the same ability to swim rapidly or for long periods of time (Xu et al., 1993; Broadhurst et al., 2006). In our experiments, we have no length or weight measurements of dead fish, only averages from each set after the fish had been transferred to the net-pens, and from live fish at the end of the experiments. If the smallest fish die first after contacts with fishing gears, as has previously been found for other fish species, e.g., herring (*Clupea harengus* L.) (Suuronen et al., 1996a), the mean size of live fish should increase in the crowded groups relative to the mean of the total catch, and should also be higher than in the control groups. The data do not support such a hypothesis, as there were no systematic changes in mean fish size at the end of the experiment. One explanation may be that the size range of the individuals in the mackerel schools caught was too narrow to reveal differences of this sort, and also that the mackerel caught in this experiment were rather large and robust individuals (weight around 500 g).

Gear-induced mortality is not necessarily instantaneous (Wassenberg and Hill, 1993; Sangster et al., 1996). Hours or days may pass from when the fish are damaged until they die, and survival rates may easily be overestimated if the observation period is too short. Due to difficult weather conditions, the observation period in our experiments varied from 2.5 to almost 6 days. Earlier experiments have shown (Lockwood et al., 1983) that most mackerel die within 3 days of exposure to crowding. The mortality levels in our experiments did not seem to be correlated with observation time. However, the lack of standardization in observation time is one argument for supplementing field trials with small-scale experiments, in which factors such as crowding densities and times, daily mortality rates and follow-up time can all be standardized.

The crowding experiments described here were all performed during the hours of daylight, while commercial purse seine fishing for mackerel in the North Sea often takes place at night. The proportion of night capture changes from year to year, depending on the distribution and migration pattern of the fish, among other factors. Traditionally, mackerel change schooling behaviour in a way that makes them more easily available for night capture during the autumn, when they occur in the form of dense shoals at night, producing large catches that increase the risk of having to regulate catches by slipping. During darkness, the schooling behaviour of mackerel is disrupted (Blaxter and Parrish, 1965), i.e. the school disperses in the water and the synchronized orientation vis-à-vis the net disappears. Therefore, it is likely that the fish may be more easily injured by collisions with the net or with other fish during the hours of darkness (Cui et al., 1991) with a risk of an even higher mortality of mackerel that are slipped at night than during the day (Olla et al., 2000). Trawl experiments have indeed shown that the gear-induced mortality may be substantially higher during low light levels than during daylight hours (Suuronen et al., 1995; Olla et al., 1997).

In order to obtain a better understanding of mackerel mortality as a function of crowding time and density, and of the mechanisms that underlie the high mortality, more thorough experiments should be performed. Davis (2002) suggested that the complexity of the task means that the problem of fishery-dependent unaccounted mortality would best be addressed through a combination of laboratory investigations and field experiments under realistic fishing conditions, as has been successfully done with sardine (Marçalo et al., 2006, 2007, 2010). The key stressors can then be studied individually as well as in interaction. A possibly less resource-intensive method of studying gear-induced mortality than the full-scale fishing experiments used today is the reflex impairment method (Davis, 2007; Davis and Ottmar, 2006). Once a relationship between reflex impairment and mortality in controlled experiments has been established, the method can be used to predict mortality during commercial fishing conditions without the costly interventions used in survival experiments today.

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