THE EFFECT OF LIGHT INTENSITY ON PREDATION OF SOCKEYE SALMON FRY BY PRICKLY SCULPIN AND TORRENT SCULPIN

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Abstract

Recent dramatic declines in sockeye salmon (*Oncorhynchus nerka*) in Lake Washington, WA, have caused considerable alarm among concerned managers, scientists and citizens. Many factors may be involved, however, one possibility is that the increasing incidence of residential and commercial nighttime lighting along the lower portions of the Cedar River, the major sockeye producing tributary of Lake Washington, has led to substantially increased predation on emigrating fry by nocturnal predators. Freshwater sculpins are a major predator of sockeye salmon fry and are also the most abundant predator in the Cedar River. Previous research has shown that sculpin predation on salmon fry is greater under high levels of natural nighttime light (i.e., under moonlight). We tested the hypothesis that above-natural nighttime light levels further increase sculpin predation of sockeye salmon fry.

Light may differentially affect behavior of both sockeye fry and sculpin. Thus, we first tested the ability of sculpin to prey on sockeye fry under six light levels (0.0-1.0 lm/ft^2) in laboratory tanks with minimal water circulation to separate the effect of the migratory behavior of the fry from the ability of sculpin to capture them. The two species of sculpin most abundant in the lower portions of the Cedar River, *Cottus asper* and *C. rhotheus*, were each tested separately in groups of 20 by exposing them to 100 sockeye fry for 40 min. This experiment showed that both species preyed effectively on sockeye fry but surprisingly, that they preyed most effectively in complete darkness, capturing an average of 82 and 87% for *C. asper* and *C. rhotheus*, respectively (N = 6 trials each). As light level was increased, predation rate declined for both species with least predation occurring at the highest light level (42 and 21% for *C. asper* and *C. rhotheus*, respectively). Additional trials at 1.0 lumens/ft^2 with one of the species, *C. rhotheus*, given shorter, longer, and the same duration trials as used in the first experiment, showed that similar numbers of fry were captured regardless of trial duration. This suggested that reduced predation with increased light was likely due to enhanced ability of the fry to detect and avoid sculpin, rather than increased inhibition of sculpin predatory behavior.

We next tested the predation ability of sculpin at four light levels (0.0-0.5 lumens/ft^2) in a pair of artificial streams which simulated more natural conditions. One contained no sculpin and the other *C. asper*. In this environment, fry were released at the upstream end of the streams and successful emigrants were recovered in a trap in the downstream end during the next six hours. Fry were recovered in the trap and counted after 20 minutes, and at 2, 4, and 6 hours. Trials without sculpin showed results consistent with other studies, i.e., the majority of fry passed quickly through the streams under complete darkness but fewer fry emigrated and at a slower rate as light level was increased. The trials with sculpin showed that with increased light even fewer fry emigrated but they did so at a faster rate than did fry in the stream without sculpin. The difference between trials with sculpin and those without indicated that sculpin probably preyed on about 5% under complete darkness and about 45% at the highest light level tested.

Taken together, our results show that sculpin can capture sockeye fry even in complete darkness. They also indicate that under conditions where fry can behave naturally and sculpin are camouflaged against natural substrate, increased light, especially that above natural levels, appears to slow or stop emigration of fry which makes them more vulnerable to capture by sculpin. Existing conditions in the lower Cedar River may mitigate some sculpin predation under higher than natural nighttime light levels. However, artificial lighting should not be ignored as a factor contributing to increased predation by sculpin and other aquatic predators.

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Introduction

The few studies that have examined predation rates on juvenile salmonids under varying light intensities have generally shown that within the natural range of light intensities occurring at night (e.g., from overcast, moonless nights to clear, moonlit nights), predation increases with increasing light (Patten 1971; Ginetz and Larkin 1976; Mace 1983). This has led to the speculation that with the increasing occurrence of high intensity artificial nighttime lighting near waterways through which juvenile salmonids migrate, predation may increase substantially beyond natural levels. Sockeye salmon, *Oncorhynchus nerka,* production has declined dramatically in the Cedar River, Washington, in recent years coincidentally with increased use of residential and industrial lighting. Concerned managers and scientists have considered that increased predation on migrating sockeye fry due to this increased nighttime lighting may be one of numerous possible factors in the decline of Cedar River sockeye salmon.

Field studies have shown that four sculpin species of the genus *Cottus* are the most abundant piscivores in the Cedar River, and also are frequently captured with sockeye salmon fry in their stomachs (Tabor and Chan 1996a, b). Increased light intensity would presumably allow sculpin to better see sockeye salmon fry. However, the sensory mechanism by which cottids are able to effectively capture sockeye salmon fry is not well understood. The importance of vision in locating prey for cottids is not known. Patten (1971) and Mace (1983) speculated that increased predation rates with increased light intensities were due to increased visual acuity of sculpin. The lateral line system and olfaction also appear to be important for cottids to locate their prey. Hoekstra and Janssen (1985) found that blinded mottled sculpin (*C. bairdi*) primarily used their lateral line system to feed on a variety of motile prey. Cottids also appear to use olfaction to detect immobile prey such as salmon eggs (Dittman et al. in press).

Besides the foraging ability of sculpin, changes in light intensity may also alter the behavior of sockeye salmon fry. Increased light intensity may cause sockeye salmon fry to migrate slower and be closer to the bottom and thus become more vulnerable to predation. McDonald (1960) found that the downstream migration of sockeye salmon fry was closely related to light intensity. The nightly downstream migration was initiated after light intensity was < 0.01 lumens/ft^2. This migration was almost completely stopped with the addition of artificial lights (3 lumens/ft^2).

The objective of our study was to determine the effect of light intensity on predation of sockeye salmon fry by two species of sculpin in the Cedar River, prickly sculpin, *Cottus asper*, and torrent sculpin, *C. rhotheus* (Tabor and Chan 1996a). Because sculpins and sockeye fry may alter their behavior in relation to light intensity, and the sensory abilities of one to detect the other may be differentially affected by light intensity, we took a dual experimental approach to answer the question of whether sculpins prey more effectively at light levels generated by standard artificial light sources. We first tested predation rates of sculpin in circular hatchery tanks with minimal water flow to separate the effect of changes in the migratory behavior of fry from the ability of sculpin to prey on them. To assess the effect of light intensity on sockeye salmon fry behavior, a second experiment was done in artificial streams under more natural conditions which allowed fry to migrate downstream.

Experimental Design and Methods

During May-June 1997, experiments were conducted at the Northwest Biological Science Center, U.S. Geological Survey. Prickly and torrent sculpin were collected from the Cedar River and Lake Washington by electrofishing and transported to the lab, where they were kept in circular holding tanks. Lengths ranged from 74-103 mm TL for prickly sculpin and from 74-98 mm TL for torrent sculpin. Sockeye salmon fry were obtained periodically from the Washington Department of Fish and Wildlife fry enumeration trap located near the mouth of the Cedar River. Fry were presumably both migration- and predator-experienced. Fry were transported back to the lab were they were also held in circular holding tanks. After collection, a subset of 30 fish from each batch of fry was measured for average total length. Fry were fed commercial fry food daily throughout the experimental period. Sculpin were fed available salmonid fry prior to the experiment. Sculpin were divided into three size classes: large (90-99 mm TL), medium (80-89 mm), and small (70-79 mm).

Light intensity levels used in the experiments represent a range of levels observed from field measurements in the lower Cedar River. All light intensity measurements were made with an International Light Inc. model IL1400A radiometer/photometer. Light intensity was measured as lumens/ft^2. The light source consisted of one or two strings of small ornamental lights (small clear Christmas tree lights) taped to the underside of lids for the tanks and artificial streams. Lights were suspended directly above the water. Each light string was connected to an outlet box and a dimmer switch. Predation trials in both experiments were run during daylight hours. Testing environments were covered with layers of black sheeting to exclude all light except that produced by our artificial light source.

Circular tank experiments.-- Because both sculpins and sockeye fry may alter their behavior in relation to light intensity, we took a dual experimental approach to better understand the change in behavior of both predator and prey. We first tested predation rates of sculpins in circular hatchery tanks with minimal water flow. The purpose of this experiment was to separate the effect of changes in the migratory behavior of fry in relation to light from the ability and motivation of sculpins to prey on them. The second set of experiments was done in artificial streams to simulate natural conditions. The sockeye fry released upstream in each trial could behave more naturally in this environment in relation to our treatment light levels, i.e., they could migrate quickly through the artificial stream or they could delay their passage by stationing in eddies or burying in the gravel substrate. We compared the number of fry recovered at timed intervals from a trap in the downstream end of each of two artificial streams which were identical except that one stream contained sculpin and one did not.

The tank experiments were conducted in 1.2 m-diameter circular tanks. Water depth averaged 30 cm. Throughout the study, water temperature in the tanks was maintained at approximately 12˚C. We tested six light intensities (0.000, 0.003, 0.006, 0.010. 0.100, 1.000 lumens/ft^2) during the predation experiments. Prior to each experimental trial, the light level was randomly selected and measured in each of the three replicate tanks. Three large, nine medium, and eight small sculpin were randomly selected for each predation trial from holding bins of each size class. We used single-species groups of 20 sculpin and 100 fry in each trial. Six replicates for each light intensity level were done for both prickly sculpin and torrent sculpin. The fry were given 15 minutes to adjust to the experimental setup prior to the addition of the sculpin. The sculpin were provided with two black Plexiglas shelves within each tank to serve as a refuge/hiding place during the experiments. Upon addition of the sculpin, each trial lasted 40 minutes. The addition and removal of both fry and sculpin were staggered to facilitate collection of all fish with a small aquarium net and flashlight. The predation rate was determined as the number of sockeye salmon fry lost during the experiment. Prickly and torrent sculpin were utilized on alternate days in order to allow adequate digestion time between trials. The stomach contents of three replicate groups of sculpins from both the 0.000 and 1.000 lumen/ft^2 light intensities were removed by gastric lavage in order to establish whether predation rates differed with sculpin size and to confirm digestion of previously consumed fry. Results of the light intensity experiment were analyzed with one-way analysis of variance (ANOVA) tests and post-hoc Tukey's Honestly Significant Difference (HSD) tests.

Six additional experimental trials were done to determine if more time is necessary for sculpin to 'settle down' and initiate predatory behavior at the highest level of light intensity (1.0 lumens/ft^2). These trials were only done with torrent sculpin. Two replicates of 20-, 40-, and 60-minute trials were conducted. Three other experimental trials were conducted to determine if additional fry would be consumed if 200 fry were added instead of 100 fry. In these trials we used prickly sculpin and the lowest light intensity level (0.000 lumens/ft^2).

Artificial stream experiments.-- Sockeye salmon fry migration/behavior experiments were done in two identical artificial streams. Each stream is 9 m long by 1.5 m wide and contained within a fiberglass trough. We only used a 3 m section of each stream in order to allow enough space downstream for a fish trap to collect the fry. Each experimental section consisted of a 2.5 m long pool and a short riffle section. Riffles had a 2% gradient with a water depth of 18 cm. The maximum depth of each pool was approximately 75 cm. Surface velocities ranged from 0.37 m/s near the inflow to 0.12 m/s at the outflow. Near the bottom of each pool the water velocity was negligible. The light level was measured approximately 10 cm below the surface of the water in both streams. One hundred and twenty five fry were released at the upstream end of each experimental section and allowed to move downstream. The fry traps were checked with a flashlight at 20 minutes, and at 2, 4, and 6 hours; the fry were then removed with a small aquarium net and counted. After six hours, all lights were turned off and the fry given 12-16 hours (over night) to migrate through the streams to the trap. We did not collect the remaining fry. Preliminary work indicated that the fry were extremely difficult to capture in the artificial streams. In non-predator trials, the number of fry not accounted for by the beginning of the next trial was added to the number of fry released (125) at the start of the next trial. Consequently, the results are presented as a cumulative percent of the total fry in each stream which migrated downstream to the fry trap within the trial periods. In the predator trials, we assumed that the fry not accounted for were all consumed by sculpin. Because very few fry migrated overnight in the predator trials when the streams were darkened, this appeared to be a valid assumption. For the predator trials, twenty prickly sculpin were placed in the artificial stream. These sculpin remained in the stream throughout the duration of the experiment. Trials occurred once every 2-3 days to allow the sculpin enough time to digest fry from the previous trial.

The artificial stream trials were conducted in two parts. The first part occurred with no predators present. Two replicates of three light intensities (0.000, 0.100, and 0.500 lumens/ft^2) each were tested . In the second part, predators were present in one stream and absent in the other. Two replicates of four light intensities (0.000, 0.020, 0.100, and 0.500 lumens/ft^2) each were tested. We were unable to evaluate additional light levels due to time and fry supply limitations.

Results

Circular tank experiments.-- Prickly sculpin and torrent sculpin displayed similar predation abilities with respect to increasing experimental light intensity. Both species captured greater mean numbers of fry under low light conditions than under the highest light level (Figure 1). Prickly sculpin captured a mean of 82.3 fry (SD = 7.4) at 0.000 lumens/ft^2, whereas they captured a mean of 41.5 fry (SD = 8.7) at 1.0 lumens/ft^2. Torrent sculpin captured a mean of 86.8 fry (SD = 5.3) at 0.000 lumens/ft^2 and a mean of 21.3 fry (SD = 8.3) at 1.0 lumens/ft^2. A separate one-way ANOVA was performed on untransformed data of number of fry eaten for the two sculpin species. The ANOVA indicated a significant difference among the six light levels for both species. The results from a post-hoc Tukey HSD test for prickly sculpin showed no difference in fry consumption among light levels 1-5 but substantially and significantly lower fry consumption at 6, the highest light level, compared to the other five (Figure 1). The same test for the torrent sculpin indicated more differences among the six light levels. As with the prickly sculpin, treatments 1-5 all differed from 6. In addition, all non-adjacent means differed significantly from each other ($p < 0.05$). Adjacent means did not differ significantly (e.g., 1&2, 2&4, 4&3, 3&5). Overall, it is clear from this experiment that sculpin of both species can be highly effective predators in complete or near complete darkness and increased ambient light does not necessarily enhance their ability to prey on sockeye fry.

Comparison of counts of fry found in stomach samples and those determined from the number of fry missing from live fry counts indicated there was usually some small error in our counts. Only one of the 12 counts were in agreement. However, 10 of the 12 counts compared were within two fry of each other. One count was off by three fry and the other was off by six fry. The error in the counts would probably be due to: 1) miscounting the number of fry that are added or recovered from the tanks; 2) overlooking fry at the end of each trial; and/or 3) gastric flushing was < 100% and some fry remained in the stomachs. Nine of the twelve trials had more fry found in the stomach samples than was determined from live fry counts, which would indicate that one or two extra fry were often used in each trial. This seems reasonable because sockeye salmon fry are quite small. However, the error associated with our counting was quite small and we don't believe it affected the results.

Gastric flushing of three replicate trials of 20 sculpins each (total, 60 sculpin per species) from the 0.000 and 1.000 lumens/ft^2 trials verified that both prickly sculpin and torrent sculpin consumed more sockeye salmon fry at the lowest light intensity than at the highest light intensity. Ninety-five percent of the prickly sculpin had consumed at least one fry at 0.000 lumens/ft^2, while 87% consumed fry at 1.000 lumens/ft^2 (Figure 2). Thirty-eight percent of the prickly sculpin had consumed more than 4 fry at 0.000 lumens/ft^2 , whereas only 5% had consumed more than 4 fry at 1.000 lumens/ft^2. The maximum number consumed by a prickly sculpin was 9 fry (0.000 lumens/ft^2). Ninety-two percent of the torrent sculpin had consumed at least one fry at 0.000 lumens/ft^2, while only 68% consumed fry at 1.000 lumens/ft^2 (Figure 2). Fifty -two percent of the torrent sculpin had consumed more than 4 fry at 0.000 lumens/ft^2 , whereas only 7% had consumed more than 4 fry at 1.000 lumens/ft^2. The maximum number consumed by a torrent sculpin was 12 fry (0.000 lumens/ft^2).

At the highest light intensity, 1.000 lumens/ft^2, large prickly sculpin (N = 9) consumed a mean of 3.1 fry (SD = 1.8) while medium (N = 27) and small (N = 24) prickly sculpin consumed a mean of 1.9 fry (SD = 1.4) and 1.6 fry (SD = 0.9), respectively. In contrast, fry consumption was more evenly distributed among the prickly sculpin size classes in complete darkness. Both large and medium prickly sculpin consumed similar numbers of fry, 4.3 fry (SD = 2.4) for large prickly sculpin and 4.7 fry (SD = 2.4) for mediums. Small prickly sculpin consumed a mean of 2.9 fry (SD = 1.9) at the lowest light intensity.

Differences in size seemed to have less effect on the predation rate of torrent sculpin at the highest light intensity, 1.0 lumens/ft^2. Large torrent sculpin consumed a mean of 1.8 fry (SD = 1.5) while the medium and small torrent sculpin consumed a mean of 1.3 fry (SD = 1.6) and 1.3 fry (SD = 1.1), respectively. Consumption of fry by torrent sculpin was also more evenly distributed among the size classes at the lowest light intensity. Large torrent sculpin consumed a mean of 4.2 fry (SD = 2.9) while medium and small torrents consumed a mean of 5.4 fry (SD = 2.9) and 3.6 fry (SD = 2.5), respectively.

An experiment with different groups of torrent sculpin given either 20, 40, or 60 minutes (1.0 lumens/ft^2) to prey on 100 fry indicated most predation occurs in the first 20 minutes (Figure 3). A similar and low number of fry were captured in all trials regardless of duration, suggesting that sculpin quickly captured vulnerable fry and then were unable to catch the others. This result, and our observations of the willingness of sculpin to attack fry even under brightly lit conditions, indicate that fry are better able to avoid sculpin with increased light. Results also indicate that sculpin need little time to 'settle down' and initiate predatory behavior.

An additional experiment to look at predation rates of prickly sculpin given 200 fry (0.000 lumens/ft^2) indicated they were capable of consuming an excess of 100 fry. An average of 123.3 fry (SD = 12.9; Figure 4) were consumed for the three trials. Sixty-two percent of the fry were consumed, whereas in earlier trials of the same sculpin species and light intensity, 82% of the fry were consumed. In earlier trials that had few remaining fry, there may have been a depletion effect. When fry numbers are reduced to just a few individuals, sculpin may have difficulty locating and capturing fry. Differences between some light intensity levels may be difficult to detect if 100 fry and 20 sculpin are used.

Artificial stream experiments.-- The first set of experimental trials was conducted without any predators present. Two replicates of three light intensity levels each were done. Sockeye salmon fry migrated through the stream at faster rate under complete darkness (0.000 lumens/ft^2) than at the other two light intensity levels (0.100 and 0.500 lumens/ft^2). Under complete darkness, 74% (SD = 4.5%) of the fry migrated downstream within the first twenty minutes of the trials, while only an additional 25% migrated downstream over the course of the next 24 hours (Figure 5). In contrast, under the greatest light intensity, 34% (SD = 7.8%) of the fry migrated downstream within the first twenty minutes while an additional 52% migrated downstream over the course of the next 24 hours. Trials conducted at the intermediate light intensity of 0.100 lumens/ft^2 provided results similar to those at 0.500 lumens/ft^2. During the first twenty minutes, 32% (SD = 8.6%) of the fry migrated downstream while an additional 56% migrated downstream over the course of the next 24 hours.

The second set of experimental trials was conducted with sculpin present in one stream and not in the other. Predation/emigration trials showed several strong patterns even with only two trials completed at each of four light levels (Figure 6). First, similarly to earlier trials, fry readily emigrated through the artificial streams under complete darkness but increasingly delayed passage as light level increased. Second, a greater proportion of the fry emigrated faster through the stream in all non-dark trials when sculpin were present. Third, and most crucial, a greater proportion of fry were never recovered in the stream trials with sculpin and this proportion related directly to light level (Table 1). At the highest light level tested (0.5 lumens/ft^2), an average of 55% fry were not accounted for. If the average number of fry unaccounted for in all trials without sculpin (10%) is subtracted from this value, then about 45% of the fry were likely preyed upon by sculpin. At 0.020 lumens/ft^2, the light level approximating that along the urbanized sections of the Cedar River, about 28% of the fry became prey. Only about 5% were likely prey to the sculpin in the dark trials. Our results consistently indicated that fry not recovered in the first two hours of a trial with sculpin were never recovered.

Discussion

Results of the tank experiments indicated that prickly sculpin and torrent sculpin were able to forage effectively in complete darkness. Thus sculpin must use some other sensory mechanism besides vision. Most likely sculpin used their lateral line system to detect the movements of fry. Hoekstra and Janssen (1985) demonstrated that mottled sculpin (*C. bairdi*) were able to feed on mobile prey with just their lateral line system. Night snorkeling observations of sculpin in the Cedar River, also indicated that sculpin seem to react to movements of fry. In Elliot spawning channel and Cavanaugh Pond, fry were often quite numerous yet sculpin did not appear to pursue fry if they were motionless. However, when the fry were startled by the light and darted away, sculpin would become very active and strike at moving fry.

Differences in predation between light intensity levels of the tank experiment may not reflect changes in the foraging ability of sculpin but rather the ability of fry to avoid them. At higher light levels, fry may have been better able to see approaching sculpin and more effective in avoiding them. Additionally, fry may also have formed schools at higher light intensity levels and thus sculpin may have had more difficulty in pinpointing individual fry to consume. Schooling has been shown to be related to light for several freshwater species (Emery 1973).

In the tank experiments, we were unable to detect differences between most light levels. However, this may have been due to a depletion effect. As fry numbers are reduced to just a few individuals, the behavior of fry and sculpin can be altered. Locating prey at low densities may be difficult for sculpin. Additional trials done with 200 fry instead of 100, indicated 20 prickly sculpin were able to consume an excess of 100 fry. A prey to predator ratio of 10:1 would probably have been better than the 5:1 ratio we used. Differences between some light intensity levels may be difficult to detect if a 5:1 ratio is used. In designing the experiments, we underestimated the capabilities of the sculpin to prey on sockeye salmon fry. Ideally prey need to be replaced as they are consumed so the density does not change (Petersen and Gadomski 1996). However, we felt this was impractical in our experiment. We had hoped that at least 40-50% of the fry would be remaining at the end of each trial. We were better able to detect differences between light levels in torrent sculpin trials, possibly because torrent sculpin consumption rates were lower than prickly sculpin. Thus, the density of fry did not change as dramatically as in the prickly sculpin trials.

Overall consumption rates of fry by torrent sculpin were lower than prickly sculpin. The smaller mean size of the torrent sculpin probably best explains the differences. If increasing light does enhance the ability of sockeye fry to escape predation by the sculpin as we suggested above, then smaller body size correlated with reduced swimming ability would explain the reduced consumption by torrent sculpin. Torrent sculpin may also be more behaviorally inhibited at the higher light levels than prickly sculpin and take more time to adjust and 'settle down'. However, our experiment with different groups of torrent sculpin given either 20, 40, or 60 minutes to prey on 100 fry showed that there was no increase in fry consumed beyond the 20-

minute trial length. Thus, torrent sculpin appeared to adjust quickly to the tank conditions. The relative ability of torrent and prickly sculpin to prey on salmonids is unknown. However, torrent sculpin predation rates did appear to be lower than that of prickly sculpin at the highest light intensity level (1.000 lumens/ft^2). For example, only 68% of the torrent sculpin consumed any fry, whereas 87% of the prickly sculpin consumed fry at that light level. Both are capable of consuming large numbers of sockeye salmon fry in some situations (Tabor and Chan 1996a,b). Northcote (1954) found that both species are highly piscivorous at sizes > 70 mm TL. Differences in the consumption of salmonids may have more to do with habitat selection and prey availability than differences between the species. Prickly sculpin do, however, grow to a much larger size than torrent sculpin. The maximum size observed in the Lake Washington system is 239 mm TL for prickly sculpin and 155 mm TL for torrent sculpin. However, large prickly sculpin rarely consume salmonids, instead they usually prey on benthic fishes and crayfish (Tabor and Chan 1996a,b).

Earlier research on the effects of light intensity on sculpin predation (Patten 1971; Mace 1983) was conducted under different conditions than our study and thus the results are difficult to apply to our research. The authors speculated that increased predation rates with increased light intensities were due to increased visual acuity of sculpin. Both studies were conducted in flow-through systems and the fry were not allowed to outmigrate. Additionally, both studies were done with different salmonid prey (chum salmon, *O. keta,* and coho salmon, *O. kisutch*, fry) and the study of Mace (1983) focused on predation by staghorn sculpin. These predators and prey may behave differently then the fish that we used. Sockeye salmon fry and different salmon species may behave differently under varying light conditions (Ali 1959).

Experiments of Patten (1971) and Mace (1983) were also done in field enclosures and, because of large variations in environmental conditions, their work may have had biased results. First, the results of Patten (1971) confounded potential effects of light intensity with water temperature. Results showed greater predation on coho salmon fry during moonlit nights compared to moonless nights but the former trials occurred at higher water temperatures (8.5 vs 5.5 C) and this alone may have accounted for the increased predation observed during brighter nights. In addition, changes in spawning behavior of torrent sculpin could also have biased the results. Experiments of Mace (1983) were done in an estuary. Throughout the experiments, the tidal level changed, which caused changes in water depth, flow, and possibly turbidity.

Although increased light intensities did not improve the foraging ability of sculpin, it did have a pronounced effect on the movement of sockeye salmon fry. Sockeye fry moved through experimental streams at a faster rate under complete darkness than under bright lights. Increased ambient light appears to inhibit the migratory movement of the fry. McDonald (1960) found that the nightly movement of sockeye salmon fry was not initiated until light intensity was <0.01 lumens/ft^2. The author was able to experimentally stop the nightly movement with artificial lighting of 3.0 lumens/ft^2. Other levels of light intensity levels were not tested. Fraser et al. (1994) found that the movement of Atlantic salmon fry (*Salmo salar*) away from their redds did not differ between 0.0 and 0.7 lumens/ft^2. However, at 2.0 lumens/ft^2, movements were significantly reduced. In our experiments, we were able to detect differences as low as 0.020 lumens/ft^2.

The presence of sculpin also appeared to influence the movement of sockeye salmon fry. A greater proportion of the fry emigrated faster through the stream in all non-dark trials when sculpin were present. This result has also been reported in another experimental study of sockeye salmon fry with rainbow trout predators (*O. mykiss*; Ginetz & Larkin 1976). Increased downstream movement due the presence of predators has also been found in brown trout fry (*S. trutta*; Gaudin and Caillere 1985; Bardonnet and Heland 1994).

We used sculpins for our experiments because they are an abundant predator in the Cedar River, they are easy to collect, and they adjust readily to laboratory conditions. Other predators of sockeye salmon fry in the Cedar River include cutthroat trout (*O. clarki*), rainbow trout (including juvenile steelhead), juvenile coho salmon (Tabor and Chan 1996a), and potentially some species of birds. These predators are primarily visual predators and thus the effect of light intensity may be more pronounced when these predators are present. Unlike sculpin, they may forage more effectively at higher light intensity levels.

The importance of increased light intensity on sockeye salmon fry survival in the lower Cedar River is unclear. The greatest nighttime light intensity levels occur in the lower four kilometers, as the river flows through the city of Renton. Light intensity levels as high as 1.45 lumens/ft^2 have been recorded in this stretch of river. However, most light intensity levels appear to be between 0.010 and 0.020 lumens/ft^2. Under current conditions in the lower 3 km, the only area where predators appear to be abundant is along the shoreline. The substrate of most of the lower 3 km is gravel which appears to support few sculpin that are large enough to consume sockeye salmon fry. Further upstream, where large gravel and cobble are present, larger sculpin are substantially more abundant. Additionally, most of this river stretch is riffle (high velocity) type habitat with few areas of low-velocity habitat (side channels and pools). Most predation of fry appears to occur in low-velocity areas. Increased light intensity levels may cause fry to be delayed and move to areas of lower water velocities where they are more vulnerable to predators. This may be particularly important during periods of low discharge. A recently proposed flood control project in the lower Cedar River would reduce velocities in much of the lower 1.5 kilometers. Under these conditions, artificial lighting may be more of a factor in fry survival. However, because predation of sockeye salmon fry is also influenced by other factors, such as discharge, depth, and habitat complexity, it will be difficult to ascertain the overall importance of increased light intensity. It does appear that reducing artificial light would benefit sockeye salmon. Of course, any reduction of lighting must be balanced with safety and other concerns.

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Table 1. Percentage of sockeye salmon fry not recovered from emigration trials in the artificial streams in the presence or absence of prickly sculpin under different light intensities.

	Percent Fry Not Recovered (SD)			
Light Level (lumens/ft^2)	Sculpin Absent	Sculpin Present	Estimated % Eaten *	N Trials
0.00	8.1 (2.2)	15.2 (2.3)	5.2	2
0.02	13.4 (--)	38.4 (--)	28.4	1
0.10	10.0 (1.7)	34.0 (6.2)	24.0	2
0.50	8.5 (1.5)	55.2 (13.6)	45.2	2

* Note: Estimate derived by subtracting the mean percent fry not recovered from the trials with no sculpin (mean = 10.0%) from each mean of percent fry not recovered with sculpin present.

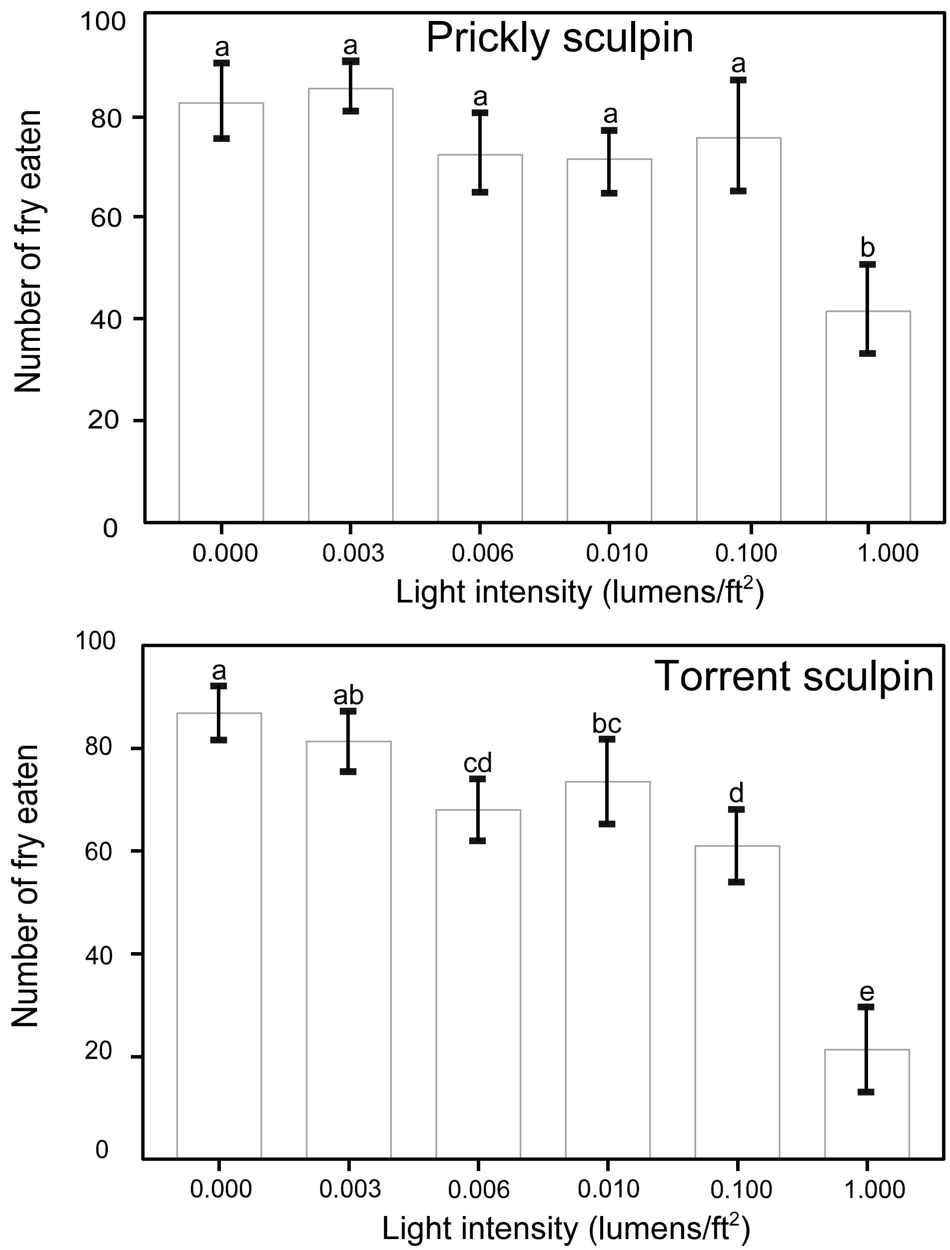

Figure 1. Number of sockeye salmon fry eaten by prickly sculpin and torrent sculpin in 40 min trials in circular tanks at different light intensities. Each bar is the mean of 6 trials. Error bars represent the standard deviation. Groups of bars with different letters are significantly different (ANOVA and Tukey HSD: P<0.05).

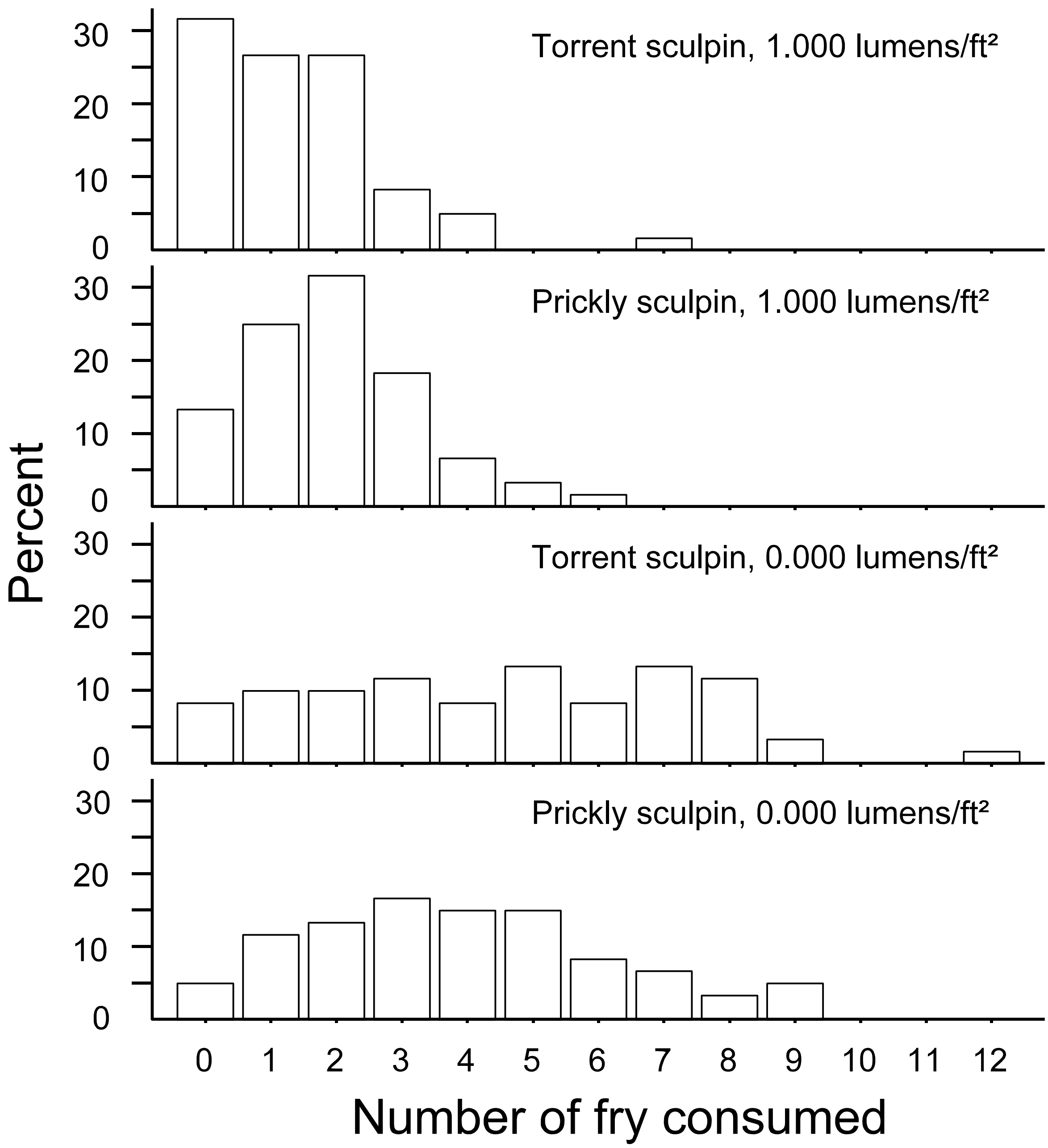

Figure 2. Frequency of occurrence (percent) of the number of sockeye salmon fry consumed by prickly sculpin and torrent sculpin in circular tanks at two light intensity levels. Numbers for each graph are based on a total of 60 sculpin from three replicates (20 sculpin each).

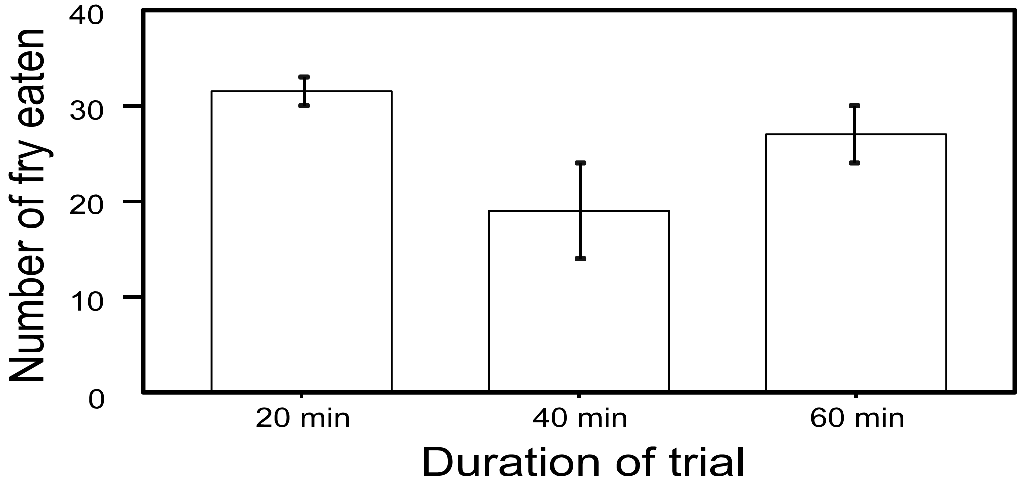

Figure 3. Mean number of sockeye salmon fry eaten by torrent sculpin in circular tank trials of different duration. Numbers are based on two replicates. Trials were all done with 100 fry and 20 sculpin; light intensity was 1.000 lumens/ft². Error bars represent the range of observations.

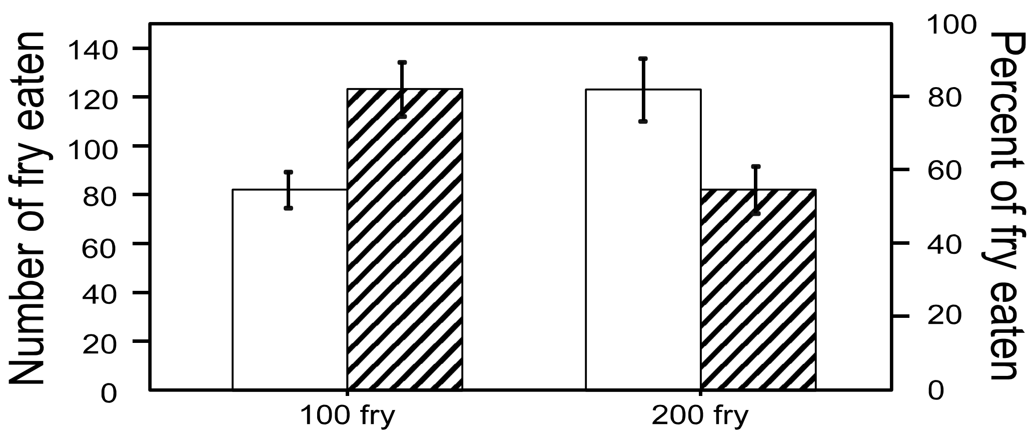

Figure 4. Mean number (shaded bars) and percent (hashed bars) of sockeye salmon fry eaten by prickly sculpin in circular tank trials of two densities of fry. Numbers for 100 fry density are based on six replicates and 200 fry density are based on three replicates. Trials were all done with 20 sculpin and light intensity of 0.000 lumens/ft². Error bars represent the standard deviation.

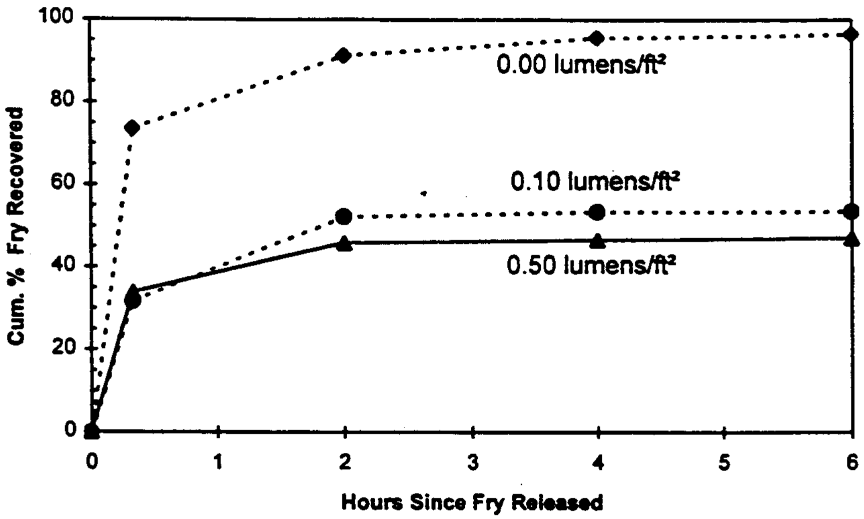

Figure 5. Cumulative percent of total sockeye salmon fry recovered after release in the artificial streams for three light intensity levels (lumens/ft^2), May 24-29, 1997. Each line is the mean of two trials. All trials were done in the absence of predators.

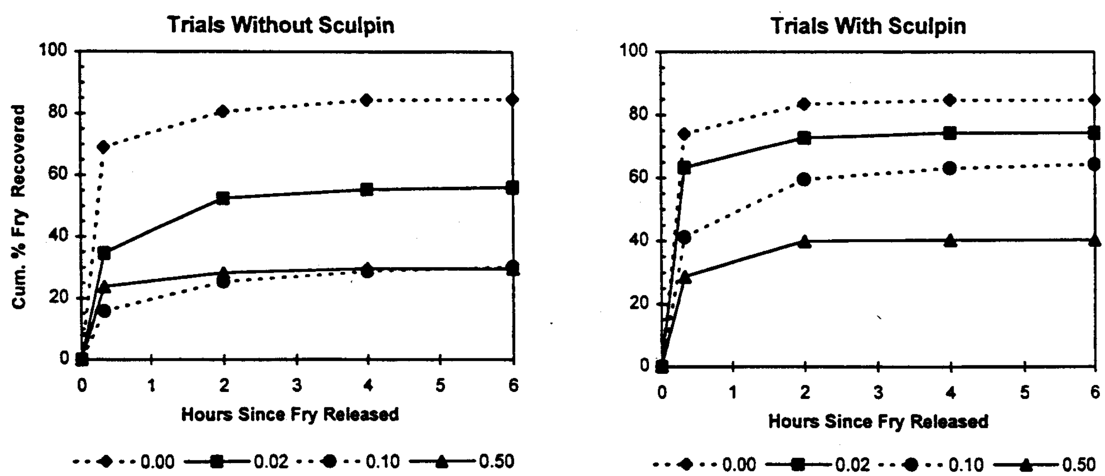

Figure 6. Cumulative percent of total sockeye salmon fry recovered after release in the artificial streams, June 4-23, 1997. Each line is the mean of 2 trials. The left and right panels show the results for trials when fry emigrated in the absence or presence of prickly sculpin, respectively. Trials were conducted at 4 light intensities shown below each panel in lumens/ft^2.