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Effects of abrupt cold shock on stress responses and recovery in brown trout exhausted by swimming

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To simulate swimming in a trawl, age 3 year brown trout *Salmo trutta* (L.) were made to swim against a flow of $0{\cdot}5\,m\,s^{-1}$ for 60 min. To simulate cold shock, similar to placing them in a chilling tank, the fish were kept for 10 min in a tank containing ice and water. To simulate the combined stressors, the fish were first made to swim followed by a cold shock. The fish were in a comatose state 10 min after cold shock and combined stressors but conscious after swimming only. All the fish survived until the end of the studied recovery period (maximum 24 h). Cold shock after swimming (combined stressors *v.* swimming only) did not produce higher blood cortisol, lactate or glucose concentrations 10 min after the treatment. The effect of cold shock, however, was evident in the delayed start of recovery in cortisol and glucose concentrations. All the stress indicators used decreased to the levels for undisturbed fish within 24 h, except in the case of glucose after the combined stressors.

Key words: by-catch; chilling; *Salmo trutta*; stress; trawl.

INTRODUCTION

The viability of non-target species after trawling has been studied several times previously (Soivio *et al.*, 1991; Turunen *et al.*, 1994; Olla *et al.*, 1997, 1998; Davis & Olla, 2001; Davis *et al.*, 2001). Trawling causes stress to fishes and swimming in a net may affect exhaustion or even mortality, if towing duration is too long and velocity too high depending on the water temperature and the swimming capabilities of the fishes (Soivio *et al.*, 1991; Turunen *et al.*, 1994; Olla *et al.*, 1997). In addition, fishes may be exposed to cold shock if transferred to a tank containing ice and water for chilling that is used to maintain quality of fishes for food. Recent results indicate that live-chilling can prevent some of the negative effects on fillet quality caused by crowding stress at high fish densities before slaughter (Skjervold *et al.*, 2001). Preserving fishes in a mixture of water and ice has recently been used during transport on board boats *e.g.* in Spanish

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anchovy *Engraulis encrasicholus* (L.) fisheries (Careche *et al.*, 2002) and Norwegian cod *Gadus morhua* L. fisheries (Joensen *et al.*, 2000).

Similar chilling has also been used by Finnish freshwater trawlers catching small-sized pelagic coregonids. After hauling the trawl net, fishermen hoist the catch from the surface water and empty it directly into a tank containing ice and water. Immediately afterwards, unwanted, especially undersized (<40 cm total length, L_T in Finland) fishes like lake-run brown trout *Salmo trutta* L. are returned to the lake (Turunen *et al.*, 1994; Jurvelius *et al.*, 2000). The returned fishes are exposed to two rapid changes of temperature: first from the lake to the chilling tank (*c.* 0° C) and then back to the surface water in the lake (1–20° C in boreal lakes, depending on the season).

The optimum temperature range for brown trout is 4–19° C, while the lower critical range is 0–4° C and the upper critical range 19–30° C (Elliott, 1981). In the case, however, when fishes were acclimated and temperature changes were gradual, salmonids have survived at very cold temperatures for quite long periods. In a laboratory, seawater-acclimated brook trout *Salvelinus fontinalis* (Mitchill) have survived for 3 days supercooled at −1·7° C, without contact with ice (Fletcher *et al.*, 1988). When contact with ice was introduced, the lethal freezing temperature was −0·87° C for brook trout and −0·81° C for brown trout (Fletcher *et al.*, 1988). Burka *et al.* (1999) found that a gradual temperature decrease (1° C per day for 5 days) did not cause any obvious stress response in Atlantic salmon *Salmo salar* L. smolts. A rapid temperature decrease (from 10 to 1° C), however, has been observed to cause a significant increase in rainbow trout *Oncorhynchus mykiss* (Walbaum) stress response (Barton & Peter, 1982), and it has been reported that fishes [mainly spot tail shiners *Notropis hudsonius* (Clinton) and pike *Esox lucuis* L.] present in a lake discharge canal died when the temperature accidentally decreased from 21·8 to 4·9° C in 30 min (Ash *et al.*, 1974).

A few recent studies have focused on the effects of cumulative stress due to elevated temperature following simulated trawling (Olla *et al.*, 1998; Davis & Olla, 2001; Davis *et al.*, 2001). The interaction effect of capture and rapid temperature decrease on the stress response of fishes, however, has not been studied. Whether discarded fishes survive after chilling following exhaustion by swimming in a trawl net may be of considerable importance for the fish populations and fisheries.

The purpose of this study was to examine, under laboratory conditions, the effect of additional stress induced by abrupt cold shock on survival, the level of stress response and the recovery time of brown trout that were first exhausted by swimming in a channel that was used to simulate disturbed swimming in a trawl codend. Three treatments: swimming, cold shock and combined stressors (swimming followed by cold shock) were used in the experiment. Changes in plasma cortisol, lactate and glucose concentration were used as stress indicators.

MATERIALS AND METHODS

BROWN TROUT REARING

The brown trout used in the study were age 3 years (Table I). The fish were reared indoors in a 3·5 m^2 fibreglass tank during their first year and outdoors in a 50 m^2 concrete

TABLE I. Mean ± S.D. total length and body temperature of brown trout exposed to cold shock, swimming and combined stressors after five recovery times. The measurements were taken at the same time as the blood sampling. All means are based on five replicates

	Cold shock		Swimming		Combined	
Recovery time (min)	Mean ± S.D. L_T (mm)	Mean ± S.D. body temperature (° C)	Mean ± S.D. L_T (mm)	Mean ± S.D. body temperature (° C)	Mean ± S.D. L_T (mm)	Mean ± S.D. body temperature (° C)
10	340 ± 23	12·4 ± 1·0	326 ± 25	14·4 ± 0·2	342 ± 23	12·2 ± 0·7
20	328 ± 44	13·8 ± 0·4	306 ± 50	14·4 ± 0·2	347 ± 21	13·8 ± 0·2
60	319 ± 26	14·2 ± 0·3	343 ± 11	14·3 ± 0·2	325 ± 27	14·2 ± 0·2
240	329 ± 22	14·4 ± 0·1	324 ± 20	14·5 ± 0·3	347 ± 22	14·5 ± 0·1
1440	355 ± 37	13·8 ± 0·1	344 ± 10	14·0 ± 0·2	340 ± 11	14·0 ± 0·1

pond during the next 2 years, using the standard rearing methods of the Aquaculture Unit of the Finnish Game and Fisheries Research Institute (Det Norske Veritas Quality system certificate no. 2000-HEL-AQ-833, SFS-EN ISO 9001) for fish to be used for stocking. Two weeks before the experiment, 400 fish were randomly sampled and transferred to four indoor 4 m^2 fibreglass holding tanks, 100 individuals to each tank. The fish were fed daily with commercial pellets without a fasting period before the experiment.

EXPERIMENTAL DESIGN

Six fish at a time were selected randomly from one of the four holding tanks (temperature 13·7–14·1° C) using a dip-net. After removing a set of six fish from a holding tank, the remaining fish in this particular tank were allowed 24 h to recover (feeding continued) before the next sampling from this tank, except in three of the 15 cases, when the same holding tank had to be used twice in 1 day with a recovery time of 4 h. No significant differences, however, were found in the measured stress indicators between undisturbed fish from the three sets after 4 h recovery and from the other 12 sets after 24 h recovery (Mann–Whitney *U*-test: cortisol, d.f. = 1, $P = 0{\cdot}885$; lactate d.f. = 1, $P = 0{\cdot}773$; glucose d.f. = 1, $P = 0{\cdot}514$), allowing all 15 sets to be used as equal samples. Previously, Barton *et al.* (1980) have found that gentle netting did not cause stress for the remaining fingerling rainbow trout based on the cortisol concentrations measured.

One fish of the six fish set was killed immediately with a sharp blow on the head to obtain a blood sample from an undisturbed fish. One fish was taken from each of the 15 sets resulting in a group of 15 undisturbed fish without any impact other than lifting by a dip-net from the tank. The remaining five fish from the set were transferred (*c.* 60 s) in a steel tank containing 250 l water (at the same temperature as in the holding tank) to the stressor treatment.

The treatments used in this study simulated different parts of catch handling in a trawler: swimming stressor simulating time in a trawl during a haul, cold shock simulating the time in a chilling tank and combined stressors including swimming followed by cold shock and simulating the whole catch treatment in the trawler. The time inside the trawl net, the swimming speed and the distress during the trawl and catch handling may vary considerably between individual fish. This variation depends, for example, on the time the fish entered the trawl net, the amount of other fish in the net, and the location of the fish in relation to other fish in the net. The time that an unwanted fish spends in the chilling tank before being returned to the lake will also vary due, for example, to the time it takes for it to be found among the other fish in the tank. Despite this real variation that can occur, the swimming and chilling stressors in the experiment were standardized to improve interpretation of the cold shock treatment results.

Towing speed in commercial trawling in Finnish lakes is usually *c.* 0·66–1·39 m s^{-1} and the duration of the trawl *c.* 1–2 h (Turunen *et al.*, 1994; Suuronen *et al.*, 1995; Jurvelius *et al.*, 2000). In the hatchery, swimming stress was induced by forced swimming for 60 min against a flow of 0·5 m s^{-1} (temperature 13·7–14·1° C). This took place in a fibreglass channel 0·4 m wide and 0·6 m long closed using gratings with 12 mm mesh: the channel provided no shelter for the fish. During the treatment, the flow was stopped regularly at 0·5 min intervals for 2 s to disturb the fish and prevent them from resting.

Commercial fishermen usually check their catch in the chilling tank immediately after hoisting it aboard. This is usually done manually using a small dip-net to remove the unwanted fishes, which are then returned to the lake (Jurvelius *et al.*, 2000). In the hatchery, cold shock was induced in a tank containing 100 l of water and ice in equal amounts (temperature 0·2° C). The fish had no shelter in the tank and thus came into contact with the ice. During the cold shock treatment (10 min) the temperature in the chilling tank was monitored and held stable by adding ice if necessary.

Combined stressors were produced by forced swimming followed by a cold shock. Immediately after swimming, the fish were transferred a distance of 10 m in the air by a dip-net (*c.* 10 s) into the chilling tank.

After the stressor treatment, each fish was placed in an individual plastic tube restrainer (60 cm length, 20 cm diameter) closed by 12 mm mesh gratings at both ends and transferred (*c.* 10 s) to a recovery pond (50 m^2 concrete pond, temperature 13·7–14·1° C). The fish were isolated in the restrainers (one fish per restrainer) to ensure identical conditions for all the fish within the recovery period. The method was similar to that previously used by Soivio *et al.* (1975, 1991). All the restrainers were placed in the same recovery pond. By being isolated in this way each fish was sheltered from the disturbance caused by transferring other fish into the pond for recovery or from the pond for blood sampling. For the blood samples, one fish at a time was taken from its restrainer and killed immediately with a sharp blow on the head.

All together the experiment consisted of three levels of stressor (swimming, cold shock and combined stressors) together with five recovery times (10, 20, 60, 240 and 1440 min), resulting in 15 (3×5) combinations. In each combination five replicates were used, resulting in a group of 25 (5×5) fish in each treatment (Table I).

BLOOD SAMPLING AND ANALYSIS

Blood samples were taken from the caudal vessels into preheparinized tuberculin syringes fitted with 21-gauge (0·8 mm diameter) needles. Plasma was separated from the blood sample by centrifugation (3 min at *c.* 10 000 *g*), and frozen and stored in liquid N_2 until analysis. The plasma cortisol levels were measured using a commercial radioimmunoassay kit (Coat-A-Count, Diagnostic Products Corporation). Plasma glucose and lactate concentrations were analysed fluorometrically with a Transcon 102 FN analyser. The body temperature of the fish was measured from the intestine through the anus using a digital thermometer.

The data were subjected to ANOVA with treatment (swimming, cold shock and combined stressors) and the recovery time (10, 20, 60, 240 and 1440 min). *A posteriori* comparisons of means were performed using Tukey's test. Despite slight skewness and variance heterogeneity, the data were analysed on the original scale to ensure clear interpretation of the test results. SAS version 8.02 was used.

RESULTS

SURVIVAL AND BODY TEMPERATURE

All the fish subjected to stress treatment in the experiment ($n = 75$) survived (maximum 24 h) until they were killed for blood samples. In addition, 15 undisturbed fish were killed for blood sampling. The mean ± S.D. temperature of the undisturbed fish (mean ± S.D. $L_T = 336 \pm 12$ mm) was $14{\cdot}1 \pm 0{\cdot}3°$ C. Immediately after the 10 min chilling in the mixture of ice and water (0·2° C), the average body temperature of the fish was $5{\cdot}5 \pm 0{\cdot}9°$ C, and the fish were in a comatose state as evidenced by lack of movement and no reaction to being touched. Within 10 min of recovery after cold shock fish had regained consciousness, and within 20 min of recovery their body temperature had reached the level of the undisturbed fish (Table I). The body temperature of the fish exposed only to swimming (Table I) did not differ from that of the undisturbed fish.

CORTISOL

In the ANOVA, a significant interaction between stressor and recovery time indicated different recovery rates for the plasma cortisol concentration after different stressors (Table II). After swimming and the combined stressors, cortisol was at its highest 10 min after treatment, and no significant difference was

TABLE II. Summary of the ANOVA results on the effects of each treatment (cold shock, swimming and combined stressors) and each recovery time (10, 20, 60, 240 and 1440 min) on brown trout plasma concentrations of cortisol, lactate and glucose

Source of variation	d.f.	MS	*P*
Cortisol ($ng\,ml^{-1}$)			
Stressor	2	18 125	0·064
Recovery time	4	229 353	0·000
Interaction	8	17 753	0·010
Error	60	6306	
Lactate ($mg\,dl^{-1}$)			
Stressor	2	16 295	0·000
Recovery time	4	38 573	0·000
Interaction	8	2133	0·048
Error	60	1006	
Glucose ($mg\,dl^{-1}$)			
Stressor	2	13 152	0·000
Recovery time	4	624	0·436
Interaction	8	1048	0·140
Error	60	650	

found between these two treatments (Fig. 1). Ten minutes after cold shock, however, cortisol was significantly lower than after swimming or the combined stressors (Fig. 1). Twenty minutes after cold shock, the cortisol concentration increased, though not significantly, whereas 20 min after swimming the cortisol concentration had significantly decreased (Table III) and was significantly lower than the concentration observed 20 min after the combined stressors (Table III, and Fig. 1). No difference was found in cortisol between treatments 60 min after exposure or later on up to 24 h after exposure. The plasma cortisol concentration 60 min after all treatments, however, still differed significantly from that of undisturbed fish (Fig. 1). The plasma cortisol concentration in fish after swimming or combined stressors returned to the levels of undisturbed fish within 4 h, and after cold shock within 24 h (Fig. 1).

LACTATE

In the ANOVA, significant differences were found in the concentration of plasma lactate both between treatments and between recovery times, and the interaction term was also significant (Table II). Tukey's test showed significantly lower values 10 and 20 min after cold shock than after swimming or the combined stressors (Fig. 1). Lactate concentrations did not differ between fish exposed to swimming and fish exposed to the combined stressor treatment (Fig. 1). After 60 min and later, lactate in fish exposed to cold shock did not significantly differ from that in fish exposed to the two other treatments (Fig. 1). Lactate concentrations in fish exposed to cold shock or combined stressors decreased significantly 4 h after treatment (Table III) and the concentration returned to the levels of undisturbed fish but in fish exposed to swimming this level was reached only after 24 h (Fig. 1).

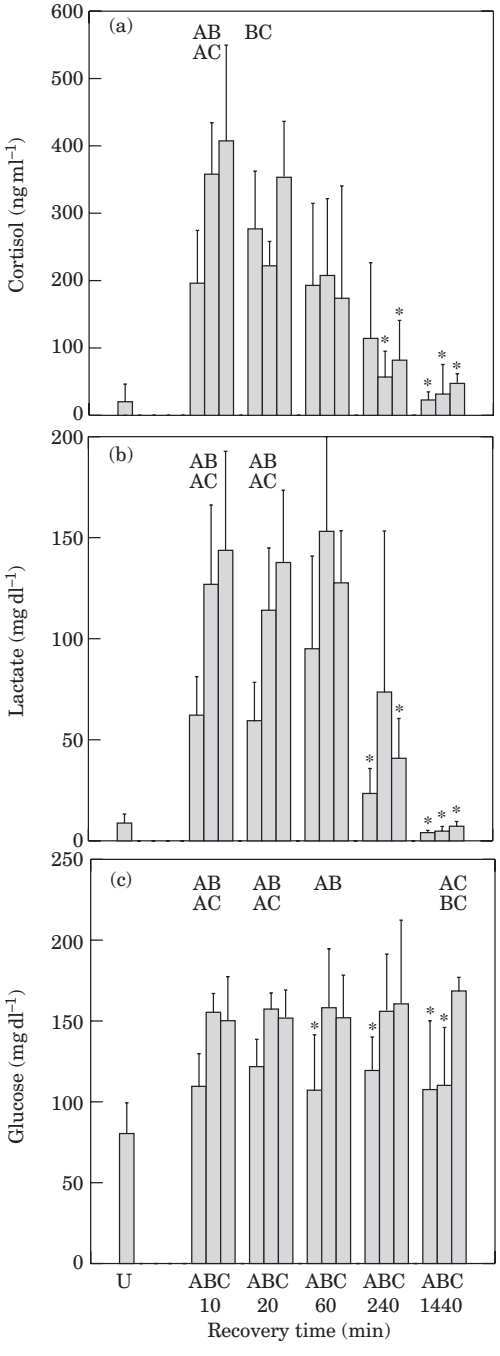

FIG. 1. Mean ± S.D. blood (a) cortisol, (b) lactate and (c) glucose values of brown trout at different recovery times after induced stressors: (A) cold shock, (B) swimming and (C) combined stressors. Significant differences between treatments, obtained using Tukey's test ($P < 0{\cdot}05$), are indicated by letters and are presented above the bars. $n = 25$ for each treatment (five fish at each recovery time), and $n = 15$ for undisturbed fish (U). *, a significant difference ($P < 0{\cdot}05$) was not found between the undisturbed fish and the fish at different recovery times after induced stressors.

TABLE III. Summary of the comparison of mean concentrations of cortisol, lactate and glucose using Tukey's test ($P < 0{\cdot}05$) for recovery after cold shock, swimming and combined stressors (Fig. 1). All means are based on five replicates. Significant differences between recovery times are indicated by letters

		Comparison of means for recovery time (min)				
Stressor	Significant differences of means between recovery times	10 A	20 B	60 C	240 D	1440 E
Cold shock						
Cortisol (ng ml^{-1})	AE, BD, BE, CE	196	277	193	114	23
Lactate (mg dl^{-1})	AE, BE, CD, CE	62	59	95	23	4
Glucose (mg dl^{-1})		110	122	107	119	108
Swimming						
Cortisol (ng ml^{-1})	AB, AC, AD, AE, BD, BE, CD, CE	358	222	208	57	31
Lactate (mg dl^{-1})	AE, BE, CE	127	114	153	74	5
Glucose (mg dl^{-1})	CE	155	157	158	156	110
Combined						
Cortisol (ng ml^{-1})	AC, AD, AE, BC, BD, BE	407	353	174	82	47
Lactate (mg dl^{-1})	AD, AE, BD, BE, CD, CE	144	138	128	41	7
Glucose (mg dl^{-1})		150	152	152	161	169

GLUCOSE

ANOVA indicated significant differences in the concentration of plasma glucose between the treatments, but showed no significant difference between recovery times (Table II). Based on Tukey's test, glucose concentration stayed on a significantly lower level after cold shock than after swimming or combined stressors (Fig. 1). Glucose concentrations in fish exposed only to cold shock decreased to the level of undisturbed fish already 60 min after treatment (Fig. 1), whereas glucose concentration of fish exposed to swimming decreased to the level of undisturbed fish 24 h after treatment (Fig. 1). Regardless of a non-significant ANOVA interaction term between treatment and recovery time, one noteworthy difference was found using Tukey's test: the glucose concentration in fish 24 h after swimming was significantly lower than that in fish 24 h after the combined stressors and the fish exposed to the combined stressors did not start to reduce their glucose levels at all within 24 h (Fig. 1 and Table III).

DISCUSSION

Exposing brown trout to an abrupt cold shock after forced swimming did not lead to mortality within 24 h. Neither did it produce higher blood cortisol, lactate or glucose concentrations 10 min after treatment. It did cause, however,

a temporary comatose state for fish and delayed start of recovery of blood cortisol and glucose levels. This was indicated by the significant difference in levels of stress indicators between fish exposed to swimming and fish exposed to the combined stressors 20 min after treatment in the case of cortisol and 24 h after treatment in the case of glucose.

Both the cold shock and swimming were stressors for the brown trout in this study. The forced swimming, simulating swimming in a trawl, however, caused significantly higher primary (elevation of cortisol) and secondary (elevation of lactate and glucose concentrations) stress responses than cold shock. By forcing the brown trout to swim against a current in the hatchery stress responses comparable with trawled brown trout were obtained (Soivio *et al.*, 1991; Turunen *et al.*, 1994). The handling of the fish with a dip-net caused mild stress response, which could be seen in the slightly elevated cortisol value of undisturbed fish compared with resting values of brown trout given by Barton (2000). The lactate and glucose values of the undisturbed fish, however, were at the same level as in the undisturbed brown trout in the studies of Soivio *et al.* (1991) and Barton (2000).

Stress responses of combined stressed (exposed to swimming following cold shock) fish were not cumulative. Intense handling can cause a rapid increase in stress response to maximal levels, whereas with gentle handling the stress effect can be cumulative (Barton *et al.*, 1980, 1986; Davis *et al.*, 2001). Swimming possibly produced close to maximal stress levels, which allowed cold shock to produce only a minor additional increase in the measured blood chemicals. Chilling may actually decrease the energy responses to stressors (Skjervold *et al.*, 2001). During chilling, the fish in this study were in a comatose state and immobile, suggesting decreased energy metabolism. This may be one reason why it was not possible to show any additional significant increase of measured stress indicators affected by cold shock to fish already exhausted by swimming. There was evidence, however, that cold shock delayed the start of recovery for cortisol and glucose after swimming.

Many enzyme activities are temperature dependent and may affect the recovery time from stress. Thus, recovery of the fish started immediately after swimming, but this was not the case after additional cold shock, as the body temperature took up to 20 min to return to the normal level. The decrease in plasma glucose concentrations was slow after both swimming and the combined stressors. After swimming, the glucose concentration, however, did return to the level of undisturbed fish within 24 h, but this was not the case with fish exposed to the combined stressors, indicating the effect of the cold shock. The slow decrease in the plasma glucose concentration in stressed fish has been observed in earlier studies (Barton *et al.*, 1986; Soivio *et al.*, 1991; Tanck *et al.*, 2000; Staurnes, 2001). In addition, the plasma cortisol concentration 20 min after exposure to the combined stressors was significantly higher than that in fish exposed to swimming, suggesting that cold shock delayed the reduction in cortisol levels. This also agrees with the results for fish exposed only to cold shock, because the highest cortisol values were measured 20 min after treatment.

Even though some evidence of delayed recovery of glucose and cortisol levels due to cold shock were found in this study, these results do not necessarily indicate any damaging effects on the viability of returned fish, for example, on

their immediate ability to avoid predation. Stressed juvenile salmonids have been shown to be more vulnerable to predation than unstressed fishes, but the stressed fishes did regain the ability to avoid predation within 1–1·5 h even though the concentrations of stress indicators were still elevated as a result of the exposure to stressors (Olla & Davis, 1992; Mesa, 1994).

The fish that were transferred to the chilling tank soon stopped moving and were in a comatose state at the end of the 10 min exposure to 0·2° C. The first sample was taken 10 min after chilling, at which time the fish had already regained consciousness even though it took 20 min for the fish to retain internal temperature they had before treatment. If discarded fish were in a comatose state caused by cold shock, they would certainly be vulnerable to predation. Even if the fish was comatose for just a short period, this could be fateful at least for small fish that could be eaten by birds flocking behind the trawlers. Relatively large discarded fish could also be in danger if there were predator fish in the trawling area large enough to ingest discarded comatose fish. In northern regions, pike, burbot *Lota lota* (L.) and pike-perch *Sander lucioperca* (L.) have been found to be important predator species, which may prey on migratory salmonids (Larsson, 1985; Vehanen, 1995; Jepsen *et al.*, 2000), and these species are usually present in lakes where trawling is common in Finland (Vehanen, 1995; Jurvelius *et al.*, 2000).

It has been stated in previous studies (Olla & Davis, 1992; Mesa, 1994) that the condition of the prey may be crucial in its ability to avoid predation. Based on the present results, it is evident that additional stress by chilling will adversely affect the condition of trawl-stressed fish for at least the time it takes the fish to regain consciousness. Because this extends the period which time the discarded fish is vulnerable to predation, it is suggested that unwanted fish should be left to recover in the fishing vessel so that they at least recover consciousness before being released back to the lake. If the fish are to recover successfully, however, they must be treated gently and the extra recovery tank must contain good quality water.

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