Powering forward. Together.

SMUD™

October 21, 2014

Dana Mahaffey, Associate Planner
City of Sacramento Community Development Department
300 Richards Blvd., Third Floor, Sacramento, CA 95811
DMahaffey@cityofsacramento.org

Subject: Notice of Preparation of an Environmental Impact Report for the I Street Bridge Replacement Project

Dear Ms. Mahaffey,

The Sacramento Municipal Utility District (SMUD) appreciates the opportunity to provide comments on the Notice of Preparation (NOP) of an Environmental Impact Report for the I Street Bridge Replacement Project. SMUD is the primary energy provider for Sacramento County and the proposed project location. SMUD's vision is to empower our customers with solutions and options that increase energy efficiency, protect the environment, reduce global warming, and lower the cost to serve our region. As a Responsible Agency, SMUD aims to ensure that the proposed project limits the potential for significant environmental effects on SMUD facilities, employees, and customers.

It is our desire that the I Street Bridge Replacement Project will acknowledge any project impacts related to the following:

- Overhead and or underground transmission and distribution line easements
- Electrical load needs/ requirements
- Energy Efficiency
- Utility line routing
- Climate Change

SMUD would like to be involved in discussing these issues as early as possible. We aim to be partners in the efficient and sustainable delivery of the proposed project. Please ensure that the information included in this response is conveyed to the project planners and the appropriate project proponents.

Environmental leadership is a core value of SMUD and we look forward to collaborating with you on this project. Again, we appreciate the opportunity to provide input on the NOP. If you have any questions regarding this letter, please contact Rob Ferrera, SMUD Environmental Specialist at (916) 732-6676.

Sincerely,

Rob Ferrera
Environmental Specialist
Environmental Management
Legislative & Regulatory Affairs
Sacramento Municipal Utility District

Cc: Pat Durham
Beth Tincher
Steve Johns
Joseph Schofield

SACRAMENTO METROPOLITAN
AIR QUALITY
MANAGEMENT DISTRICT

Larry Greene
AIR POLLUTION CONTROL OFFICER

October 9, 2014

Dana Mahaffey, Associate Planner
City of Sacramento Community Development Department
300 Richards Blvd, Third Floor
Sacramento CA 95811
DMahaffey@cityofsacramento.org

RE: I Street Bridge Replacement Project (SAC201401517)

Ms. Mahaffey,

The Sacramento Metropolitan Air Quality Management District (The District) thanks the City of Sacramento for the opportunity to comment on the proposed project to replace the I Street Bridge with a multi-modal facility. The District is required by law to "represent the citizens of the Sacramento district in influencing the decisions of other public and private agencies whose actions may have an adverse impact on air quality within the Sacramento district."[1] We offer our comments in that spirit.

Construction Emissions

Construction of the project may result in significant emissions of criteria pollutants and precursors of primary concern. These emissions should be discussed, quantified, and disclosed in the manner described in Chapter 3 of the District's "CEQA Guide to Air Quality Assessment."[2] Should the project exceed District thresholds, we recommend that construction mitigation be adopted as part of the mitigation monitoring and reporting plan (Attachment).

With respect to greenhouse gas emissions generated from the construction of the project, these emissions should be discussed, quantified, and disclosed in the manner described in Chapter 6 of the District's "CEQA Guide to Air Quality Assessment." Per the guidance, the District recommends that GHG emissions be minimized during the construction phase utilizing the District's "Guidance for Construction GHG Emissions Reductions."[3]

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[1] California Health and Safety Code §40961
[2] http://www.airquality.org/ceqa/ceqaguideupdate.shtml
[3] http://www.airquality.org/ceqa/cequguideupdate/Ch6ConstructionMitMeasures.pdf

Consistency with existing Air Quality Management Plan

A portion of the project is located within the Railyards Specific Plan, which has construction mitigation and an operational air quality mitigation plan. All activity within the Railyards Specific Plan must be consistent with this mitigation, including paying the per acre fee on all land disturbed and the emission reduction requirements outlined in the mitigation monitoring and reporting plan.

Greenhouse Gas Emissions

Operation of the project may result in an increase in Greenhouse Gas emissions. These emissions should be discussed, quantified, and disclosed in the manner described in Chapter 6 of the District's "CEQA Guide to Air Quality Assessment." The proponents should also discuss the project's consistency with existing Greenhouse Gas reduction plans, such as the Metropolitan Transportation Plan/Sustainable Communities Strategy, the California Air Resources Board Scoping Plan and the City of Sacramento Climate Action Plan.

General comments

To summarize, the District requests that the City consider construction and operational emissions, and ensure compliance with the Railyards Specific Plan mitigation monitoring and reporting plan.

The SMAQMD thanks the City of Sacramento for the opportunity to comment on this project. If you have additional questions or require further assistance, please contact me at pphilley@airquality.org or (916) 874-4882.

Sincerely,

Paul Philley

Paul Philley, AICP
Associate Air Quality Planner/Analyst
Sacramento Metropolitan Air Quality Management District
777 12th Street, 3rd Floor
Sacramento, CA 95814

Attachment: Construction Mitigation

BASIC CONSTRUCTION EMISSION CONTROL PRACTICES

The following practices are considered feasible for controlling fugitive dust from a construction site. Control of fugitive dust is required by District Rule 403 and enforced by District staff.

- **Water all exposed surfaces two times daily. Exposed surfaces include, but are not limited to soil piles, graded areas, unpaved parking areas, staging areas, and access roads.**
- **Cover or maintain at least two feet of free board space on haul trucks transporting soil, sand, or other loose material on the site. Any haul trucks that would be traveling along freeways or major roadways should be covered.**
- **Use wet power vacuum street sweepers to remove any visible trackout mud or dirt onto adjacent public roads at least once a day. Use of dry power sweeping is prohibited.**
- **Limit vehicle speeds on unpaved roads to 15 miles per hour (mph).**
- **All roadways, driveways, sidewalks, parking lots to be paved should be completed as soon as possible. In addition, building pads should be laid as soon as possible after grading unless seeding or soil binders are used.**

The following practices describe exhaust emission control from diesel powered fleets working at a construction site. California regulations limit idling from both on-road and off-road diesel powered equipment. The California Air Resources Board enforces the idling limitations.

- **Minimize idling time either by shutting equipment off when not in use or reducing the time of idling to 5 minutes [required by California Code of Regulations, Title 13, sections 2449(d)(3) and 2485]. Provide clear signage that posts this requirement for workers at the entrances to the site.**

Although not required by local or state regulation, many construction companies have equipment inspection and maintenance programs to ensure work and fuel efficiencies.

- **Maintain all construction equipment in proper working condition according to manufacturer's specifications. The equipment must be checked by a certified mechanic and determine to be running in proper condition before it is operated.**

Lead agencies may add these emission control practices as Conditions of Approval (COA) or include in a Mitigation Monitoring and Reporting Program (MMRP).

ENHANCED EXHAUST CONTROL PRACTICES

1. The project representative shall submit to the lead agency and District a comprehensive inventory of all off-road construction equipment, equal to or greater than 50 horsepower, that will be used an aggregate of 40 or more hours during any portion of the construction project.
    - The inventory shall include the horsepower rating, engine model year, and projected hours of use for each piece of equipment.
    - The project representative shall provide the anticipated construction timeline including start date, and name and phone number of the project manager and on-site foreman.
    - This information shall be submitted at least 4 business days prior to the use of subject heavy-duty off-road equipment.
    - The District's Equipment List Form can be used to submit this information.
    - The inventory shall be updated and submitted monthly throughout the duration of the project, except that an inventory shall not be required for any 30-day period in which no construction activity occurs.
2. The project representative shall provide a plan for approval by the lead agency and District demonstrating that the heavy-duty off-road vehicles (50 horsepower or more) to be used in the construction project, including owned, leased, and subcontractor vehicles, will achieve a project wide fleet-average 20% NO_X reduction and 45% particulate reduction compared to the most recent California Air Resources Board (ARB) fleet average.
    - This plan shall be submitted in conjunction with the equipment inventory.
    - Acceptable options for reducing emissions may include use of late model engines, low-emission diesel products, alternative fuels, engine retrofit technology, after-treatment products, and/or other options as they become available.
    - The District's Construction Mitigation Calculator can be used to identify an equipment fleet that achieves this reduction.
3. The project representative shall ensure that emissions from all off-road diesel powered equipment used on the project site do not exceed 40% opacity for more than three minutes in any one hour.
    - Any equipment found to exceed 40 percent opacity (or Ringelmann 2.0) shall be repaired immediately.

Enhanced Exhaust Control Practices

- Non-compliant equipment will be documented and a summary provided to the lead agency and District monthly.
- A visual survey of all in-operation equipment shall be made at least weekly.
- A monthly summary of the visual survey results shall be submitted throughout the duration of the project, except that the monthly summary shall not be required for any 30-day period in which no construction activity occurs. The monthly summary shall include the quantity and type of vehicles surveyed as well as the dates of each survey.

4. The District and/or other officials may conduct periodic site inspections to determine compliance. Nothing in this mitigation shall supercede other District, state or federal rules or regulations.

I STREET BRIDGE
REPLACEMENT PROJECT

OPEN HOUSE
COMMENT CARD

Please share your thoughts, comments, or questions about the project or potential environmental effects

First Input of hard copy regarding Light on the river and impact on Salmon

"Light on the Ruor kills Salmon"

I present 6 different cases of light and predation of Salmon

Name Jack Sales
email jesales@surewest.net
phone 916-726-7405

You may submit your comments to staff tonight or directly to Ciara Zanze at czanze@aimconsultingco.com or fax (916) 442-1186.

File: Unsaved Document 1 | Page 1 of 1

Submission #___
Subject: Puntledge River

Puntledge River 5th. St. Bridge, Courtenay B.C., Poster - used as display and introduction

Comments, Notes, Internet locations (URLs)

Experimental Attempts to Reduce Predation by Harbor Seals on Out-Migrating Juvenile Salmonids
H.Yurk, A.W.Trits American Fisheries Society 129: 1360-1366, 2000

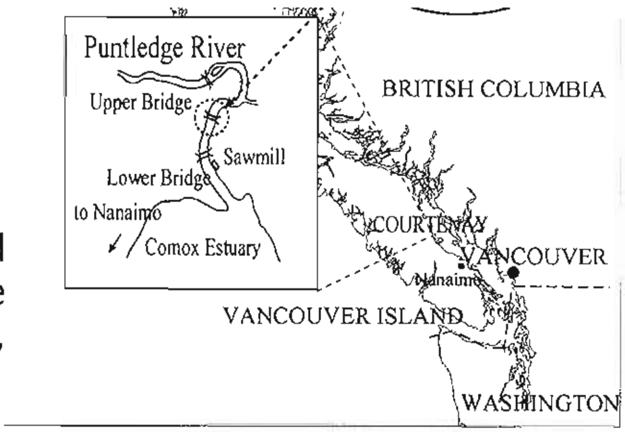
Evaluation of an Electric Barrier as a Deterrent on the Puntledge River (Draft) (Selected pages referencing "lighting")
Prepared by Pacific Salmon Commission, Vancouver B.C. Canada December 2008

Puntledge River

5th. St. Bridge, Courtenay, B.C.

The Puntledge River was historically one of the largest producers of chinook salmon in British Columbia. However, by 1995, only 208 chinook salmon returned.

At one time harbor seals congregated under artificial lights to eat juvenile salmonids as they migrated downstream, turning the lights off reduced predation.



Harbor seals Phoca vitulina in the Puntledge River regularly position themselves side by side, ventral side up, in the upstream shadow of two bridges near the light–shadow boundary. The seals swim against the river current and hold their position in the water. Minimal movements of their hind flippers cause no apparent disturbance to the surface waters. This feeding strategy allows the seals to form an almost continuous barrier so they can intercept smolts that drift downstream near the surface. The seals are assisted in their feeding efforts by the bridge and sports lights that illuminate the water surface. It was estimated that harbor seals consumed an average of 140,000 chum salmon fry and 13,000 coho salmon smolts per night in 1994.

The Puntledge River was historically one of the largest producers of chinook salmon in British Columbia. However, by 1995, only 208 chinook salmon returned to spawn (Trites at al. 1996).

Reference - *Experimental Attempts to Reduce Predation by Harbor Seals on Out-Migrating Juvenile Salmonids, H. YURK & A. W. TRITES , 2000*

------------- Puntledge River Comments ----------------

Experimental Attempts to Reduce Predation by Harbor Seals on Out-Migrating Juvenile Salmonids, H. Yurk,
A. W. Trites, 2000
NOTE Discussion of lighting and the failure to recognize lighting as the root cause.
URL = http://www.zoology.ubc.ca/~consort/pdfs/YurkTrites2000-sealpredation.pdf
URL = https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=69621
URL = http://www.tandfonline.com/doi/abs/10.1577/1548-8659%282000%29129%3C1360%3AEATRPB%3E2.0.CO%
3B2#preview

Evaluation of an Electric Barrier as a Seal Deterrent on the Puntledge River (Draft) December 2008
Pages 1, 12, 13, 18
URL = http://www.nwd-wc.usace.army.mil/tmt/documents/FPOM/2010/2010_FPOM_MEET/2010_MAR/Seal Fence
Report_Dec8_1.pdf

Follow up comments required to show full context.

More?

Transactions of the American Fisheries Society 129:1360–1366, 2000

Experimental Attempts to Reduce Predation by Harbor Seals on Out-Migrating Juvenile Salmonids

H. YURK*

Marine Mammal Research Unit, Fisheries Centre, University of British Columbia,
6248 Biological Sciences Road, Vancouver, British Columbia, Canada V6T 1Z4, and
Vancouver Aquarium Marine Science Centre,
Post Office Box 3232, Vancouver, British Columbia, Canada V6B 3X8

A. W. TRITES

Marine Mammal Research Unit, Fisheries Centre, University of British Columbia,
6248 Biological Sciences Road, Vancouver, British Columbia, Canada V6T 1Z4

Abstract.—During spring, harbor seals *Phoca vitulina* feed at night under two bridges spanning the Puntledge River in Courtenay, British Columbia, Canada. Positioned parallel to one another, ventral side up, the seals form a feeding line across the river to intercept thousands of out-migrating salmonid smolts. During a 4-week observation period in the spring of 1996, we attempted to disrupt the seals' feeding patterns by (a) deploying a mechanical feeding barrier (cork line), (b) altering the lighting conditions (lights on a bridge were turned off), and (c) installing an acoustic harassment device. We found acoustic harassment to be the most effective feeding deterrent. Of the other two deterrents, turning off the bridge lights was more effective than deploying a cork line, which had little effect. Acoustic harassment devices appear to be the most effective, nonlethal means for protecting juvenile salmonids from harbor seal predation in portions of the Puntledge River.

Natural predators that prey upon both out-migrating and returning anadromous fish can detrimentally affect the survival of depressed fish populations (Bigg et al. 1990; Fraker 1994; Olesiuk et al. 1995). In the northeast Pacific, seals and sea lions are commonly observed feeding on returning adult Pacific salmon *Oncorhynchus* spp. in rivers and estuaries during summer and fall (Spalding 1964; Olesiuk et al. 1990). Seals also intercept out-migrating smolts in spring and early summer (Olesiuk et al. 1995). Among the better-studied seal–salmon interactions are those in the Puntledge River on Vancouver Island, British Columbia (Bigg et al. 1990; Olesiuk et al. 1995; Trites et al. 1996; Figure 1).

Harbor seals *Phoca vitulina* in the Puntledge River regularly position themselves side by side, ventral side up, in the upstream shadow of two bridges near the light–shadow boundary. The seals swim against the river current and hold their position in the water. Minimal movements of their hind flippers cause no apparent disturbance to the surface waters. This feeding strategy allows the seals to form an almost continuous barrier so they can intercept smolts that drift downstream near the surface. Apparently, the seals are assisted in their feeding efforts by the bridge lights that illuminate the water surface.

One way to enhance the survival of salmonids is to disrupt the feeding patterns of their predators. Techniques vary, but include making the smolts foul-tasting, creating a mechanical barrier that prevents seals from entering estuaries or river systems, and installing optic or acoustic harassment devices (AHD) to hinder the seals from feeding in particular areas (Gearin et al. 1986; Mate and Harvey 1987; Pfeifer 1989)

The AHDs are generally considered to be effective in deterring seals and sea lions from preying on fish in certain areas. The widespread use of these devices by aquaculture operators, who use them to deter seals and sea lions from entering netpens, attests to this claim. The AHDs have also deterred a large number of California sea lions *Zalophus californianus* from preying on returning winter steelhead *Oncorhynchus mykiss* in the Chittenden Locks, Seattle, Washington (Fox et al. 1996). However, at aquaculture sites and at the Chittenden Locks, some pinnipeds appear to become acclimated to AHD sounds and may have to be physically removed (Fox et al. 1996).

The goal of our study was to disrupt the feeding patterns of harbor seals feeding on smolts in the Puntledge River. During an observation period in April and May 1996, we evaluated three methods: installation of a mechanical feeding barrier, alteration of artificial light on the river, and deployment of an AHD.

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* Corresponding author: yurk@zoology.ubc.ca

Received November 29, 1999; accepted June 5, 2000

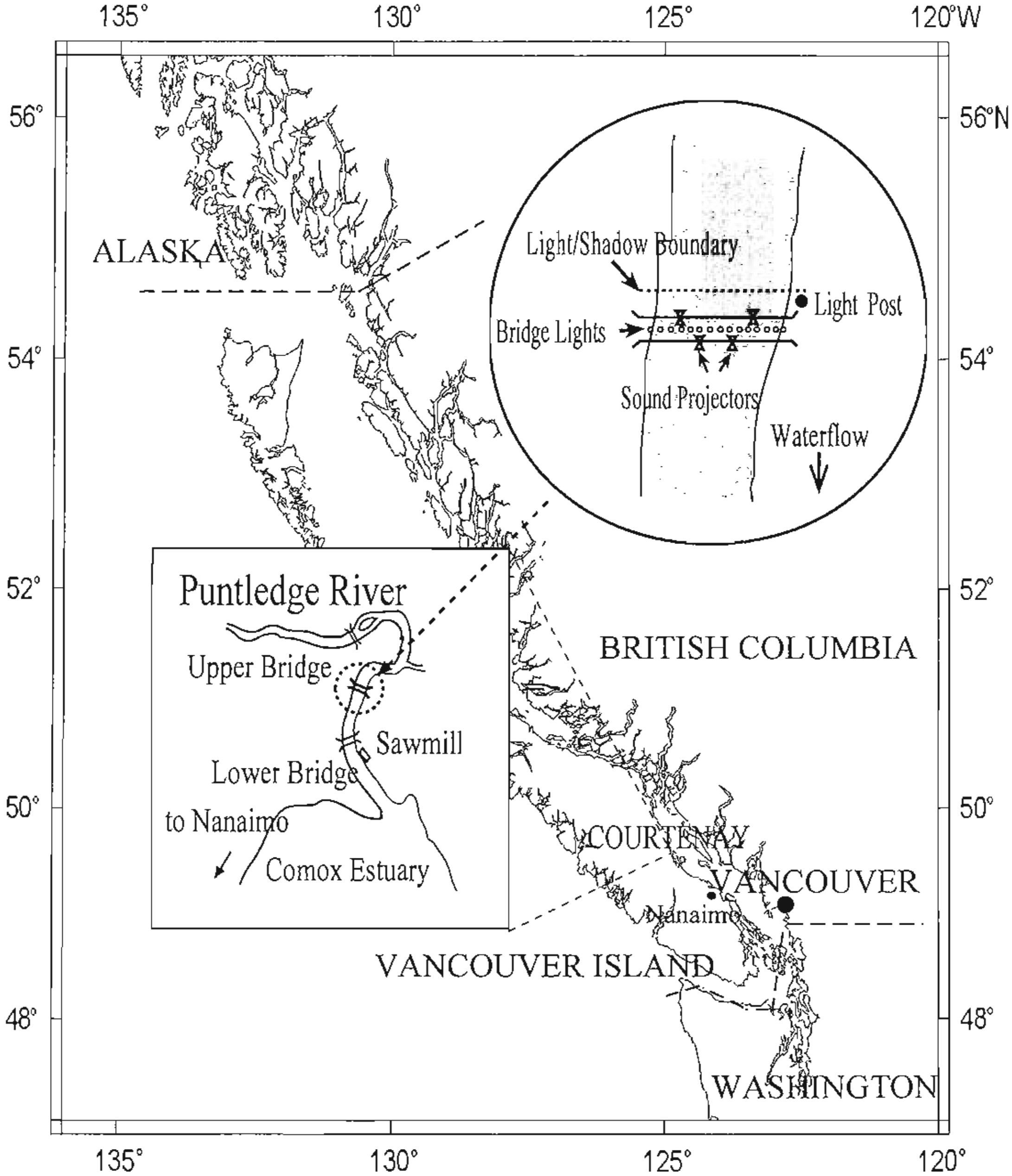

FIGURE 1.—Geographic area and detail map showing placement of sound projectors at the upper bridge on the Puntledge River, Courtenay, British Columbia.

Study Site and Background

The Puntledge River flows out of the north end of Comox Lake and continues through the city of Courtenay until it reaches Comox Harbor and the Strait of Georgia (Figure 1). Chinook salmon *O. tshawytscha,* pink salmon *O. gorbuscha,* coho salmon *O. kisutch,* and steelhead are raised at the Puntledge River Hatchery and return to spawn in the Puntledge River system. The Puntledge River was historically one of the largest producers of chinook salmon in British Columbia. However, by 1995, only 208 chinook salmon returned to spawn (Trites at al. 1996).

Salmon smolts migrate out of the Puntledge River from March to May (C. Beggs, Puntledge River Hatchery, personal communication). Each year, the migration period begins with pink salmon smolts in March and April, followed by smolts of chum salmon *O. keta* during April and the first half of May. These are followed by coho salmon smolts at the beginning of May and chinook salmon smolts during the second half of May. The outmigrating smolts are of both wild and hatchery origin. The hatchery annually releases 3,000,000–6,000,000 chum salmon, 150,000–400,000 coho salmon, and around 1,000,000 pink salmon. However, in the year of our study (1996), pink salmon smolts were released directly into the estuary, thereby reducing the number of smolts in the river.

Approximately 200 harbor seals (increasing to 700 during the fall) haul out on log booms in the estuary of the Puntledge River year round (Bigg et al. 1990; Jurk et al. 1997; Figure 1). A considerably smaller number of harbor seals enter the river to feed on salmon smolts during the spring (Olesiuk et al. 1995). Visual scans of the river show that the seals feed in two primary areas: under the upper bridge (5th Street) and under the lower bridge (17th Street; Figure 1).

Seals entered the river at around dusk; the majority arrived later in the evening when a clearly defined light–shadow boundary formed under the two bridges (Olesiuk et al. 1995). Illumination of the water at the upper bridge was produced by 14 lights hanging over the center line of the bridge above the roadway (Figure 1). Depending on the height of the river, which was tidally influenced, the lights produced a relatively distinct, straight light–shadow line on the water surface 8–12 m both upstream and downstream of the upper bridge (Figure 1). The lower bridge did not have a row of center lights and, therefore, did not have a similar light–shadow boundary.

Methods

We tested three methods of seal deterrence to determine whether any prevented the seals from feeding at the upper bridge, their primary feeding site. The first treatment at the upper bridge involved the temporary installation of a mechanical feeding barrier. We strung a 60-m rope that had cork floats spaced 1 m apart across the river beneath the bridge. Though we tried to place the rope along the shadow line, changes in tidal movements and river currents often caused it to move a few meters downstream (Figure 1). Therefore, we had to adjust the cork line several times during the experiment. For the second treatment, we extinguished all of the upper bridge lights for four nights (Figure 1). For the third treatment, we used two different AHDs: (1) the "Seal-Scarer," produced by Airmar Technology (New Hampshire), which was used in seven of the eight experiments, and (2) the "MK3 Seal Scrammer," produced by Ferranti Thompson, Ltd. (Dorset, UK), which was only used once as we did not receive it in time to conduct a thorough test of its effectiveness.

The Airmar Seal-Scarer device consisted of a control unit and four sound projectors that were each attached by 30 m of cable. The AHD was configured to produce broadband signals that pitched at 27 kHz and had a maximum source intensity at 10 kHz (194 decibels [dB], referenced to 1 Pa/V at 1 m from the sound source). The four sound projectors or transducers were suspended 40 cm below the water surface by ropes attached to floats. Attached to the bottom of each projector was a lead weight to ensure that the projectors remained upright and steady in the river current. The Airmar device was set to reach full intensity 1 min after being turned on. It then continuously alternated a 2-s sound burst through each of the transducers. The MK3 "Seal Scrammer" consisted of a control unit with one hydrophone-like transducer. It produced sounds ranging from 10 to 40 kHz and had a peak intensity at 27 kHz (195 dB).

The experiments were conducted by two observers in one 4-d period (two cork line treatments and two control nontreatments) and two 10-d periods (lights out, acoustic harassment, and control) during the nights of 22–26 April, 30 April–10 May, and 15–25 May 1996. We chose this study design after considering peak migration periods of smolts and the time that observers were available. Observations started each night at 2100 hours and ended at 0300 hours, for a total of 161 h of observation over 23 d. Treatment (experiment) and nontreatment (control) nights were randomly selected throughout the observation period. The number of treatments during each observation period could not be kept constant because of a few nights of extreme rainy weather; bridge lights could not be turned off because of public safety concerns. In all, two experiments involved the mechanical feeding barrier (cork line), four experiments involved decreased illumination, and eight experiments involved an AHD. The total number of nontreatment (control) nights was nine.

The observers counted harbor seals every 30 min from the upper bridge decks with a red-filtered, 10^6-candlepower spotlight to illuminate the river. Observers also counted seals at the lower

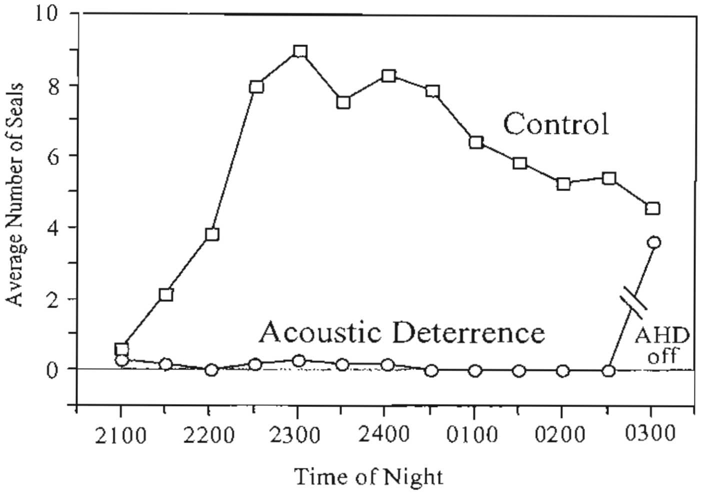

FIGURE 2.—Average number of seals present at the upper bridge on the Puntledge River, Courtenay, British Columbia, during count sessions on seven control nights and seven experimental nights when the Airmar acoustic harassment device was deployed. Note that the Airmar device was turned off at 0235 hours each experimental night.

bridge to determine whether the deterrents forced the animals to relocate. The maximum number of observations per night was 13 (Figure 2) at the upper bridge and 12 at the lower bridge. The seals were repeatedly counted by the two observers for a 5-min period; the highest number was retained as the best estimate of the number of animals present (counts by the two observers rarely differed). This procedure reduced the probability of underestimating the number of seals present.

We used a two-sample *t*-test to compare the mean number of seals present when the AHD device was deployed with the mean number present when no deterrent was used. The average number of seals present was calculated for each night of observation and treated as a single observation. Means of the nightly average number of seals were then calculated and compared for seven control nights and seven experimental nights.

Results and Discussion

On the control nights, when no deterrences were used, an average of 8 seals (range, 1–26) fed at the upper bridge. In contrast, we observed only 1 seal on average at the lower bridge (range, 0–8). During their nightly feeding routine, most seals appeared at the upper bridge 1.0–1.5 h after nightfall (between 2030 and 22:30 hours; Figure 2), and the majority appeared to stay until 0300 hours. The mean number of seals at the upper bridge rose from one at 2100 hours to nine at 2300 hours, dropping to an average of five by 0300 hours (Figure 2). Seals started to appear downriver from the lower bridge earlier in the evening than at the upper bridge, but did not stay there long.

The presence of seals near the bridges did not always mean they were feeding. For example, a lack of head movement and absence of fish in the water column indicated that no feeding took place on the night of 23 April and that only sporadic feeding occurred on the night of 22 April. Feeding behavior also changed over the course of the study. From 24 April to 9 May, the seals stationed themselves at the water surface near the upstream shadow line and, with their ventral sides up, "gulped" the salmon fry (mainly chum salmon) that drifted downstream. After 15 May, the animals stayed further back in the bridge's shadow and more actively pursued their prey (mainly coho salmon smolts).

Olesiuk et al. (1995) estimated that harbor seals consumed an average of 140,000 chum salmon fry and 13,000 coho salmon smolts per night in 1994. We did not remeasure the feeding rates because we were concerned that illuminating the animals with a red spotlight for long stretches of time might affect their behavior and confound our experiment. In contrast to Olesiuk et al. (1995), we observed a behavioral response to the red light: the seals often moved away and seemed sensitive near the light–shadow line of the spotlight. Our procedure of continuous counts during a 5-min period paid special attention to the possibility of animals avoiding the spotlight.

Tidal heights and freshwater flow influenced

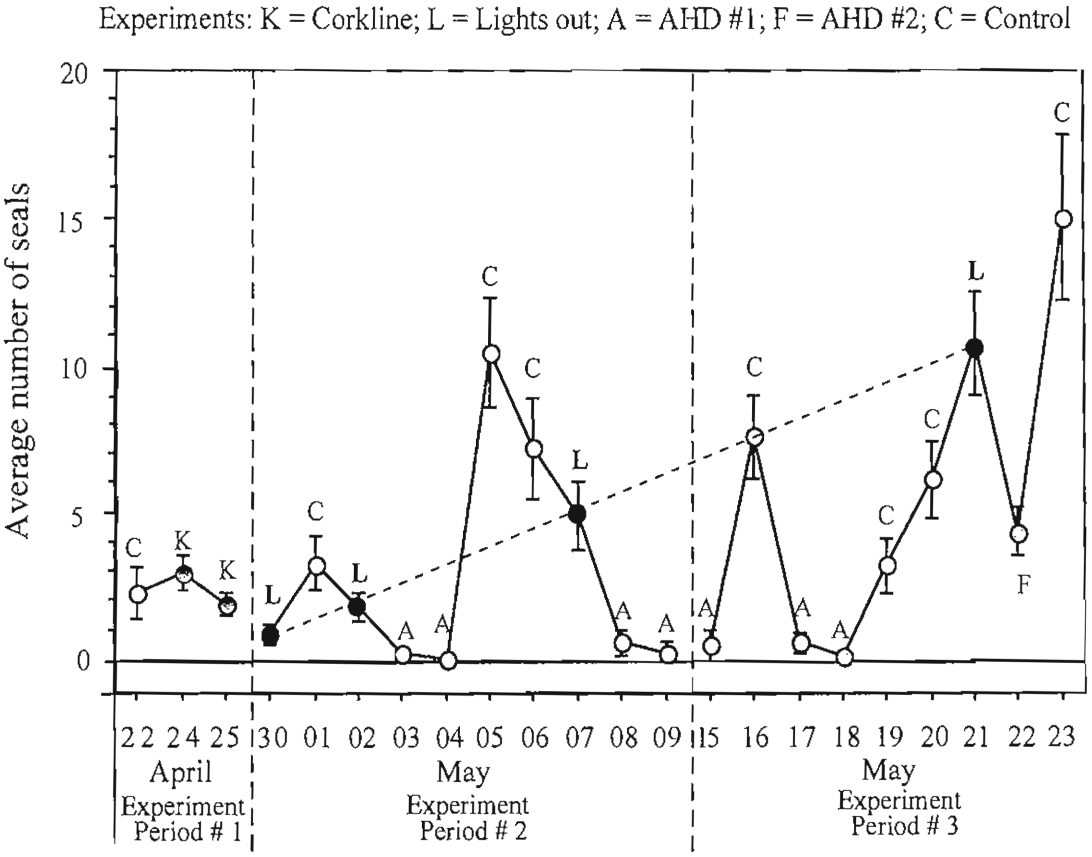

FIGURE 3.—Average number of seals present at the upper bridge on the Puntledge River, Courtenay, British Columbia, on each observation night. Seals were counted every 30 min, for a total number of 13 counts/night (bars = ±SE). Letter symbols indicate the type of treatment applied.

feeding activities at the upper bridge. During extreme low tides, the water depth was below 1.5 m. Our observations found that the seals did not attempt to feed until the tide raised the river to almost 2 m. Tidal heights were estimated by comparing hydrographic charts of the river with tidal heights published in regional tide tables. However, our estimates neither took into account the amount of runoff from the lake nor the effects of variable rainfall. During the first 2 weeks of observations in 1996, rainfall exceeded the annual average and caused the Puntledge River to flow faster and at a higher level than normal. This seemed to affect feeding; we did not observe seals feeding on nights of extreme rainfall.

Spot checks along the river away from the bridges revealed a number of seals feeding in areas illuminated by other light sources. For example, we observed as many as seven seals feeding in a stretch of river that was lit by halogen lights from a ballpark at Lewis Park (upstream of upper bridge). In addition, halogen lights used by a sawmill (below the lower bridge) illuminated another area frequented by feeding seals.

Treatment 1: Cork Line

At the upper bridge, we deployed the cork line on two nights for an average of 3 h each night (Figure 3). Within 1 h of setting the cork line on the first night, the number of seals feeding at the lower bridge increased from one to four. As the night progressed, the number of seals at the lower bridge steadily dropped and more seals began appearing next to the cork line at the upper bridge. On the following night, we deployed and retrieved the cork line twice. The animals were not at either bridge during the first deployment and did not seem to be disturbed by the second deployment. A drop in the number of seals toward the end of the second deployment suggested a mild response

TABLE 1.—Number of harbor seals counted at the upper bridge on 7 control nights and 7 nights when the acoustic harassment device (AHD) was deployed. The means (standard deviations) for the control and AHD nights were 7.57 (2.96) and 0.36 (0.20), respectively.

Night	Control	AHD
1	3.31	0.23
2	10.46	0.08
3	7.23	0.62
4	7.62	0.31
5	3.23	0.54
6	6.15	0.62
7	15.00	0.15

to the deterrent. However, the seals that remained appeared to engage in some form of play with the cork line. We concluded that though the cork line had a short-term initial effect on the seals, the animals were quick to habituate to it. We did not attempt any further trials with the cork line after these two nights of testing.

Treatment 2: Lights Out

Fewer seals were observed feeding the first night we turned off the lights at the upper bridge compared with adjacent control nights when the lights were left on (Figure 3). However, on subsequent experimental nights, we noted a progressive increase in the number of seals feeding in the residual light (closed circles in Figure 3; $F_{1,3} = 17.5$, $P = 0.05$). By the end of four experimental nights, numbers appeared to reach and even exceed those observed during comparable control nights (Figure 3). Although we do not know whether the reduced light affected their feeding efficiency, the results of this experiment suggest that the seals learned to compensate for the reduced lighting by making effective use of the residual city lighting. Therefore, we concluded that, though the "lights-out" treatment was initially effective as a deterrent, the seals eventually habituated to the lighting change.

Treatment 3: Acoustical Deterrence

Significantly fewer seals fed at the upper bridge on the seven nights we deployed the Airmar device compared with seven control nights when no deterrent was used ($t_{12} = 4.60$, $P = 0.001$; Figures 2, 3; Table 1). A mean of 0.4 animals was present during the acoustical tests (range, 0–1) compared with a mean of 8 animals on control nights (range, 0–26). On most experimental nights, no seals fed within a 50-m radius of the bridge.

The first two nights we deployed the Airmar device at the upper bridge, significantly more seals appeared at the lower bridge than were previously counted on control nights and during the lights-out experiment. On subsequent experimental nights, the numbers dropped steadily at the lower bridge until no seals were observed feeding there. We presume this drop in numbers at the lower bridge reflected poor feeding conditions at this location.

Conclusions

Our results show that AHDs were the most effective of the three methods tested to deter seals from feeding on salmon smolts in the Puntledge River. Extinguishing the bridge lights was the second most effective deterrent, followed by the cork line, which had little, if any, effect. The upper bridge appeared to be the preferred feeding site for the harbor seals, as lighting and river topography at this bridge are probably ideal for optimal foraging success. Given that it is doubtful that all incandescent light sources around this bridge can be extinguished, acoustic deterrence could be used to control predation during the months of April and May.

The AHDs are effective within a limited range, but cannot prevent seals from entering the river or from moving or feeding in other areas of the river. The seals only have to swim with their heads out of the water to avoid the underwater noise. By installing AHDs at the Chittenden Locks in Seattle, Washington, the number of sea lions feeding on returning steelhead decreased over the course of 2 years (Fox et al. 1996). Similarly, AHDs could be effective for deterring seals in the Puntledge River and other salmon-producing streams until better measures to protect salmonids are implemented. However, acoustic deterrence can probably only be used as a temporary predation-control mechanism because pinnipeds have a strong ability to learn and adapt to sounds (Fraker 1994). For example, changes in the abundance and availability of prey may lead to motivational changes in pinniped behavior (from avoiding AHDs to ignoring them). Therefore, the effectiveness of the AHDs in the Puntledge River should be tested again during spring out-migrations and, possibly, during fall returns. Hopefully, the Department of Fisheries and Oceans, which is responsible for protecting salmon and seals in Canada, will undertake the necessary steps to continue testing the effectiveness of AHDs.

Acknowledgments

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Evaluation of an Electric Barrier as a Seal Deterrent on the Puntledge River

Prepared For

Pacific Salmon Commission
Southern Boundary Restoration & Enhancement Fund Committee
600 – 1155 Robson Street
Vancouver, B.C., Canada
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December 2008

DRAFT

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4. RESULTS

4.1 Baseline Observations

Following observations and assessments conducted in the 1990s on seal predation on outmigrating fry and smolts (Olesiuk et al. 1995), it was strongly recommended that shielding of the lights at the 5th and 17th Street bridges should be evaluated as a mitigative measure to deter seals from foraging beneath them. Predation on outmigrants was determined to be a relatively localized behaviour. With assistance from the City of Courtenay, modifications to the lights on the 5th Street bridge were finally completed in the fall of 2007. This included turning off every second light on the bridge truss above the road, and erecting a shield around the remaining lights to prevent light from spilling beyond the bridge deck and into the river, significantly reducing the light shadow used by foraging seals.

Observations of seal foraging behaviour were collected by Puntledge Hatchery personnel during the months of April and May 2008 (before the arrays began operating and during their operation) at 5 main areas of the Puntledge / Courtenay River: Condensory Road bridge, Lewis Park tennis courts, 5th Street bridge, Central Builders, and the 17th Street bridge using night vision equipment (see Figure 1). Observations were conducted between dusk and dawn and during favourable tides (when seals typically enter the river for foraging at the 5th Street bridge). The 2008 observations are compared to 2007 observations collected during the same months and illustrated in Figure 4.

It appears that the light shields were effective in reducing the number of seals feeding under the 5th Street bridge. For the period prior to the start of the electric fence trial on April 27, the maximum number of seals observed on any given monitoring event was 4 in 2008 compared to 9 in 2007 and 10 in 2006. The average number of seals observed during this period was 5.2 in 2006, 3.7 in 2007 and 0.7 in 2008. It was noted that the light shields appeared to have eliminated the distinct shadow line where seals have congregated to feed on outmigrating juveniles in past years. Seals may have been displaced to other well lit areas of the river to feed such as the tennis courts (upstream) or the area adjacent Central Builders (downstream). A comparison of 2007 and 2008 observations at the Lewis Park Tennis Courts provides limited information due to the disproportion in sampling effort between the 2 years (Figure 5). No observations were collected at the Central Builders site downstream of the 5th Street bridge in 2007 for comparison. These comparisons do not take into account other variables that may have influenced seal activity such as tide level and river discharge.

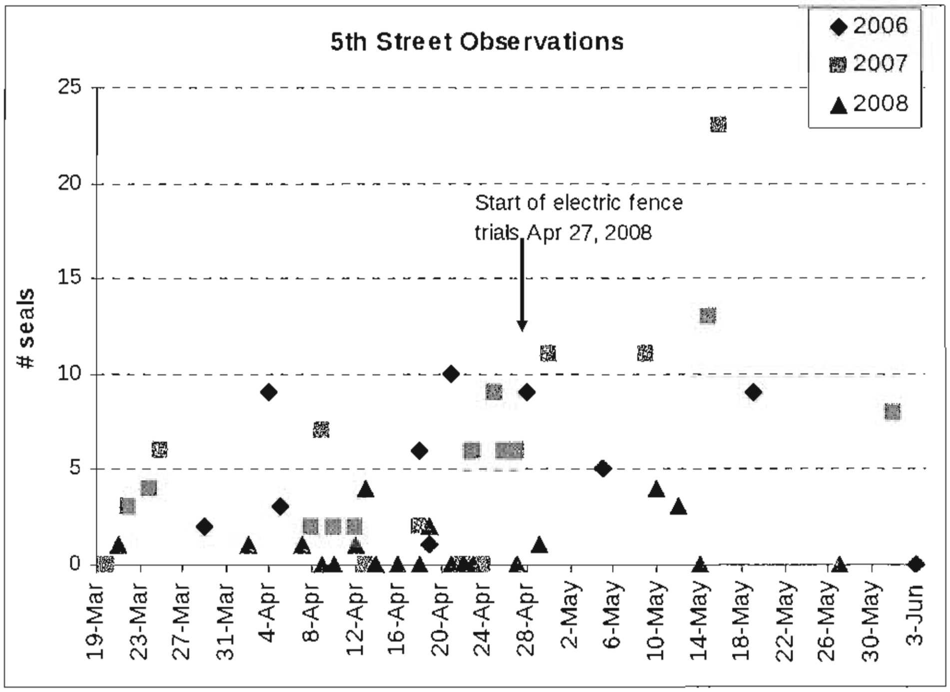

Figure 4. Observations of seals in the Courtenay River at the 5th Street bridge between April and June before lights were shielded (2006-2007) and after (2008). Commencement of the 2008 electric deterrent trials is noted. Trials in 2007 were conducted on April 12-13 and April 23-25

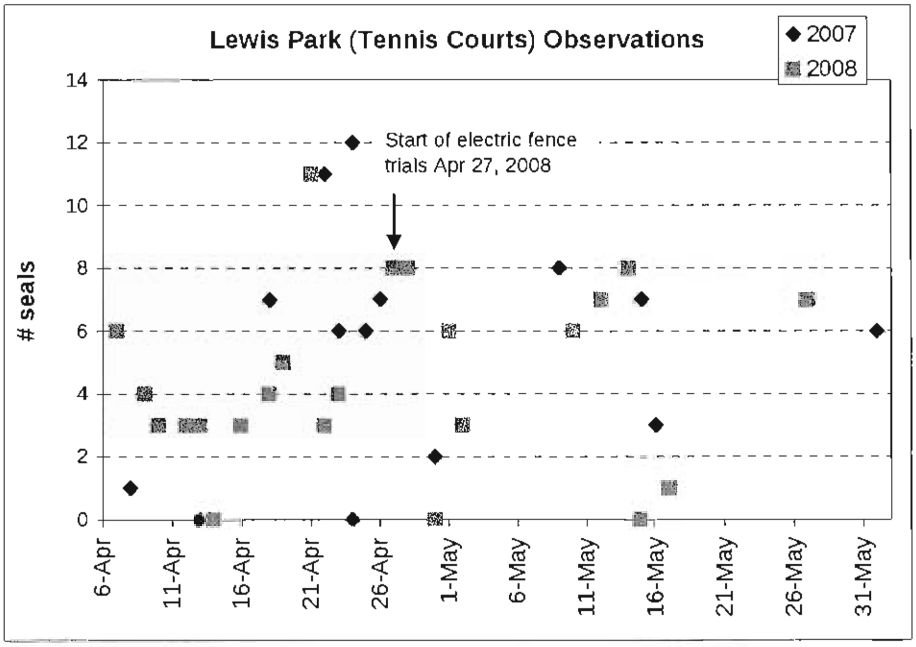

Figure 5. Observations of seals in the Courtenay River at the Lewis Park Tennis Courts (upstream of the 5th Street bridge), between April and June before lights were shielded (2007) and after (2008). Commencement of the 2008 electric deterrent trials is noted. Trials in 2007 were conducted on April 12-13 and April 23-25.

Pulse width settings greater than 3 msec appeared to cause physiological stress in the seals that were exposed to this electric field, leading the project team to recommend an upper threshold of 3 msec for future trials.

The effectiveness of the barrier was dependent on the strength of the field provided by the pulse width parameter, but may also have been dependent on the environmental conditions during which the array was operated. As the river depth over the array increased due to tidal inundation and increased discharge, the electric field weakened at the surface, potentially creating openings in the electric barrier that seals would quickly learn and habituate to. (data pending from SR).

While the barrier may be considered effective at deterring the upstream movement of a large proportion of seals that approached it, it was noted that even at the highest electrical field strengths tested some seals continued to challenge the array exposing themselves to significant physiological stress and potentially harmful levels. The commencement of trials at the lowest pulse width setting (1 msec) and ramping up gradually to higher levels (4-5 msec) has been criticized by Dr Jennifer Hurley, who has considerable experience with captive sea lions, as essentially training seals to tolerate the electrical stimulus, and charge through the array at levels that may be harmful. However, the gradual ramping up of field strength was necessary to determine the upper threshold for invoking an acceptable behavioural response in seals.

Based on the DIDSON images and shoreline observations there was no apparent effect of the electrical field on juvenile salmon migration behaviour at the levels tested. Conversely, upstream migrating adults appeared to have been obstructed at levels that were considered effective at deterring seals. The delay and/or obstruction of 11 of 14 adult salmon targets in DIDSON imagery recorded on May 18 lead to the conclusion that operation of the electric deterrent at a setting that affects the upstream passage of seals (3msec) adversely affects the migratory behaviour of adult salmon. Therefore, with respect to the second objective, the current technology may only be useful at reducing seal predation on juvenile salmon smolts and fry in localized foraging areas and preventing naive seals from accessing feeding areas further upstream during a brief operating window (late April to mid May). Even during this period, there remains the potential that operation of an electric barrier in the Courtenay River to reduce predation on outmigrating juvenile salmonids will overlap with migrating adults (late steelhead migrants and early summer chinook migrants).

The displacement of seals from the 5th Street bridge area to other foraging areas downstream continues to be an issue where lighting provides the distinctive shadow that seals utilize to their advantage such as the Central Builders parking lot downstream of the 5th Street bridge and the 17th Street bridge. Periodic observations at these two locations identified between 8 and 24 seals. Light shielding at the 5th Street bridge installed in 2007 appears to have significantly reduced the number seals foraging at this location. Efforts to design similar solutions in other well lit sections of the river should be explored with the City of Courtenay, Ministry of Transportation and other riverside property owners as this treatment seems to have a positive effect at reducing the number of seals from these areas.

Submission #1
Subject: Ecological Light Pollution General

Ecological Consequences of Artificial Night Lighting By Catherine Rich, Travis Longcore is now at the Sacramento Public Library under Call Number 577.272 E19 2006

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Ecosphere esa Ecological Society of America
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Elizabeth K. Perkin, Franz Hölker, John S. Richardson, Jon P. Sadler, Christian Wolter, and Klement Tockner 2011. The influence of artificial light on stream and riparian ecosystems: questions, challenges, and perspectives. Ecosphere 2:art122
http://www.esajournals.org/doi/pdf/10.1890/ES11-00241.1

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Ecological light pollution

Travis Longcore and Catherine Rich

Ecologists have long studied the critical role of natural light in regulating species interactions, but, with limited exceptions, have not investigated the consequences of artificial night lighting. In the past century, the extent and intensity of artificial night lighting has increased such that it has substantial effects on the biology and ecology of species in the wild. We distinguish "astronomical light pollution", which obscures the view of the night sky, from "ecological light pollution", which alters natural light regimes in terrestrial and aquatic ecosystems. Some of the catastrophic consequences of light for certain taxonomic groups are well known, such as the deaths of migratory birds around tall lighted structures, and those of hatchling sea turtles disoriented by lights on their natal beaches. The more subtle influences of artificial night lighting on the behavior and community ecology of species are less well recognized, and constitute a new focus for research in ecology and a pressing conservation challenge.

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As diurnal creatures, humans have long sought methods to illuminate the night. In pre-industrial times, artificial light was generated by burning various materials, including wood, oil, and even dried fish. While these methods of lighting certainly influenced animal behavior and ecology locally, such effects were limited. The relatively recent invention and rapid proliferation of electric lights, however, have transformed the nighttime environment over substantial portions of the Earth's surface.

Ecologists have not entirely ignored the potential disruption of ecological systems by artificial night lighting. Several authors have written reviews of the potential effects on ecosystems or taxonomic groups, published in the "gray" literature (Health Council of the Netherlands 2000; Hill 1990), conference proceedings (Outen 2002; Schmiedel 2001), and journal articles (Frank 1988; Verheijen 1985; Salmon 2003). This review attempts to integrate the literature on the topic, and draws on a conference organized by the authors in 2002 titled *Ecological Consequences of Artificial Night Lighting*. We identify the roles that artificial night lighting plays in changing ecological interactions across taxa, as opposed to reviewing these effects by taxonomic group. We first discuss the scale and extent of ecological light pollution and its relationship to astronomical light pollution, as well as the measurement of light for ecological research. We then address the recorded and potential influences of artificial night lighting within the nested hierarchy of behavioral and population ecology, community ecology, and ecosystem ecology. While this hierarchy is somewhat artificial and certainly mutable, it illustrates the breadth of potential consequences of ecological light pollution. The important effects of light on the physiology of organisms (see Health Council of the Netherlands 2000) are not discussed here.

In a nutshell:

- Ecological light pollution includes chronic or periodically increased illumination, unexpected changes in illumination, and direct glare
- Animals can experience increased orientation or disorientation from additional illumination and are attracted to or repulsed by glare, which affects foraging, reproduction, communication, and other critical behaviors
- Artificial light disrupts interspecific interactions evolved in natural patterns of light and dark, with serious implications for community ecology

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Astronomical and ecological light pollution: scale and extent

The term "light pollution" has been in use for a number of years, but in most circumstances refers to the degradation of human views of the night sky. We want to clarify that this is "astronomical light pollution", where stars and other celestial bodies are washed out by light that is either directed or reflected upward. This is a broad-scale phenomenon, with hundreds of thousands of light sources cumulatively contributing to increased nighttime illumination of the sky; the light reflected back from the sky is called "sky glow" (Figure 1). We describe artificial light that alters the natural patterns of light and dark in ecosystems as "ecological light pollution". Verheijen (1985) proposed the term "photopollution" to mean "artificial light having adverse effects on wildlife". Because photopollution literally means "light pollution" and because light pollution is so widely understood today to describe the degradation of the view of the night sky and the human experience of the night, we believe that a more descriptive term is now necessary. Ecological light pollution includes direct glare, chronically increased illumina-

Figure 1. *Diagram of ecological and astronomical light pollution.*

tion, and temporary, unexpected fluctuations in lighting. Sources of ecological light pollution include sky glow, lighted buildings and towers, streetlights, fishing boats, security lights, lights on vehicles, flares on offshore oil platforms, and even lights on undersea research vessels, all of which can disrupt ecosystems to varying degrees. The phenomenon therefore involves potential effects across a range of spatial and temporal scales.

The extent of ecological light pollution is global (Elvidge *et al.* 1997; Figure 2). The first atlas of artificial night sky brightness illustrates that astronomical light pollution extends to every inhabited continent (Cinzano *et al.* 2001). Cinzano *et al.* (2001) calculate that only 40% of Americans live where it becomes sufficiently dark at night for the human eye to make a complete transition from cone to rod vision and that 18.7% of the terrestrial surface of the Earth is exposed to night sky brightness that is polluted by astronomical standards. Ecosystems may be affected by these levels of illumination and lights that do not contribute to sky glow may still have ecological consequences, ensuring that ecological light pollution afflicts an even greater proportion of the Earth. Lighted fishing fleets, offshore oil platforms, and cruise ships bring the disruption of artificial night lighting to the world's oceans.

The tropics may be especially sensitive to alterations in natural diel (ie over a 24-hour period) patterns of light and dark because of the year-round constancy of daily cycles (Gliwicz 1999). A shortened or brighter night is more likely to affect tropical species adapted to diel patterns with minimal seasonal variation than extratropical species adapted to substantial seasonal variation. Of course, temperate and polar zone species active only during a portion of the year would be excluded from this generalization. Species in temperate zones will also be susceptible to disruptions if they depend on seasonal day length cues to trigger critical behaviors.

Measurements and units

Measurement of ecological light pollution often involves determination of illumination at a given place. Illumination is the amount of light incident per unit area – not the only measurement relevant to ecological light pollution, but the most common. Light varies in intensity (the number of photons per unit area) and spectral content (expressed by wavelength). Ideally, ecologists should measure illumination in photons per square meter per second with associated measurements of the wavelengths of light present. More often, illumination is measured in lux (or footcandles, the non-SI unit), which expresses the brightness of light as perceived by the human eye. The lux measurement places more emphasis on wavelengths of light that the human eye detects best and less on those that humans perceive poorly. Because other organisms perceive light differently – including wavelengths not visible to humans – future research on ecological light pollution should identify these responses and measure light accordingly. For example, Gal *et al.* (1999) calculated the response curve of mysid shrimp to light and reported illumination in lux adjusted for the spectral sensitivity of the species.

Ecologists are faced with a practical difficulty when communicating information about light conditions. Lux is the standard used by nearly all lighting designers, lighting engineers, and environmental regulators; communication with them requires reporting in this unit. Yet the use of lux ignores biologically relevant information. High-pressure sodium lights, for instance, will attract moths because of the presence of ultraviolet wavelengths, while low-pressure sodium lights of the same intensity, but not producing ultraviolet light, will not (Rydell 1992). Nevertheless, we use lux here, both because of the need to communicate with applied professionals, and because of its current and past widespread usage. As this research field develops, however, measurements of radiation and spectrum relevant to the organisms in question should be used, even though lux will probably continue to be the preferred unit for communication with professionals in other disciplines.

Ecologists also measure aspects of the light environment other than absolute illumination levels. A sudden change in illumination is disruptive for some species (Buchanan 1993), so percent change in illumination, rate, or similar measures may be relevant. Ecologists may also measure luminance (ie brightness) of light sources that are visible to organisms.

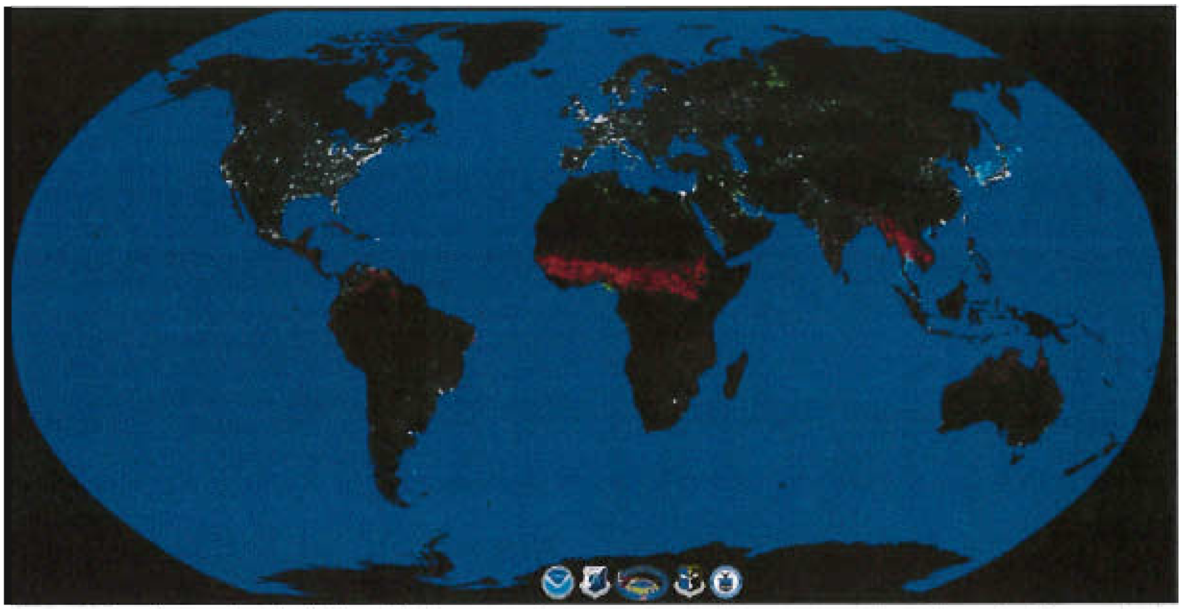

Figure 2. Distribution of artificial lights visible from space. Produced using cloud-free portions of low-light imaging data acquired by the US Air Force Defense Meteorological Satellite Program Operational Linescan System. Four types of lights are identified: (1) human settlements – cities, towns, and villages (white), (2) fires – defined as ephemeral lights on land (red), (3) gas flares (green), and (4) heavily lit fishing boats (blue). See Elvidge et al. *(2001) for details. Image, data processing, and descriptive text by the National Oceanic and Atmospheric Administration's National Geophysical Data Center.*

Behavioral and population ecology

Ecological light pollution has demonstrable effects on the behavioral and population ecology of organisms in natural settings. As a whole, these effects derive from changes in orientation, disorientation, or misorientation, and attraction or repulsion from the altered light environment, which in turn may affect foraging, reproduction, migration, and communication.

Orientation/disorientation and attraction/repulsion

Orientation and disorientation are responses to ambient illumination (ie the amount of light incident on objects in an environment). In contrast, attraction and repulsion occur in response to the light sources themselves and are therefore responses to luminance or the brightness of the source of light (Health Council of the Netherlands 2000).

Increased illumination may extend diurnal or crepuscular behaviors into the nighttime environment by improving an animal's ability to orient itself. Many usually diurnal birds (Hill 1990) and reptiles (Schwartz and Henderson 1991), for example, forage under artificial lights. This has been termed the "night light niche" for reptiles and seems beneficial for those species that can exploit it, but not for their prey (Schwartz and Henderson 1991).

In addition to foraging, orientation under artificial illumination may induce other behaviors, such as territorial singing in birds (Bergen and Abs 1997). For the northern mockingbird (*Mimus polyglottos*), males sing at night before mating, but once mated only sing at night in artificially lighted areas (Derrickson 1988) or during the full moon. The effect of these light-induced behaviors on fitness is unknown.

Constant artificial night lighting may also disorient organisms accustomed to navigating in a dark environment. The best-known example of this is the disorientation of hatchling sea turtles emerging from nests on sandy beaches. Under normal circumstances, hatchlings move away from low, dark silhouettes (historically, those of dune vegetation), allowing them to crawl quickly to the ocean. With beachfront lighting, the silhouettes that would have cued movement are no longer perceived, resulting in disorientation (Salmon *et al.* 1995). Lighting also affects the egg-laying behavior of female sea turtles. (For reviews of effects on sea turtles, see Salmon 2003 and Witherington 1997).

Changes in light level may disrupt orientation in nocturnal animals. The range of anatomical adaptations to allow night vision is broad (Park 1940), and rapid increases in light can blind animals. For frogs, a quick increase in illumination causes a reduction in visual capability from which the recovery time may be minutes to hours (Buchanan 1993). After becoming adjusted to a light, frogs may be attracted to it as well (Jaeger and Hailman 1973; Figure 3).

Birds can be disoriented and entrapped by lights at night (Ogden 1996). Once a bird is within a lighted zone at night, it may become "trapped" and will not leave the lighted area. Large numbers of nocturnally migrating birds are therefore affected when meteorological conditions bring them close to lights, for instance, during inclement weather or late at night when they tend to fly lower.

Figure 3. Attraction of frogs to a candle set out on a small raft. Illustration by Charles Copeland of an experiment in northern Maine or Canada described by William J Long (1901). Twelve or fifteen bullfrogs (Rana caresbeiana) *climbed on to the small raft before it flipped over.*

Within the sphere of lights, birds may collide with each other or a structure, become exhausted, or be taken by predators. Birds that are waylaid by buildings in urban areas at night often die in collisions with windows as they try to escape during the day. Artificial lighting has attracted birds to smokestacks, lighthouses (Squires and Hanson 1918), broadcast towers (Ogden 1996), boats (Dick and Donaldson 1978), greenhouses, oil platforms (Wiese *et al.* 2001), and other structures at night, resulting in direct mortality, and thus interfering with migration routes.

Many groups of insects, of which moths are one well-known example (Frank 1988), are attracted to lights. Other taxa showing the same attraction include lacewings, beetles, bugs, caddisflies, crane flies, midges, hoverflies, wasps, and bush crickets (Eisenbeis and Hassel 2000; Kolligs 2000; Figure 4). Attraction depends on the spectrum of light – insect collectors use ultraviolet light because of its attractive qualities – and the characteristics of other lights in the vicinity.

Nonflying arthropods vary in their reaction to lights. Some nocturnal spiders are negatively phototactic (ie repelled by light), whereas others will exploit light if available (Nakamura and Yamashita 1997). Some insects are always positively phototactic as an adaptive behavior and others always photonegative (Summers 1997). In arthropods, these responses may also be influenced by the frequent correlations between light, humidity, and temperature.

Natural resource managers can exploit the responses of animals to lights. Lights are sometimes used to attract fish to ladders, allowing them to bypass dams and power plants (Haymes *et al.* 1984). Similarly, lights can attract larval fish to coral reefs (Munday *et al.* 1998). In the terrestrial realm, dispersing mountain lions avoid lighted areas to such a degree that Beier (1995) suggests installing lights to deter them from entering habitats dead-ending in areas where humans live.

Reproduction

Reproductive behaviors may be altered by artificial night lighting. Female *Physalaemus pustulosus* frogs, for example, are less selective about mate choice when light levels are increased, presumably preferring to mate quickly and avoid the increased predation risk of mating activity (Rand *et al.* 1997). Night lighting may also inhibit amphibian movement to and from breeding areas by stimulating phototactic behavior. Bryant Buchanan (pers comm) reports that frogs in an experimental enclosure stopped mating activity during night football games, when lights from a nearby stadium increased sky glow. Mating choruses resumed only when the enclosure was covered to shield the frogs from the light.

In birds, some evidence suggests that artificial night lighting affects the choice of nest site. De Molenaar *et al.*

Courtesy of PJ DeVries

Figure 4. Thousands of mayflies carpet the ground around a security light at Millecoquins Point in Naubinway on the Upper Peninsula of Michigan.

(2000) investigated the effects of roadway lighting on black-tailed godwits (*Limosa l. limosa*) in wet grassland habitats. Breeding densities of godwits were recorded over 2 years, comparing lighted and unlighted conditions near a roadway and near light poles installed in a wet grassland away from the road influence. When all other habitat factors were taken into account, the density of nests was slightly but statistically lower up to 300 m away from the lighting at roadway and control sites. The researchers also noted that birds nesting earlier in the year chose sites farther away from the lighting, while those nesting later filled in sites closer to the lights.

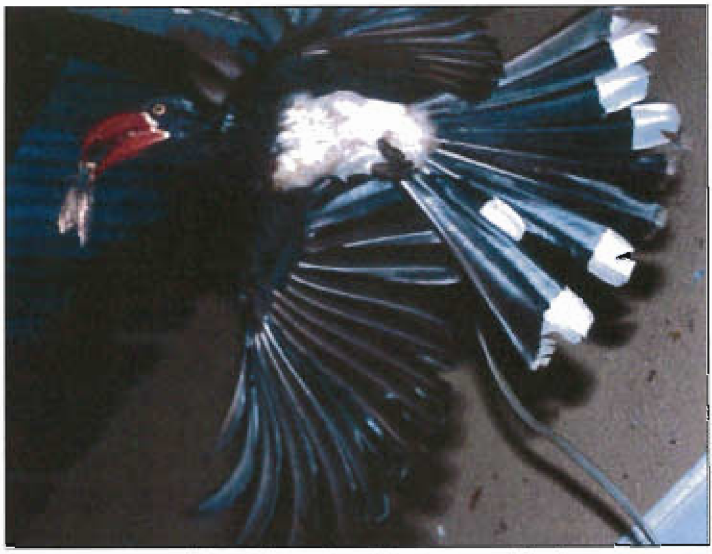
Courtesy of PJ DeVries

Figure 5. *Crowned hornbill (*Tockus alboterminatus*) hawking insects at a light at the Kibale Forest National Park, Uganda.*

Communication

Visual communication within and between species may be influenced by artificial night lighting. Some species use light to communicate, and are therefore especially susceptible to disruption. Female glow-worms attract males up to 45 m away with bioluminescent flashes; the presence of artificial lighting reduces the visibility of these communications. Similarly, the complex visual communication system of fireflies could be impaired by stray light (Lloyd 1994).

Artificial night lighting could also alter communication patterns as a secondary effect. Coyotes (*Canis latrans*) group howl and group yip-howl more during the new moon, when it is darkest. Communication is necessary either to reduce trespassing from other packs, or to assemble packs to hunt larger prey during dark conditions (Bender *et al.* 1996). Sky glow could increase ambient illumination to eliminate this pattern in affected areas.

Because of the central role of vision in orientation and behavior of most animals, it is not surprising that artificial lighting alters behavior. This causes an immediate conservation concern for some species, while for other species the influence may seem to be positive. Such "positive" effects, however, may have negative consequences within the context of community ecology.

Community ecology

The behaviors exhibited by individual animals in response to ambient illumination (orientation, disorientation) and to luminance (attraction, repulsion) influence community interactions, of which competition and predation are examples.

Competition

Artificial night lighting could disrupt the interactions of groups of species that show resource partitioning across illumination gradients. For example, in natural communities, some foraging times are partitioned among species that prefer different levels of lighting. The squirrel treefrog (*Hyla squirrela*) is able to orient and forage at lighting levels as low as 10^{-5} lux and under natural conditions typically will stop foraging at illuminations above 10^{-3} lux (Buchanan 1998). The western toad (*Bufo boreas*) forages only at illuminations between 10^{-1} and 10^{-5} lux, while the tailed frog (*Ascaphus truei*) forages only during the darkest part of the night at below 10^{-5} lux (Hailman 1984). While these three species are not necessarily sympatric (ie inhabiting the same area), and differ in other niche dimensions, they illustrate the division of the light gradient by foragers.

Many bat species are attracted to insects that congregate around light sources (Frank 1988). Although it may seem that this is a positive effect, the increased food concentration benefits only those species that exploit light sources and could therefore result in altered community structure. Faster-flying species of bats congregate around lights to feed on insects, but other, slower-flying species avoid lights (Blake *et al.* 1994; Rydell and Baagøe 1996).

Changes in competitive communities occur as diurnal species move into the "night light niche" (Schwartz and Henderson 1991). This concept, as originally described, applies to reptiles, but easily extends to other taxa, such as spiders (Frank pers comm) and birds (Hill 1990; Figure 5).

Predation

Although it may seem beneficial for diurnal species to be able to forage longer under artificial lights, any gains from increased activity time can be offset by increased predation risk (Gotthard 2000). The balance between gains from extended foraging time and risk of increased predation is a central topic for research on small mammals, reptiles, and birds (Kotler 1984; Lima 1998). Small rodents forage less at high illumination levels (Lima 1998), a tendency also exhibited by some lagomorphs (Gilbert and Boutin 1991), marsupials (Laferrier 1997), snakes (Klauber 1939), bats (Rydell 1992), fish (Gibson 1978), aquatic invertebrates (Moore *et al.* 2000), and other taxa.

Unexpected changes in light conditions may disrupt predator–prey relationships. Gliwicz (1986, 1999) describes high predation by fish on zooplankton during nights when the full moon rose hours after sunset. Zooplankton had migrated to the surface to forage under cover of darkness, only to be illuminated by the rising moon and subjected to intense predation. This "lunar light trap" (Gliwicz 1986) illustrates a natural occurrence, but unexpected illumination from human sources could disrupt predator–prey interactions in a similar manner, often to the benefit of the predator.

Available research shows that artificial night lighting disrupts predator–prey relationships, which is consistent with the documented importance of natural light regimes in mediating such interactions. In one example, harbor seals (*Phoca vitulina*) congregated under artificial lights to eat juvenile salmonids as they migrated downstream; turning the lights off reduced predation levels (Yurk and Trites 2000). Nighttime illumination at urban crow roosts was higher than at control sites, presumably because this helps the crows avoid predation from owls (Gorenzel and Salmon 1995). Desert rodents reduced foraging activity when exposed to the light of a single camp lantern (Kotler 1984). Frank (1988) reviews predation by bats, birds, skunks, toads, and spiders on moths attracted to artificial lights. Mercury vapor lights, in particular, disrupt the interaction between bats and tympanate moths by interfering with moth detection of ultrasonic chirps used by bats in echolocation, leaving moths unable to take their normal evasive action (Svensson and Rydell 1998).

From these examples, it follows that community structure will be altered where light affects interspecific interactions. A "perpetual full moon" from artificial lights will favor light-tolerant species and exclude others. If the darkest natural conditions never occur, those species that maximize foraging during the new moon could eventually be compromised, at risk of failing to meet monthly energy budgets. The resulting community structure would be simplified, and these changes could in turn affect ecosystem characteristics.

■ Ecosystem effects

The cumulative effects of behavioral changes induced by artificial night lighting on competition and predation have the potential to disrupt key ecosystem functions. The spillover effects from ecological light pollution on aquatic invertebrates illustrates this point. Many aquatic invertebrates, such as zooplankton, move up and down within the water column during a 24-hour period, in a behavior known as "diel vertical migration". Diel vertical migration presumably results from a need to avoid predation during lighted conditions, so many zooplankton forage near water surfaces only during dark conditions (Gliwicz 1986). Light dimmer than that of a half moon ($<10^{-1}$ lux) is sufficient to influence the vertical distribution of some aquatic invertebrates, and indeed patterns of diel vertical migration change with the lunar cycle (Dodson 1990).

Moore *et al.* (2000) documented the effect of artificial light on the diel migration of the zooplankton *Daphnia* in the wild. Artificial illumination decreased the magnitude of diel migrations, both in the range of vertical movement and the number of individuals migrating. The researchers hypothesize that this disruption of diel vertical migration may have substantial detrimental effects on ecosystem health. With fewer zooplankton migrating to the surface to graze, algae populations may increase. Such algal blooms would then have a series of adverse effects on water quality (Moore *et al.* 2000).

The reverberating effects of community changes caused by artificial night lighting could influence other ecosystem functions. Although the outcomes are not yet predictable, and redundancy will buffer changes, indications are that light-influenced ecosystems will suffer from important changes attributable to artificial light alone and in combination with other disturbances. Even remote areas may be exposed to increased illumination from sky glow, but the most noticeable effects will occur in those areas where lights are close to natural habitats. This may be in wilderness where summer getaways are built, along the expanding front of suburbanization, near the wetlands and estuaries that are often the last open spaces in cities, or on the open ocean, where cruise ships, squid boats, and oil derricks light the night.

■ Conclusions

Our understanding of the full range of ecological consequences of artificial night lighting is still limited, and the field holds many opportunities for basic and applied research. Studies of natural populations are necessary to investigate hypotheses generated in the laboratory, evidence of lunar cycles in wild populations, and natural history observations. If current trends continue, the influence of stray light on ecosystems will expand in geographic scope and intensity. Today, 20% of the area of the coterminous US lies within 125 m of a road (Riiters and Wickham 2003). Lights follow roads, and the proportion of ecosystems uninfluenced by altered light regimes is decreasing. We believe that many ecologists have neglected to consider artificial night lighting as a relevant environmental factor, while conservationists have certainly neglected to include the nighttime environment in reserve and corridor design.

Successful investigation of ecological light pollution will require collaboration with physical scientists and engineers to improve equipment to measure light characteristics at ecologically relevant levels under diverse field conditions. Researchers should give special consideration to the tropics, where the constancy of day–night lighting patterns has probably resulted in narrow niche breadths relative to illumination. Aquatic ecosystems deserve increased attention as well, because despite the central importance of light to freshwater and marine ecology, consideration of artificial lighting has so far been limited. Research on the effects of artificial night lighting will enhance understanding of urban ecosystems – the two National Science Foundation (NSF) urban Long Term Ecological Research sites are ideal locations for such efforts.

Careful research focusing on artificial night lighting will probably reveal it to be a powerful force structuring local communities by disrupting competition and predator–prey interactions. Researchers will face the challenge of disentangling the confounding and cumulative effects of other facets of human disturbance with which artificial night lighting will often be correlated, such as roads, urban development, noise, exotic species, animal harvest, and resource extraction. To do so, measurements of light disturbance should be included routinely as part of environmental monitoring protocols, such as the NSF's National Ecological Observatory Network (NEON). Future research is likely to reveal artificial night lighting to be an important, independent, and cumulative factor in the disruption of natural ecosystems, and a major challenge for their preservation.

Ecologists have studied diel and lunar patterns in the behavior of organisms for the greater part of a century (see Park 1940 and references therein), and the deaths of birds from lights for nearly as long (Squires and Hanson 1918). Humans have now so altered the natural patterns of light and dark that these new conditions must be afforded a more central role in research on species and ecosystems beyond the instances that leave carcasses on the ground.

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LIGHTS OUT!
FOR NATURE

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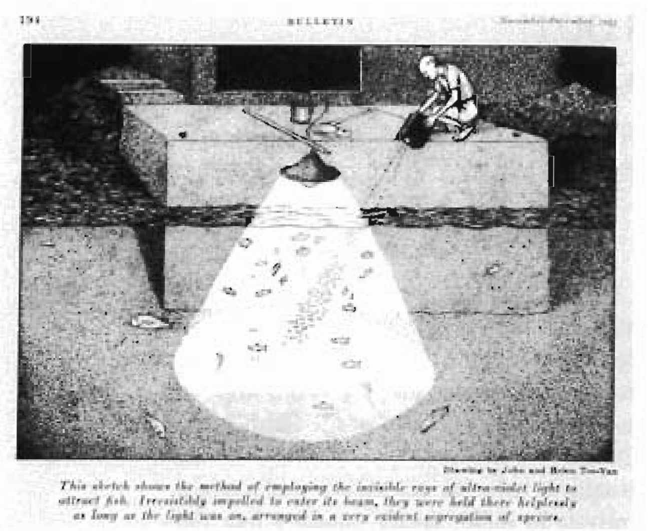
Humans have radically transformed the physical characteristics of the nighttime hours in ways that would have been unimaginable only a hundred years ago (*Figure 1*, Longcore and Rich 2004). The cost of industrial development, affluence, and mass consumption has been the loss of natural patterns of darkness over vast expanses of the Earth's surface, both on land and at sea (Cinzano et al. 2001).

Those concerned with the nighttime environment, whether scientists or advocates, regulators or lighting manufacturers, in the private or public sector, together face the challenge of restoring the night sky and natural patterns of light and dark in a global economy. We are motivated by an affinity for the night sky (Mizon 2002), respect for our natural heritage, concern for our own health (Stevens and Rea 2001, Pauley 2004), and a desire to protect the night for the other living beings with which we share the planet.

Astronomers were the first to express concern about the widespread proliferation of artificial night lighting, and they rightfully raised the alarm about the degradation of the night sky (Riegel 1973). Concern about the effects of artificial lighting on wildlife and plants has been a relatively recent phenomenon (Verheijen 1985, Upgren 1996, Outen 1998). This is not to say that scientists were not interested in the effects of light on other species. Naturalist William Beebe was fascinated with the ability of ultraviolet lights to attract juvenile fish, as documented in a sketch from an expedition in 1935 (*Figure 2*). But Beebe's observations were not motivated by concern that lights had widespread ecological consequences.

Figure 1. The view of Los Angeles from the Mount Wilson Observatory showing the extent of night lighting.

A substantial and growing body of research on the ecological effects of artificial night lighting is now available (see Rich and Longcore 2006). New scientific articles that extend this knowledge are being published at a steady rate (e.g., Oro et al. 2005, Baker and Richardson 2006, Miller 2006). Sufficient information is now available to devise policies to mitigate and avoid the range of profound, adverse consequences on other



BULLETIN

Drawing by John and Helen Tee-Van

This sketch shows the method of employing the invisible rays of ultra-violet light to attract fish. Irresistibly impelled to enter its beam, they were held there helplessly as long as the light was on, arranged in a very evident segregation of species.

Figure 2. William Beebe shows the attractive effect of different light types on fish on an expedition to Bermuda in 1935. Reprinted from the *Bulletin*, published by the former New York Zoological Society, now known as the Wildlife Conservation Society.

species caused by artificial light at night.

Urban planners and open space managers can incorporate this knowledge to better protect nature at night. Here we provide examples of three general types of impacts on wildlife: direct mortality, altered reproductive behaviors, and disrupted interactions between species. These examples give an indication of the breadth of this problem and of the opportunities for solutions.

Lights that kill

Anyone with a porch light knows that lights can kill. Many insects are attracted to their deaths at lights; in Germany alone, the estimate of total insect deaths at streetlights in a summer is 100 billion (Eisenbeis 2006).

Migratory birds are attracted to the lights on tall towers when weather conditions are adverse. In North America, an estimated 4–5 million birds are killed per year in collisions with towers, their guy wires, and each other. Most of these are Neotropical migrants, birds that migrate to Central and South America, which are already under severe population stress (Banks 1979, Shire et al. 2000, Longcore et al. 2007). Based on past patterns, we have calculated that two species of federal conservation concern, blackpoll warbler and bay-breasted warbler, suffer losses of over 100,000 individuals each year (Longcore et al. 2007). Over 10,000 individuals of an additional 20 species of conservation concern are killed annually. A change in lighting type would probably eliminate up to 80% of this mortality (Gehring and Kerlinger 2007), and the U.S. Federal Communications Commission is considering such a change based on expert testimony from us, other groups, and the U.S. Fish and Wildlife Service.

Although they are not afforded the same attention as birds, the mortality of insects can be significant. In a study along a forested stream, a single streetlight installed on the bank attracted and killed as many caddisflies as emerged from the stream along an entire 200 meter stretch (Scheibe 1999). This process is described by Professor Gerhard Eisenbeis as the "vacuum cleaner effect," vividly evoking the image of lights sucking insects out of the surrounding habitat (Eisenbeis 2006).

Beachfront lighting and sky glow threaten the survival of hatchling sea turtles and affect the nest site choice of female turtles (Witherington 1992, Salmon et al. 2000).

Hatchlings are disoriented by lights and fail to make their dash to the ocean and out to sea. This problem was identified first in the 1960s (MacFarlane 1963) and many programs have been put in place to control beachfront lighting (Salmon 2006).

Interference with reproduction

Even when lights do not kill wildlife, they can interrupt important behaviors such as those associated with reproduction. For example, stray light can wash out the visual messages between male and female fireflies (Lloyd 2006).

In a recently published article, two Canadian researchers investigated the effects of intermittent light on the reproductive behavior of northern green frogs (Baker and Richardson 2006). They counted the number of calls by males to attract mates under natural ambient darkness and under the light of a flashlight shined on them. This simulates the effects of a security light on a motion detector or the flash of lights from a passing car. The results show a significant 44% decrease in the number of calls and a 675% increase in the number of moves made by individuals (Baker and Richardson 2006).

Under different circumstances, extra light causes species to expend energy calling at night. In another recent article, current and historic singing records for American robins were used to show that males sing well before dawn only in those locations with high light levels (Miller 2006). Subsequent research on European robins concluded that daytime noise is a more important predictor of nighttime singing, although locations where birds sang at night were on average brighter than areas where birds did not sing at night (Fuller et al. 2007). Our analysis of the data reported by Fuller et al. (2007) suggests a threshold effect where increased illumination allows nocturnal singing in noisy locations; no birds sang at night at any of the darkest 20% of locations, even if the location was noisy during the day.

The effects of lighting can extend to the ocean. Seabirds are attracted to and incinerated at flares at oil platforms, migratory birds are killed running into cruise ships, and lighted squid boats each shine 30,000 Watts into the ocean (Montevecchi 2006). But even sky glow at the level of the full moon could easily disrupt the tightly synchronized spawning of corals. Under normal lunar cycles the release of coral larvae, also known as *planula*, always follows the new moon, presumably to reduce predation on these larvae. This synchronization breaks down in experiments where corals are subjected to perpetual full moon illumination (Jokiel et al. 1985).

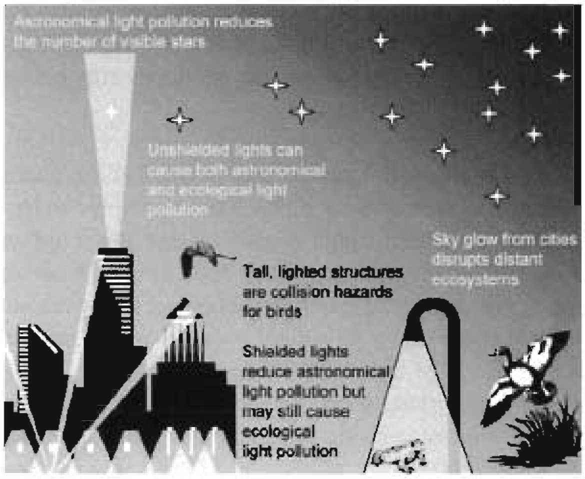


Figure 3. Ecological and astronomical light pollution is caused by lights at night. Figure reprinted from Longcore and Rich (2004).

Predators, prey, and night lights

Lights at night also disrupt ecological interactions. Predator–prey interactions are particularly vulnerable to influence by lighting. In general, additional light benefits the predator, except when the prey are found in groups where individuals warn each other of predators, such as flocks of birds and schools of fish (Longcore and Rich 2004). But examples of lights increasing nocturnal predation are many.

In a study of European storm-petrel nests in caves on an island off the coast of Spain, the birds in the cave illuminated by city lights were killed far more often by gulls than those in the cave facing away from the city (Oro et al. 2005). In addition, bird survival decreased after completion of a major lighting project in the city, declining significantly in the years that followed (Oro et al. 2005). In a separate study of black-vented shearwaters, another seabird, nesting birds were predated far more in the light of the full moon than the dark of the new moon, again by gulls (Keitt et al. 2004).

Young salmon, known as salmon fry, migrate from the streams where they hatch to the ocean. They migrate en masse at night, cued by illumination levels, and this timing is designed to reduce predation. Researchers in the Pacific Northwest documented harbor seals positioning themselves under lights on a bridge to locate and capture the outmigrating fry (Yurk and Trites 2000). When they turned off the lights, predation levels declined at first but then increased as the seals relocated under other lights from the town. They were found eating salmon fry under the lights of a ball field, a sawmill, and other urban glow (Yurk and Trites 2000).

A recent study from Florida showed alteration in the foraging behavior of beach mice under night lighting (Bird et al. 2004). Some species of these small rodents are federally endangered and they are an important part of the coastal dune ecosystem. The research found that beach mice reduced the proportion of bait stations they visited closer to lights. In addition, this pattern was found for both low-pressure sodium vapor lights, which are generally considered to have fewer environmental impacts because they are less attractive to insects, and for yellow "bug lights," which are also promoted as being turtle-friendly and mandated for this reason (Bird et al. 2004). In this example, we see that lights that reduce impacts for one species are not necessarily benign for others.

Nature needs the night

Our question, from this ecological perspective, is whether the international community is up to the challenge of restoring the night. The geographic scope is great, extending throughout the world from urban lights, roadway lights, tower lighting, light-induced fisheries, offshore oil production, and many other sources (Longcore and Rich 2004).

The range of species is also great, extending across all major taxonomic groups and habitats. Any species that evolved with natural patterns of light and dark is potentially susceptible to adverse effects of artificial lighting. Direct glare, sky glow, and steady and intermittent lights from urban to rural environments, both on land and at sea, all alter the nighttime environment, causing both ecological and astronomical light pollution (Longcore and Rich 2004).

Unfortunately, there is no one-size-fits-all solution to mitigate the effects of artificial night lighting on nature. Some species are sensitive to yellow light, others to blue.

As we have seen, turtle-friendly lights still disrupt foraging of endangered beach mice (Bird et al. 2004). Attraction of migratory birds to tall towers can be reduced by using flashing lights (Gauthreaux and Belser 2006), while flashing lights in other contexts would be detrimental. Effective solutions will be place- and habitat-specific, such as a road in Florida where lights that attract turtles were replaced by LED lights embedded in the pavement (*Figure 4*, Salmon 2006).

Our message is simple. Nature needs the night. Substantial progress has been made in understanding the many effects of light on other species and indeed on humans as well. We hope that readers will put this knowledge to work — as researchers, as advocates, as regulators, and as informed citizens.

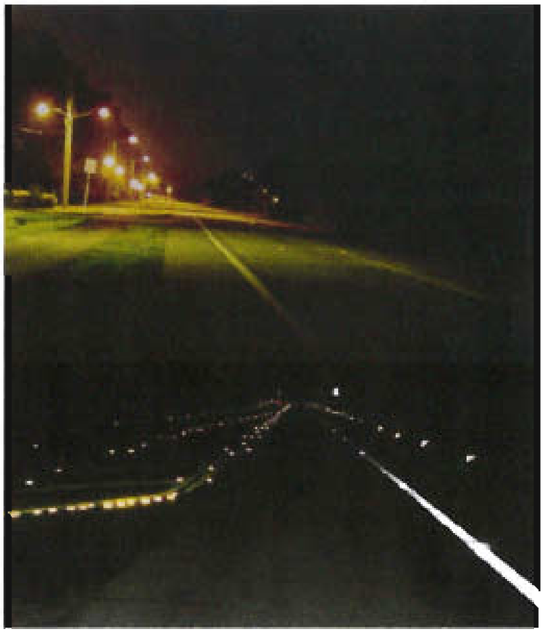


Figure 4. An example of embedded roadway lighting from Boca Raton, Florida. In the top view, the streetlights are visible from the sea turtle nesting beach, while the embedded lights in the lower view are not visible from the beach (Bertolotti and Salmon 2005). Figure reprinted from "Protecting Sea Turtles from Artificial Night Lighting at Florida's Oceanic Beaches" by Michael Salmon. Found in *Ecological Consequences of Artificial Night Lighting* by Catherine Rich and Travis Longcore, eds. Copyright © 2006 Island Press. Reproduced by permission of Island Press, Washington, D.C.

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esa ECOSPHERE

CONCEPTS & THEORY

The influence of artificial light on stream and riparian ecosystems: questions, challenges, and perspectives

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Abstract. Artificial light at night is gaining attention for its potential to alter ecosystems. Although terrestrial ecologists have observed that artificial light at night may disrupt migrations, feeding, and other important ecological functions, we know comparatively little about the role artificial light might play in disrupting freshwater and riparian ecosystems. We identify and discuss four future research domains that artificial light may influence in freshwater and associated terrestrial ecosystems, with an emphasis on running waters: (1) dispersal, (2) population genetics and evolution, (3) ecosystem functioning, and (4) potential interactions with other stressors. We suggest that future experimental and modeling studies should focus on the effects of different spectral emissions by different light sources on freshwater organisms, the spatial and temporal scale over which artificial light acts, and the magnitude of change in light at night across the landscape relative to the distribution of running and standing waters. Improved knowledge about the effects of artificial light on freshwater ecosystems will inform policy decisions about changes to artificial light spectral emissions and distributions.

Key words: aquatic invertebrates; artificial illumination; ecosystems; fish; multiple stressors; riparian; streams; urbanization.

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Introduction

Human activities influence and have modified the majority of the Earth's ecosystems (Vitousek et al. 1997). Freshwater ecosystems are especially affected, both because they accumulate and integrate the effects of activities within their catchments, and because they have always been preferred sites for human activities (Ricciardi and Rasmussen 1998, Dudgeon et al. 2006, Balian et al. 2008).

The effects of chemical pollution (Likens et al. 1996), alteration to natural flows (Poff et al. 1997) and nutrient cycles (Turner and Rabalais 1991), invasive species (Ricciardi and Rasmussen 1998), increasing urbanization (Morely and Karr 2004), and loss of riparian margins (Sweeney et al. 2004) on freshwater ecosystems have influenced policy decisions for the past 40–50 years (e.g., the USA Environmental Protection Agency's Clean Water Act of 1972). In contrast, the influence of artificial lighting as a human-induced impact affecting freshwater systems has only been recognized in the past 10 years or so (Moore et al. 2000, Longcore and Rich 2004, Moore et al. 2006, Nightingale et al. 2006), and there are still many gaps in empirical knowledge. This is despite the fact that the use of artificial lighting is now widespread and has increased over the past century (Holden 1992). While Cinzano et al. (2001) reported that approximately 67% of Americans and 20% of people world-wide now live in locations where Milky Way is no longer visible due to interference from artificial light sources, the wider effects of artificial light on other organisms and on ecosystems are poorly quantified. While many studies have focused on the control of natural light on biorhythms (Bishop 1969, Grau et al. 1981), few have looked at the potential of artificial light as a disrupter of these rhythms (Moore et al. 2000). This is surprising as approximately 30% of vertebrates and 60% of invertebrates are nocturnal (Hölker et al. 2010*a*) and could, therefore, be highly influenced by the presence of artificial light.

Longcore and Rich (2004) and Navara and Nelson (2007) presented broad reviews of artificial light and summarized a range of evidence, yet over two thirds of their examples relate to terrestrial organisms. Both Moore et al. (2006) and Nightingale et al. (2006) identified some effects of artificial light on lakes and fish, but in general, freshwater ecosystems are poorly represented in the current literature. An initial search of Web of Science (13 October 2011) of peer-reviewed literature using various terms relating to human alterations and ecosystems revealed a noticeable lack of research on artificial light and freshwater systems, especially when compared to other common pressures to which these systems are subjected (Table 1). This is despite freshwaters having high biodiversity and being disproportionally affected by species loss. Globally, freshwaters are inhabited by more than 125,000 known species, and even though freshwaters cover only about 0.8% of the Earth's surface, they are home to about 9.5% of all animal species, and one-third of all vertebrates (Balian et al. 2008). Nevertheless, there have been some seminal contributions to our understanding, for example in the use of artificial lights to: (1) increase fish growth rates in hatcheries (Boeuf and Le Bail 1999), (2) understand how it influences zooplankton movements (Moore et al. 2000), and (3) guide fish around dangerous in-stream structures (Johnson et al. 2005).

Table 1. Number of references returned on a Web of Science search (13 October 2011) for various human impacts and ecosystem type terms.

	Ecosystem term			
Human impact term	River	Lake	Wetland	Riparian
"Artificial light"	7	8	0	1
"Light pollution"	4	4	0	0
"Environmental flows"	90	14	9	24
"Climate change"	241	213	64	41

Notes: Terms were searched for in the category of "Topic," with lemmatization option off. "Ecology" was added as term to all searches to limit results to ecologically relevant papers.

Here, we attempt to redress the balance in available literature to date by focusing on freshwaters, and in particular streams with their associated riparian margins, defined as areas that are "transitional semiterrestrial areas regularly influenced by fresh water, usually extending from the edges of water bodies to the edges of upland communities" (Naiman et al. 2005:2). We give special attention to adult aquatic insects, as they represent a key in the exchange of nutrients between stream and riparian systems (Richardson et al. 2010).

Our goal is to illustrate how artificial light influences species interactions and processes in stream and riparian ecosystems, and to stimulate research in an area that we consider of major importance for their future conservation and management. Ecologists have only recently started to acknowledge the alteration of the nightscape as a major concern in conservation policy and freshwaters are no exception (Rich and Longcore 2006, Hölker et al. 2010*a*).

RESEARCH DOMAINS

We begin by presenting four major research domains relating to the ways artificial light can

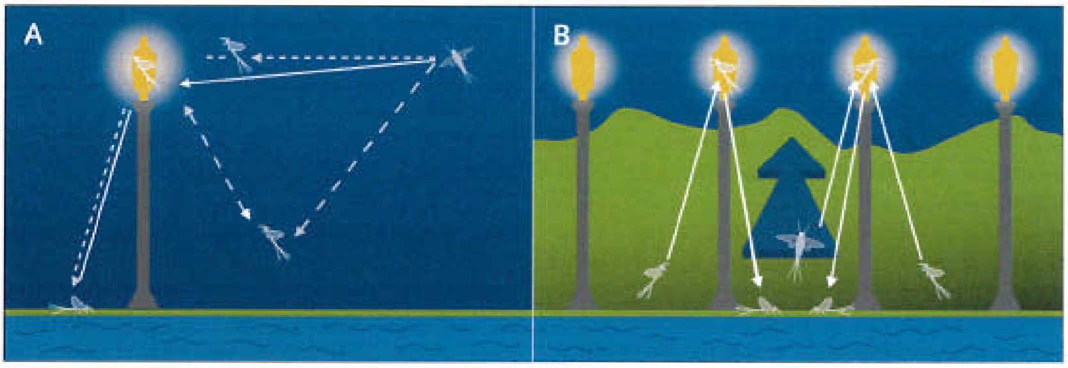

Fig. 1. Eisenbeis (2006:281–304) proposes three different ways for artificial lights to trap flying insects. Two are shown here: fixation (dashed line), captivity (dotted line), and directly lethal (solid line) effects (A) and the crash barrier effect (B). Fixated insects do not suffer mortality directly from artificial light, but are stunned by it and are easy targets for predators or fail to engage in basic behaviors, such as reproduction. Captive insects fly to the light and circle around it endlessly until they die of exhaustion or are consumed by predators. The crash barrier effect is the result of a row of lights (like those lining a street) preventing the dispersal of insects through their attractive properties.

act on stream and riparian ecosystems, through altering: dispersal, population genetics and evolution, ecosystem functioning, and interactions with other common stressors; and then outline a range of key research questions which need addressing.

Dispersal

There is evidence that artificial lights located near streams change the behavior of adult aquatic insects as they disperse through the terrestrial environment. Eisenbeis (2006) proposes three different ways for artificial lights to trap flying insects (Fig. 1). The first is through fixation or captivity effects (Fig. 1A). Here insects located near lights fly directly to them and are killed immediately, or they circle close to the light and are unable to leave eventually dying from exhaustion, predation, or heat. The lights may also induce settling behavior that incapacitates the insects, rendering them easy targets for predators. The second mechanism is the crash barrier effect (Fig. 1B), where insect dispersal and migration are impeded by running into a "barrier" of lights, such as a row of street lights. The final mechanism is termed the vacuum cleaner effect, whereby insects from a large area are attracted to a nearby light source. However, these are only hypotheses and carefully designed experiments are needed to determine how much of an effect these mechanisms actually play in disrupting aquatic insect dispersal.

Studies comparing different trapping techniques provide evidence for the vacuum cleaner effect. These studies illustrate that light traps differentially capture certain insects (e.g., Trichoptera) more readily than other kinds of traps (e.g., Collier and Smith 1998). While the height of streetlights is designed to maximize safety for car drivers, lights that are used along walking and bike paths, as well as those used for decorative purposes could be adjusted to attract fewer insects, if we can predict which heights have the highest concentrations of insects based on landscape features and insect species. Svensson (1974) found that light traps at 11 and 50 m height captured fewer trichopterans than those at 1 m due to the propensity of several species to fly low to the ground, suggesting that higher lights might trap fewer insects than lower lights, but this has yet to be generalized across taxa and habitats.

Overall, research on insect dispersal, especially adult aquatic insect dispersal, is extremely limited. Part of this lack is that it is very difficult to rigorously study insect dispersal. Stable isotope and elemental markers are potentially valuable tools, as is the increasing use of genetic analysis (Smock 2007); however, capturing insects in substantial numbers generally requires the use of light or pheromone traps. While these methods are adequate for most studies of aquatic insect dispersal, light traps cannot be used in studies of artificial light as they obviously create a confounding factor. In addition, while population genetic analyses hold promise for longer-term studies and determining if populations adapt to artificial light, they are not really useful as a tool for short-term dispersal studies.

It is also unclear how much the dispersal of adult aquatic insects matters for the population dynamics of these organisms. Masters et al. (2007) found that the recovery of the benthos from acidification is not limited by adult dispersal. Furthermore, Bunn and Hughes (1997) calculated that it is likely that populations of *Tasiagma* spp. (Trichoptera) in a reach are maintained through the reproduction of only 3–12 females per generation. It is not obvious how much of an effect land use changes have on adult aquatic insect dispersal (Petersen et al. 2004); however, studying the effects of artificial light on insect dispersal will likely further this field.

Clearly, we need to come up with new and innovative ways to study aquatic insect dispersal. One possibility is to use Malaise traps to capture individuals marked with fluorescent dyes or stable isotope tracers (Macneale et al. 2005). Conducting more basic studies of aquatic insect dispersal will help those studying the effects of artificial light to develop hypotheses (e.g., the effect of light height, light distances from streams) more effectively.

Aquatic insects are not the only stream organisms that may have their dispersal interrupted by the addition of artificial lights. It is well established that the migration of Pacific salmon species (*Oncorhynchus* spp.) can be slowed or stopped by the presence of artificial lights (Nightingale et al. 2006). Furthermore, exposure to constant light can decrease smoltification and increase the deterioration in body condition associated with smoltification in chinook salmon (*O. tshawytscha*) (Hoffnagle and Fivizzani 1998). This might be due to the synchronization of downstream migration with the new moon; however, it is possible that the lunar timing of downstream migration is stock-dependent (Hoffnagle and Fivizzani 1998). It is likely that any species that uses lunar cycles to cue migration or dispersal will be disrupted by the addition of artificial lights (see *Key Research Questions*; Fig. 2).

Population genetics and evolution

To our knowledge, no one has yet experimentally investigated the possibility that artificial light can act as an evolutionary force in freshwater or riparian species. However, its potential to influence evolution has received attention from Moore et al. (2006) and Nightingale et al. (2006).

Artificial light at night could reduce effective population sizes through the direct loss of individuals, reproductive failure, or changes to sex ratios. The direct mortality of individuals is probably most likely in the case of aquatic insects; either through the attraction of the adults to lights (Scheibe 2003, Eisenbeis 2006), or increased predation through improved predator vision. However, mid-trophic fish species could also suffer higher rates of predation under artificial light (see: *Ecosystem functioning: Food webs*). Reproductive failure could be due to the inability to locate suitable mates, as in the case of several amphibian species (Longcore and Rich 2004). Aquatic insects are again likely to suffer

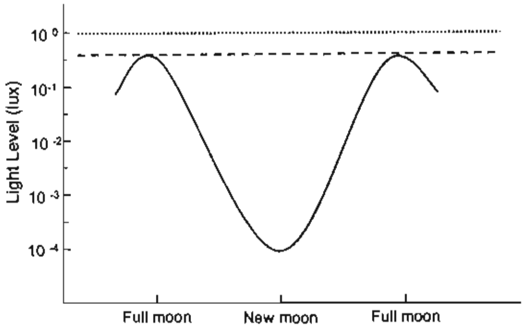

Fig. 2. Sky glow eliminates monthly variation in light levels. The solid line shows the natural light provided by a full moon in a temperate region. The dashed line is the light level measured in the center of Berlin on a clear night and is roughly equivalent to a full moon, while the dotted line is the light level in the center of Berlin on a cloudy night and is roughly four times greater (Kyba et al. 2011). The y-axis is logarithmic.

from changes to sex ratios, as there are often biases in light trap catches, depending on the species (Waringer 1989).

Reduction in effective population sizes will lead to less genetic diversity and possibly genetic drift; leaving a population with insufficient variation to adapt to future stressors, and therefore is a major concern for species conservation (Lande and Barrowclough 1987). If some populations are eliminated, it could result in reduced gene flow across the range of some species, with the potential to lead to the diversification of populations and potentially even speciation.

There is already some evidence that other environmental stressors alter genotype frequencies in a population. Populations of a common aquatic insect (*Chironomus riparius*) that were exposed to a chemical stressor (tributyltin) in a laboratory study had increased rates of larval mortality and reduced genetic variation (Nowak et al. 2009). This result was especially significant because the changes were seen in neutral markers, not in response genes, and therefore represent a true reduction in effective population size. Conversely, mosquitoes living on an arid slope showed increasing diversity (due to higher rates of recombination and mutation) as a result of exposure to greater environmental stress, such as increased temperatures and solar radiation, than those living on a humid slope of the same valley (Nevo 2001). Furthermore, females from the arid slope showed an increased tendency to mate with males that were also from the arid slope, potentially leading to sympatric speciation between the two groups (Nevo 2001). While it might be difficult to forecast which species will have increased or decreased genetic diversity, artificial light could also change the frequency of heritable behaviors that could influence the evolution of organisms.

Mating and reproductive behaviors in freshwater species are likely to be influenced by artificial light (Moore et al. 2006, Nightingale et al. 2006). Sexual selection for traits that are visually stimulating could increase or decrease with exposure to artificial light, depending on the spectral qualities of the light and species' visual sensitivities. For instance, cichlid fishes undergo strong sexual selection that favors brightly colored individuals and has driven speciation events in populations in clear water that allows plenty of light (Seehausen et al. 1997). The effects of artificial light on sexual selection could be especially interesting and unpredictable, given the common use of high pressure sodium lamps, which have a very limited emission spectra and could prevent females from recognizing male color patterns (Fig. 3). This has taken place in Lake Victoria, where turbidity from eutrophication reduces the spectral range of light entering the water to wavelengths that are similar to the emission spectra of high pressure sodium lamps, and reduces female selectivity based on color (Seehausen et al. 1997). Similarly, guppy habitat specialization has been driven by a combination of diverse ambient light conditions, predation, and sexual selection (Endler 1992). The introduction of artificial light to these streams could lead to the visual homogenization of these environments, which could lead to reduced speciation as well as increasing susceptibility to predation.

Other behaviors that could be influenced by artificial light that are potentially important to evolution are feeding behaviors. Some spiders are more likely to build their webs in close proximity to artificial light to take advantage of the increased densities of insects found at lights (Heiling 1999). If there is a genetic basis for this behavior, then the presence of artificial light could very well contribute to the evolution of this species. Ultimately, any behavior that could be altered by artificial light and is under genetic control could allow artificial light to change the evolution of a species exhibiting such a behavior.

It is also important to consider the effect of artificial light in combination with species interactions in driving rapid evolutionary change, which could lead to altered ecological dynamics, e.g., different guppy phenotypes result in altered ecosystem structure and function (Schoener 2011). To test if artificial light causes rapid evolution of exposed organisms, researchers could hatch diapausing copepod eggs that were laid before artificial light became widespread. The feeding and diel vertical migration (DVM) behavior of pre-lighting and modern copepods could then be compared (Hairston et al. 1995). To determine what percentage of the behavioral change is really due to evolution, and not some other ecological factor, genetic techniques should be used to identify genes that are likely respon-

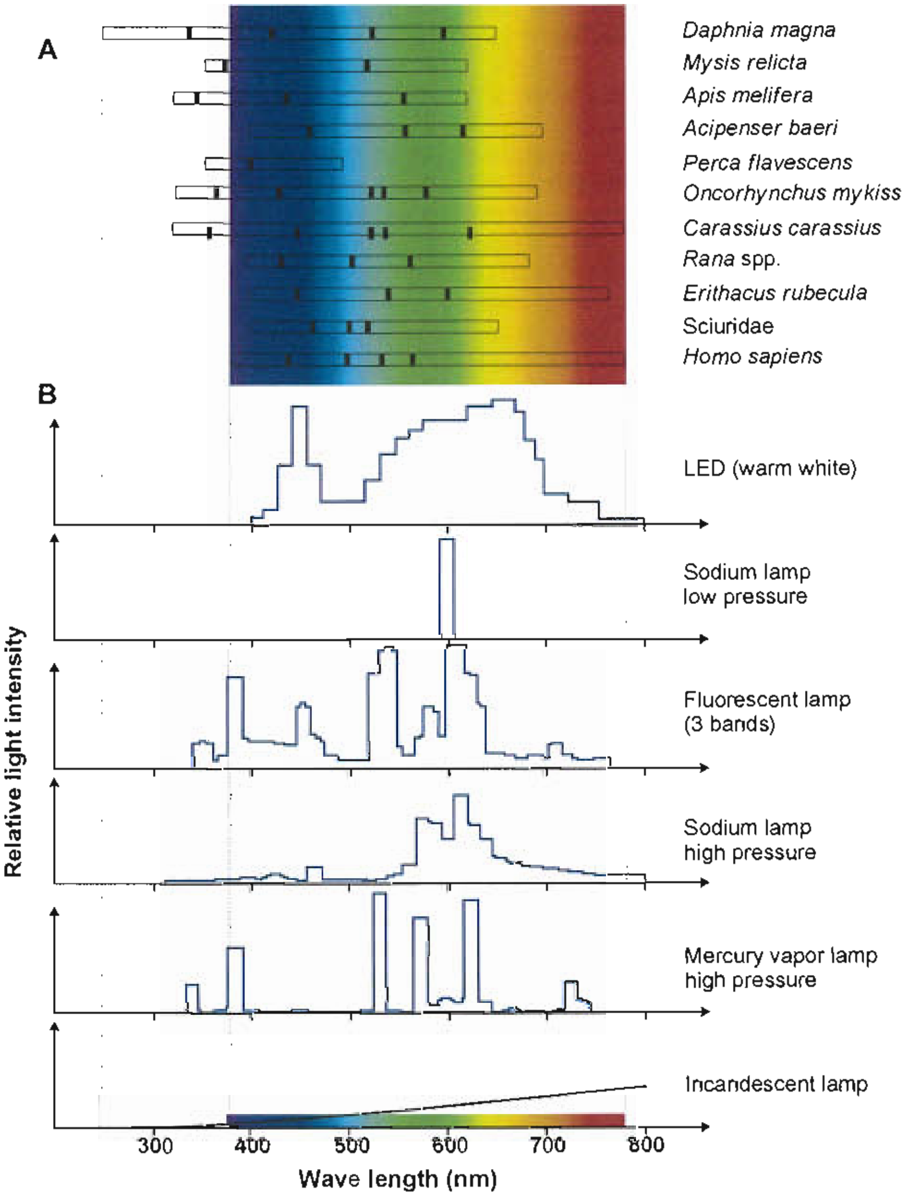

Fig. 3. The light sensitivities of various animals are displayed against a background of wavelengths that humans perceive as visible light (A). The black ovals represent the peak sensitivities for each organism; note that some organisms have sensitivities in the UV range. The dashed vertical lines designate the limits of the UV (10–400 nm) and human-visible light (390–750 nm) (Menzel and Blakers 1976, Smith and Macagno 1980, Lythgoe 1984, Loew and Wahl 1991, Fratzer et al. 1994, Hawryshyn and Hárosi 1994, Vorobyev and Osorio 1998, Gal et al. 1999, Wiltschko and Wiltschko 1999, Sillmann and Dahlin 2004). The wavelengths of light emitted from various artificial light sources (B) are highly variable, with some emitting light over a broad spectrum and others having only a few narrow peaks.

sible for the observed behavior and then tested to ensure that they are responsive to altered light conditions and change organism behavior (Hairston et al. 2005, Fussmann et al. 2007). Furthermore, it will be beneficial to establish if any of these rapid evolutionary changes results in genetic isolation, and eventually, speciation (Hendry et al. 2007).

Ecosystem functioning

As previously addressed by Moore et al. (2000), Longcore and Rich (2004), and Moore et al. (2006), we expect that modified lighting regimes will lead to a range of whole freshwater ecosystem changes and also influence the linkages between freshwater and riparian ecosystems. Of particular interest is how artificial light could alter the exchange of organic matter between stream and riparian systems. Artificial light could influence ecosystems in ways that might be unexpected from single species studies, e.g., by changing species interactions, especially predator-prey interactions, and therefore have important conservation implications (Wooten et al. 1996).

Primary production.—Primary production is a key ecosystem process controlled by light. To our knowledge, only one study has found evidence that riparian vegetation could be influenced by the presence of artificial light at night (Cathey and Campbell 1975). Their work illustrated that trees and shrubs exposed to streetlamps, particularly incandescent or high pressure sodium luminaires, may have longer growing periods, earlier leaf-out and later leaf fall times than those in darker environments (Cathey and Campbell 1975). This may have a range of bottom-up effects. For example, earlier leaf-out could cause earlier inputs of terrestrial insects (that use riparian vegetation as habitat) to freshwater systems, but only if terrestrial insects are able to use this new habitat resource. Later leaf fall could result in a mismatch of resources and consumers, as detritivorous aquatic invertebrate taxa might have evolved to match the timing of the allochthonous inputs of leaves with critical life stages (Hershey and Lamberti 1998:169–199). However, substantial changes in leaf-out/fall and growth are unlikely unless artificial lights are present with warmer temperatures that allow for a longer growing season (Cathey and Campbell 1975). While this situation is currently unlikely in temperate climates, global temperatures are projected to increase by 0.6–6.4°C in the next 90 years, with greater warming in northern temperate regions (IPCC 2007), which would increase the chances that artificial light might influence riparian vegetation. The effects of increased temperatures and light could be studied in urban areas that not only have increased levels of artificial light, but also artificially high temperatures due to the heat island effect (Oke 1973).

Food webs.—Light is an important cue for both predator avoidance and feeding in freshwater systems. Aquatic invertebrates in lotic systems drift at light levels below 10^{-3} lux (at 400–535 nm) to avoid predation by fish (Bishop 1969). However, Atlantic salmon have been shown to change foraging strategies below light levels of 10^{-1} lux, moving to areas of slow-moving water that, while not as rich in prey, allow more time for identification of prey items and night-time foraging (Metcalfe et al. 1997). Light adaptations are also evident in lentic environments, where zooplankton engage in DVM in the water column to feed on phytoplankton during the night when they are less visible to predators (Young and Watt 1996). Moore et al. (2000) were able to detect a decrease in the amplitude of DVM in *Daphnia retrocurva* as a result of artificial light from a nearby city, by monitoring the vertical migration inside darkened versus clear enclosures. Light intensity also had a significant influence on the ability of vendace (*Coregonus albula*) to feed on *Daphnia magna*, with declining efficiency down to a threshold of 0.05 lux (Ohlberger et al. 2008). On the other hand, a decrease in feeding movements to avoid artificial light has been observed in vendace (Schmidt et al. 2009). These studies suggest that artificial light can result in altered food webs in lentic systems, leading to increased algal biomass as zooplankton spend less time in the upper euphotic water column feeding on algae (Moore et al. 2000, Moore et al. 2006). Lotic systems could see higher relative abundances of armored grazers, such as glossosomatid caddisflies or snails, as invertebrates with less physical protection, such as mayflies, are eliminated through heavy predation (McNeely et al. 2007). In this case, there would eventually be a reduced number of

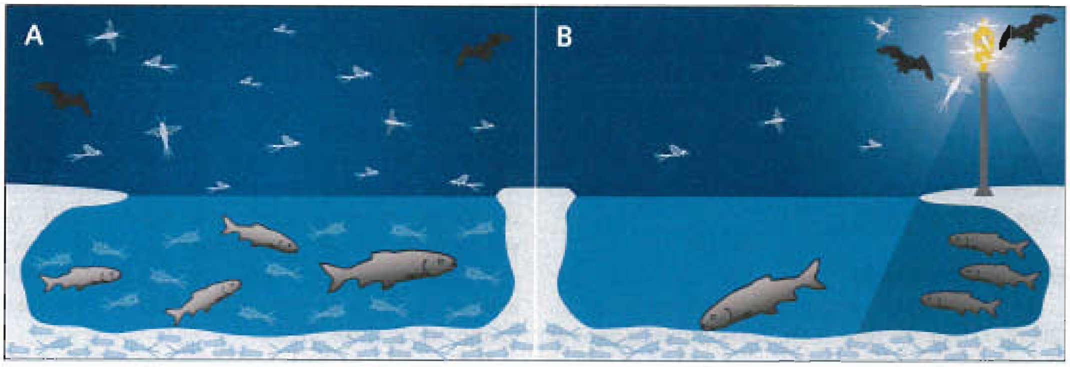

Fig. 4. A schematic of a stream ecosystem under natural nighttime conditions (A), and the same system under the influence of artificial light (B). Note the predicted shifts as light is introduced from A to B in the positions of small fishes seeking cover, suppression of streaminvertebrate drift, adult insects attracted to lights, and bats shifting their foraging efforts near the lights. Refer to *Ecosystem functioning: Food webs* in the text for details.

invertebrates available to fish predators, but if there are adequate numbers of protected invertebrate grazers, they would likely control lotic algal standing biomass.

We expect that artificial light at night not only influences freshwater food webs (Fig. 4), but also the exchange of materials between stream and riparian environments (Richardson et al. 2010; Fig. 5), which can be mediated by predators (Baxter et al. 2004). Accordingly, one key question here is how artificial light changes predator-prey relationships. Some species might be able to exploit artificial light to extend foraging opportunities, at least in the short-term (Moore et al. 2006, Nightingale et al. 2006). One example of this is the spiders who build their webs near light sources (Heiling 1999). However, foraging benefits, if they exist, may be short-lived due to resulting reductions in prey populations (Beier 2006). This will probably depend on the trophic structure of specific food webs, as apex predators will benefit more than mid-trophic species that have to avoid predation themselves.

Patterns of invertebrate drift and fish feeding are both likely to change under the influence of artificial light (Moore et al. 2006, Nightingale et al. 2006). If fish are able to feed much more efficiently on drifting insects, it could result in a decrease of emerging aquatic insects. However, light is known to depress drift rates (Bishop 1969); if fish are more active under artificial lights but prey is less available, fish could suffer from increased energetic demands. Conversely, the number of terrestrial invertebrates entering the stream and available for fish to prey on could also change. Under natural conditions, terrestrial insects are an important allochthonous resource for fish (Fig. 4A). Kawaguchi and Nakano (2001) found that terrestrial insects contribute about 50% of the total annual prey consumption of salmonids in some Japanese streams, while about 84% of the consumption in a cyprinid (*Alburnus alburnus*) in a German lake comes from terrestrial sources (Mehner et al. 2005). In the presence of artificial light near a waterbody, terrestrial insects could become an even more important food source for fish. On the other hand, juvenile and other vulnerable fish might retreat to overhangs and reduce foraging efforts in order to avoid predation (Nightingale et al. 2006; Fig. 4B).

While adult aquatic insect flight in a dark riparian forest might normally be restricted to areas immediately adjacent to streams (Petersen et al. 1999), insects may cluster around artificial lights located in floodplains (Figs. 1, 5). Many aquatic insects emerge at night (Tobias 1967, Jackson 1988, Pinder et al. 1993), and are therefore vulnerable to attraction to artificial lighting while in their adult phase. We hypothesize that as the distance of an artificial light source from a water body increases, the proportion of freshwater carbon transferred to the terrestrial ecosystem increases relative to a riparian system that does not have lights, as

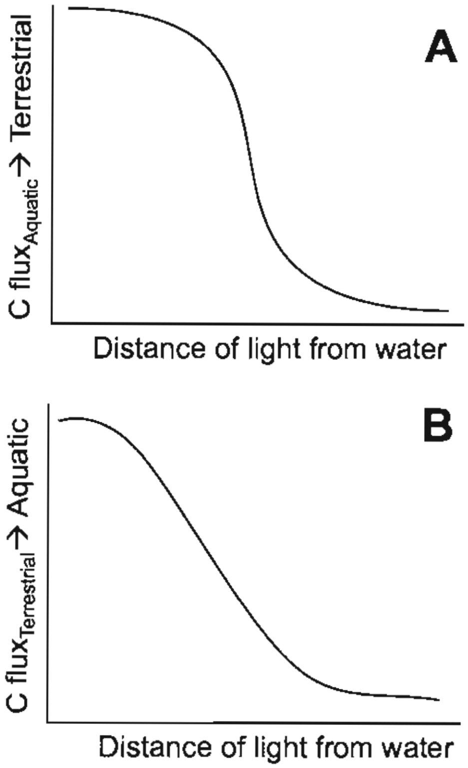

Fig. 5. Theoretical changes in carbon flux from freshwater to terrestrial systems, in the form of insects. Aquatic insects will be attracted to lights very near aquatic bodies in high densities, while lights that are farther away will increase the inland dispersal of aquatic insects, up to some threshold (A). Similarly, there will be higher inputs of terrestrial insects to the aquatic system when lights are close to the aquatic environment but these inputs will decrease quickly as the light location moves inland (B).

aquatic insects are attracted further into the terrestrial system (Fig. 5A). Preliminary support for this hypothesis comes from Kovats et al. (1996) who found adult caddisflies 5 km inland when using light traps. Conversely, we predict the amount of terrestrial carbon contributed to a freshwater system through terrestrial invertebrates will decrease as the distance of an artificial light source to a water body increases. For instance, a light situated on a dock will draw terrestrial insects to the water body, while lights from a road running parallel and several hundred meters away from a water body will draw terrestrial insects away from the water (Fig. 5B). This will create areas that are highly dense in resources for insectivorous organisms, while creating other areas that are depauperate. Outcomes of this process may be an increase in competitive interactions between insectivores (Rydell 2006) and also an increased transfer of freshwater resources to terrestrial consumers.

Interaction with other stressors

There is a growing concern about how environmental stressors might interact with each other, and in fact, an entire issue of the journal *Freshwater Biology* (see Ormerod et al. 2010) was dedicated to this topic. However, the specific ways that artificial light might interact with other common urban stressors have not yet been described in the peer-reviewed literature. As artificial light most frequently occurs in urbanized areas, its effects may be confounded with other urban stressors, making it impossible to determine how much a role artificial light has played in declines in biodiversity and ecosystem functioning. Artificial light may already play a major role in changing organism behavior and ecosystem functioning. However, to fully understand its importance, we must elucidate how it interacts with other stressors in freshwater and riparian ecosystems. Does light pollution act synergistically with other stressors to increase the stress experienced by organisms, or does it potentially lessen the effect of some stressors? How artificial light interacts with other stressors will help prioritize what areas are most important to protect. Dudgeon et al. (2006) enumerated the five major threat categories to freshwater ecosystems as overexploitation, water pollution, habitat degradation, species invasion, and flow modification. Of course, another major threat to freshwater ecosystems is climate change. Artificial light has the potential to interact with all of these threats. By conducting carefully designed studies to understand the interaction between artificial lighting and the threats mentioned in Dudgeon et al. (2006), we will be able to develop a model for when artificial light is likely to do the most harm and be carefully controlled, or conversely, when it could be used as a mitigating factor for some other stressor.

In this section, we explain the ways artificial light could combine with changes to temperature regimes, increased chemical pollution and urban development, altered flow regimes, and increased nutrient concentrations. We also describe how the effects of artificial light might be masked by the presence of other stressors and may not become apparent until the other stressors are removed.

One potential concerns is for light to interact with other common urban stressors, such as temperature and pollution, to interfere with migration and dispersal. For example, some fish have been shown to become disoriented when swimming near lights (Tabor et al. 2004, Nightingale et al. 2006), which they are more likely to encounter when traversing urban areas that also contain other stressors. In the absence of light, migratory fish, such as salmonids, travel quickly through large rivers (Økland et al. 2001) that are more likely to have sub-optimal temperatures or increased pollutants, but the disorientation caused by urban lights could increase the time these fish spend in polluted environments and, as a result, increase their risk of mortality (McCormick et al. 1998).

The interaction of artificial light and other urban stressors could also alter patterns of the dispersal of riparian obligates, such as adult aquatic insects. For instance, the presence of culverts has been shown to reduce the upstream flight of adult caddisflies (Blakely et al. 2006). These culverts are usually installed to allow roads to pass over small streams, leading to a high probability of street lighting being associated with culverts. The street lighting would most likely run perpendicular to the stream (Fig. 6), leading the insects farther away from the stream. We hypothesize that this will lead to decreased dispersal and gene flow, and potentially the elimination of up-stream populations; however, it is possible that these lights could draw the insects over to a neighboring small watershed and, as a result, enhance genetic exchange. Similarly, Málnás et al. (2011) found that a bridge reduced the upstream flight of the mayfly *Palingenia longicauda* on a river in Hungary. At least part of the disruption was caused by polarized light reflecting off the surface of the bridge, which enticed gravid females to oviposit there (Horváth et al. 2009, Málnás et al. 2011).

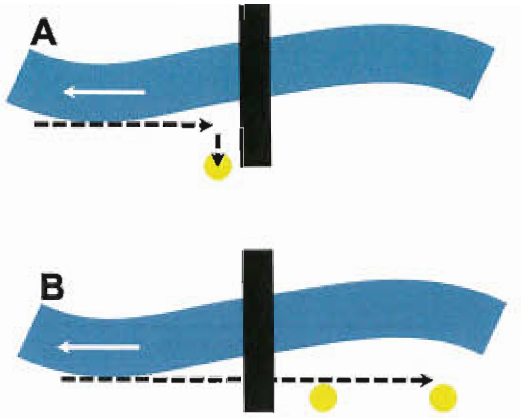

Fig. 6. Artificial lights located near culverts intersecting streams may strengthen their disruption of aquatic insect upstream flight (A) or mediate it (B), depending on their location. The white arrow represents the direction of streamflow, the dashed line is the flight path of the aquatic insects, the yellow circles are lights and the black line is a culvert.

The construction of dams has led to altered flow regimes, often with a dampening of pre-dam high flows. These high flows can serve as a signal to cue migration or spawning events (McCormick et al. 1998, Bunn and Arthington 2002). Normally, light is also a strong *Zeitgeber* for these behaviors (Grau et al. 1981, Greenstreet 1992), but where artificial lighting and flow alterations occur, there could be a complete loss of external cues for these behaviors. This could lead to asynchronous migration and spawning events, and ultimately result in lower population sizes.

While flow modifications are largely a concern of stream environments, increasing loads of nitrogen and phosphorus pollution is a common problem across all freshwater systems (Carpenter et al. 1998). Areas with increased nutrient loading that are also exposed to artificial light at night could be at an increased risk for algal blooms, largely as a result of night-time light altering the behavior of grazing macroinvertebrates (Moore et al. 2000, Moore et al. 2006). Other common pollutants in freshwater ecosystems could also interact with artificial light, most resulting in further reductions of biodiversity. However, bright artificial light could mitigate effects of pollutants that degrade under light

Table 2. Key research questions in each research domain.

Key research question	Research domain			
	Dispersal	Evolution	Ecosystem functioning	Interactions with other stressors
Spectral qualities	How do different spectra change an organism's attraction to light? How do different spectra change hormone production?	Are there changes in sexual selection as a result of specific spectra entering the environment?	Is primary production changed? Does the spectrum of artificial light fall within visual predators or prey or both?	Is the light spectra reaching aquatic organisms altered by pollution?
Spatial & temporal scales	Patterns of light across the landscape: does it create traps or barriers? What time of day do species move; does the presence of artificial lights change this?	How quickly does adaptation to/ selection from artificial light happen? Are entire populations affected or only fractions of some populations?	Are there refuges available? Is daytime behavior altered? Are there energetic costs?	Is light present year-round or seasonally? What effects might this have on spawning? What is the distribution across watersheds? Specifically, how does artificial light overlap with other stressors?
Magnitude of change in brightness	Is sky glow or direct glare a bigger problem?	Is sky glow or direct glare a bigger problem?	Is sky glow or direct glare a bigger problem? Are there thresholds of effective light levels?	Is sky glow or direct glare a bigger problem? Are there thresholds of effective light levels? Is there an increase in light brightness due to reductions in riparian vegetation (as a result of anthropogenic activities)? Are the light levels high enough to photodegrade chemicals?

exposure.

In restoration efforts, common urban stressors might act in concert to hide the negative effects of artificial light. For instance, water quality was the limiting factor in fish survival and reproduction in a central European river system. However, after decades of efforts to improve water quality, hydromorphological degradation then emerged as the main obstacle to further ecological improvement and freshwater diversity (Borchardt et al. 2005, European Commission 2007). Improving degraded habitats became important once pollutants and oxygen stress had been eliminated; similarly, after degraded habitats have been improved artificial lights could prevent a restoration site from achieving full functionality. This is important to consider as freshwater and riparian ecosystems that have undergone successful restoration often become attractive places for recreation (Woolsey et al. 2007). As recreational uses of these areas increase, user groups might call for the installation of artificial lights, particularly along biking and running paths in temperate zones with long periods of dark during winter months.

KEY RESEARCH QUESTIONS

We have identified three main general questions facing researchers in artificial light that deserve more attention. These include understanding how different spectral qualities of various sources of artificial light, spatial and temporal scales over which artificial light acts, and the magnitude of changes in light influence organisms and ecosystems (Table 2).

Diverse organisms have sensitivities in different parts of the light spectrum, and various artificial lighting sources emit very distinctive wavelengths of light (Fig. 3). Therefore, different light sources (e.g., high pressure sodium, metal halide) with distinct color spectra are expected to elicit unique responses from different organisms (Fig. 3; Moore et al. 2006). Recently, the European

Eco-Design Directive has enacted a step-by-step plan to phase out particularly energy-intensive lighting products (e.g., high-pressure mercury lamps, the European Parliament and the Council of the European Union 2009). Thus, many countries and the EU have launched a number of programs to adopt efficient lighting systems with a focus on LEDs as a promising energy-efficient lighting technique. There is some evidence that LEDs will attract fewer insects than previous bulb types (Eisenbeis and Eick 2011), but this needs to be more rigorously tested, as the light levels and luminaire construction in this study varied in addition to bulb type. Further, it is completely unknown how other freshwater organisms might respond to different wavelengths, although some fish (e.g., *Acipenser baeri* and *Oncorhynchus mykiss*) have peak sensitivities that correspond to peak emissions from LEDs (Hawryshyn and Hárosi 1994, Sillmann and Dahlin 2004; Fig. 3).

The spatial and temporal scalar influence of artificial light is also an area that requires elucidation. Scheibe (2003) showed that one street light located near a stream can attract caddisflies hatching from several hundred meters of stream, but it is unclear how applicable his results are for different habitat and ecosystem types, or what the impact of multiple light sources might be. At larger spatial scales, it is clear that the sky glow created by the cumulative lights of a large city can influence natural areas 10s and even 100s of kilometers away (Albers and Duriscoe 2001, Kyba et al. 2011). For example, Moore et al. (2000) found that artificial light from 16 km away was strong enough to alter the DVM of *Daphnia*. We need to know if wide-spread use of artificial lights near freshwater and riparian habitats will contribute to the decline or disappearance of sensitive species, lead to localized decreases close to bright light sources, or even be beneficial for other species. Even if sky glow does not cause extinctions, it could very likely alter food web structure either by changing predators' ability to detect prey or prey behavior (Moore et al. 2006). Another question that needs to be answered is if light-sensitive species are able to re-colonize areas when lights are removed. Mapping the occurrence of artificial light across landscapes will allow us to make better predictions about the likelihood of specific habitats being recolonized.

While the results of Scheibe (2003) and Moore et al. (2000) suggest that artificial light can influence organisms over a relatively large spatial area, we do not know the temporal scale of this influence. Does exposure to artificial light during the night alter the behavior of organisms during the day? Perhaps some organisms have life stages that are particularly vulnerable to exposure to artificial light, but are not sensitive during the rest of their lives. These species might be able to take advantage of dark refuges for sensitive life stages and then live in artificially lit areas at other times. If populations are negatively affected by artificial light, are they able to recover quickly once artificial light is removed from their habitat? This largely depends on whether artificial light alters the genetic structure of populations. Furthermore, spatial analysis is needed to determine the overlap of artificial lights and freshwater bodies. As noted in the introduction, freshwater environments are preferred sites for human activities, which will often lead to an increase of artificial lights. We expect to find the greatest amount of lighting in already damaged urban areas, but we also need to determine if vacation homes and highways introduce a meaningful amount of light to more natural areas.

The magnitude of changes in light also needs to be better understood. While direct glare is the most conspicuous form of light pollution, sky glow is a much more wide-spread phenomenon that is likely to influence animal behavior (Longcore and Rich 2004, Moore et al. 2006, Nightingale et al. 2006). Sky glow can increase ambient light levels hundreds of kilometers away from the cities from which it emanates. This is the case in several ecologically important U.S. National Parks (Everglades, Channel Islands, and Joshua Tree), which have night skies that are substantially brighter than natural due to sky glow from nearby cities (Albers and Duriscoe 2001). One potential problem of increased light from sky glow is that it reduces or eliminates the natural monthly variation in night-time light that arises from the lunar cycle (Longcore and Rich 2004, Kyba et al. 2011; Fig. 2). If the general increase in ambient light caused by sky glow can alter behavior and harm ecosystems, then managing artificial light becomes a much more pressing conservation concern. However, it will be very difficult to study the effects of sky glow on ecosystems, as there are very few places left in North America and Europe that do not have elevated levels of sky glow to use as control sites (Cinzano et al. 2001). Furthermore, once researchers have located a promising location, how do they mimic an increase in sky glow that would normally be produced by a city of 500,000+ inhabitants that is 50 km away? While researchers may be able to introduce direct glare by introducing a few lights to an ecosystem, those interested in understanding the influence of sky glow may have to introduce artificial darkness to an already lit area, as Moore et al. (2000) did.

CONCLUSION

How artificial light at night might influence stream and riparian ecosystems is a relatively unexplored topic, with many possibilities for relevant research. Even though the experimental knowledge of the ecological impacts of artificial light at night is still developing, governments are creating legislation to regulate it, mostly to reduce energy costs and decrease greenhouse gas emissions (Hölker et al. 2010*b*). Reducing energy consumption is a desirable goal, but if it is achieved solely through changing lighting fixtures and not necessarily reducing lighting, and without knowing how different aspects of artificial light (e.g., intensity and spectral qualities) influence ecosystems, this legislation could have unintended and even negative impacts on ecosystems. We also expect that governments will not be able to regulate artificial light everywhere, but by understanding its potential consequences, we can better prepare for or mitigate them.

Carefully designed experiments are needed to determine the exact effects of artificial light on ecosystems and over what spatial and temporal scales they act. From a management perspective, it is highly important to consider and incorporate the mitigation of potential ecological impacts and losses of biodiversity and ecosystem services into new lighting concepts (Rich and Longcore 2006, Hölker et al. 2010*a*, *b*). While there are many challenges to overcome in pursuing this research, the potential for new breakthroughs in understanding ecosystems and their functioning is high and should motivate researchers to innovate new techniques.

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Cloud Coverage Acts as an Amplifier for Ecological Light Pollution in Urban Ecosystems

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Abstract

The diurnal cycle of light and dark is one of the strongest environmental factors for life on Earth. Many species in both terrestrial and aquatic ecosystems use the level of ambient light to regulate their metabolism, growth, and behavior. The sky glow caused by artificial lighting from urban areas disrupts this natural cycle, and has been shown to impact the behavior of organisms, even many kilometers away from the light sources. It could be hypothesized that factors that increase the luminance of the sky amplify the degree of this "ecological light pollution". We show that cloud coverage dramatically amplifies the sky luminance, by a factor of 10.1 for one location inside of Berlin and by a factor of 2.8 at 32 km from the city center. We also show that inside of the city overcast nights are brighter than clear rural moonlit nights, by a factor of 4.1. These results have important implications for choronobiological and chronoecological studies in urban areas, where this amplification effect has previously not been considered.

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Introduction

The ambient light level is one of the strongest factors driving animal behavior and chronobiology, evidenced by the dramatic split of most species into diurnal or nocturnal activity. It is therefore unsurprising that changes in ambient nighttime lighting result in behavioral and physiological changes for many nocturnal species [1], whether in terrestrial [2–4], marine [5], or freshwater [6–8] habitats.

With the exception of life in the deep oceans and underground, all life on Earth has evolved to live in an environment of cycles of light and dark, with a substantial proportion of the global biodiversity being nocturnal (30% of all vertebrates and >60% of all invertebrates [9]. Most organisms, humans included, have evolved molecular circadian clocks which are set by natural day/night cycles. Until the invention of artificial light, this meant that many behavioral and physiological traits were determined by the motions of the sun, the moon, the stars, and the weather (e.g. [10–12]).

The first lighting technology was fire, which was used expressly to modify animal behavior: fire allowed human activity to continue past sundown and frightened away human predators. Small scale urban lighting began with gas lamps, but the nighttime environment drastically changed with the widespread deployment of electric lighting in the last century. Since then, the rapid global increase of artificial light has fundamentally transformed nightscapes, both in terms of quantity, increasing several percent each year, and in quality (color spectra) [13].

Light pollution, which causes the "light dome" dome of sky glow over urban areas, is an unintended result of this electric lighting, and because of it approximately 10% of the world's population, and more than 40% of the US population, no longer view the night sky with dark adapted vision [14]. In addition to emptying the night sky of stars, it has been suggested this unwanted light may be damaging to our health [15–18], although this hypothesis is debated [19].

For any given individual species, the impact of artificial light may be neutral, beneficial (e.g. increased foraging), or detrimental (e.g. collisions with lighted structures [20]). In either of the latter cases this may disrupt predator-prey relationships and ecosystem functions [21,22]. Thus, light pollution can also be considered an important driver behind the erosion of ecosystem services (e.g. pollination of plants by moths or bats, loss of biodiversity, and changes to food webs [9]). Aesthetic values, such as the visibility of the Milky Way, could be also considered a vulnerable cultural ecosystem service [23]. While the fact that artificial light affects animal behavior has been recorded since Aristotle, recognition of the potential danger posed to entire social-ecological systems by urban lighting is relatively recent [13,24].

Sky glow occurs when light escaping upwards from a city is scattered back to the ground, through interactions with atmospheric components. On clear nights with extremely good visibility, urban sky glow is caused by the scattering of light by molecules (Rayleigh scattering). Rayleigh scattering affects blue light much more strongly than red, and is responsible for making the sky blue and the sunset red. The glow of distant cities is red for the same reason [25].

Atmospheric visibility is generally reduced due to the presence of aerosols, small particles or droplets suspended in the air that can come from natural (e.g. dust, sea salt) or artificial (e.g. soot) sources. Aerosols can impact light pollution in several ways. First, higher aerosol concentrations should amplify the sky glow (particularly on cloud free nights), as aerosols increase the chance that light is scattered back to Earth. Second, if the aerosols are absorbing in the visible band (which is typical in the case of smog), they could reduce the extent to which environmental changes (e.g. snow, or as we shall see, cloud cover) amplify light pollution, as multiply scattered light would have increased chances of absorption. Third, in the case of very short visibility, the probability of light propagating to the city limits will be reduced, and thus the horizontal extent of the sky glow outside of the city should be reduced.

Clouds are effectively thick collections of aerosols (small water droplets) that almost non-absorbing at visible wavelengths. This makes clouds very reflective [26,27], and therefore we expect them to amplify sky glow. In the case of optically thick clouds, if we consider only the upward and downward propagation of light (as in the so-called two-stream approximation), then, to first order, the cloud bottom can be thought of as a two-sided, white (Lambertian) boundary, which diffusely reflects sun, moon, or city light back towards the hemisphere from which it came. While this analogy is clearly an oversimplification (e.g. one can usually see quite well outdoors in the daytime even under thick clouds), it is useful for gaining a "feel" for how clouds interact with light pollution. In the particular case of an observer under optically thick clouds and inside of a large city (where the cloud bottom is much closer to the observer than is the edge of the city), the model of the cloud bottom as a Lambertian surface is probably a reasonably good approximation.

This redirection of light back towards the ground gives rise to the effect shown in Figure 1, that while in pristine environments clouds appear as dark objects on the star filled sky, in cities clouds appear as bright objects on a dark background, nearly devoid of stars. While this phenomena has been qualitatively observed by many people, we believe that this work represents the first systematic and quantitative study of this effect presented in the scientific literature. The reasons a similar study by [28] did not observe this effect are considered in the discussion section. Measurements of the increase of light due to cloud coverage were shown in [29] and in a poster by Posch, Hollau, Kerschbaum, and Bleha presented at the Cancer and Rhythm conference, Graz Austria, 2004, but in both cases only for single nights.

Figure 1. Photograph showing the amplification effect that clouds have on the sky glow. Inside of cities clouds appear as bright objects on a dark sky. In natural environments, clouds look more like the tower in the photo: dark silhouettes against a star-lit sky. Photo: C Kyba.

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While an atmospheric model of clouds as white surfaces and "Rayleigh scattering only" skies is sufficient to qualitatively discuss the results of this paper, we should note that quantitative modeling of light pollution requires much more attention to detail. For an observer on the ground, the radiance of the sky observed in any given direction depends upon a host of variables, including the wavelength of the light in question, the makeup of the atmosphere, the distribution of city lights on the ground, the topography of the city, and the observer's position within it. In the next two paragraphs we point to more detailed references, which together describe each of the components needed to fully characterize the sky glow produced by a city.

The scattering and absorption of light in the atmosphere is of central importance to climate science, and has thus been described in detail elsewhere (see e.g. [27,30]). Modeling the interaction of light pollution with clouds requires understanding of the optical properties of the cloud, in particular the cloud optical thickness (a description of the probability that light interacts with water droplets in the cloud), the single scatter albedo (the propensity of photons to be scattered rather than absorbed), and the asymmetry parameter (the relative proportion of photons that are scattered forward rather than backward) [27]. A detailed discussion of cloud reflectance can be seen in e.g. [26].

In most cases, atmospheric scientists focus discussion on the interaction of sunlight with the atmosphere. Light pollution, however, is very different from sunlight in that the angular distribution of upward traveling light depends strongly on position, and the spectral distribution depends very strongly on local factors (i.e. what types of lamps are in common use). An evaluation the combined luminance of all of the sources of light a single city is given in [31], a comprehensive review of the spectrum of different lamp types is given in [32], and discussion of the geometry of light pollution, and sky maps showing the sky radiance caused by single or multiple lamps is given in [33].

Historically, light pollution research and advocacy has been undertaken by astronomers, who justifiably have little interest in cloudy nights. In the first serious model of light pollution [34], only the case of clear skies was considered, and with some exceptions (e.g. [33]), models and measurements generally consider only cloud-free conditions [14,35–38].

We expect the presence of clouds to significantly brighten urban skies, and to amplify the degree of ecological light pollution. We aim to show that in studying the impact of sky glow on ecology, health, or interruption of circadian rhythm, it is essential that cloud coverage be taken into account. In performing our analysis, we also expect to show that the level of light pollution in Berlin is ecologically relevant (meeting or exceeding the light levels produced by the moon), and finally that the total light produced by Berlin decreases as the night progresses.

Materials and Methods

The main goal of this paper is to measure how cloud coverage affects sky brightness in an urban environment. This measurement is referred to as the "cloud analysis". In order to allow for comparisons to the sky brightness typical of natural environments, we also study how the elevation of the moon above the horizon affects sky brightness. This is called the "moon analysis".

Our night sky brightness data were taken using the "Sky Quality Meter" (SQM) produced by Unihedron (Grimsby, Canada), shown in Figure 2. The SQM measures luminance (surface brightness) for a patch of the sky, in units of magnitudes per square arc second (mag/arcsec^2). The photosensitive element of the meter is a silicon photodiode (TAOS TSL237S light-to-frequency converter), which responds to light with wavelengths in the range of 320 to 1050 nm, with a peak at about 680 nm. The photodiode is covered by a HOYA CM-500 filter, which reduces the wavelength response to 320 to 720 nm, in order to provide better agreement with the wavelength response of human night vision. The response of the TSL237S has a small, stable, temperature dependence, so the SQM contains an internal temperature sensor which is used by the SQM software to provide compensation (i.e. the results reported by the SQM should have no temperature dependence over the range -25 to 70 degrees Celsius).

Unihedron produces several different models of the SQM, which are differentiated by their method of data readout and by their field-of-view (FOV). The SQM is available as a hand-held device with a digital display, or as a continuous measurement device using either a USB or Ethernet connection. We made use of Ethernet enabled SQMs, as Ethernet allows longer cable runs than USB. The field-of-view is determined by the presence (SQM-LE) or absence (SQM-E) of a focusing lens, which reduces the FOV from a wide angle to a small patch of the sky. The half-width at half-maximum has been measured to be 42° and 10° for the SQM-E and SQM-LE respectively [39]. For the measurements reported in this paper, we made use of one SQM-LE and two SQM-E devices.

The SQM reports the sky brightness in units of magnitudes per square arcsecond (mag/arcsec^2), a logarithmic unit in use by the astronomy community. The scale is defined so that an *increase* of 5 in mag/arcsec^2 corresponds to a factor of 100 *decrease* in luminance. It is possible to approximately convert mag/arcsec^2 into nit (cd/m^2) using the formula: $\mathrm{cd/m^2} = 9.0 \times 10^4 \times 10^{-0.4x}$, where x is the luminance in mag/arcsec^2. (This equation was provided to us by Unihedron, and originates from the webpage of Paul Schlyter: www.stjarnhimlen.se/comp/radfaq.html) This conversion, however, contains an implicit assumption about the wavelength distribution of star light, which we can neither assume to be the same as light pollution, nor the same for both clear and cloudy conditions. A general conversion from mag/arcsec^2 to lux is not possible, as converting luminance measurements to illuminance measurements requires making an assumption about the angular distribution of the sky brightness intensity, which we expect to change in the presence of clouds. The SQMs have a quoted systematic uncertainty of $\sim 10\%$ (0.10 mag/arcsec^2).

Figure 2. Photograph showing the Sky Quality Meter installed in its protective housing (SQM-LU left), along with an expanded view (SQM-LE right). The housing at left is shown with the two included hose clamps that allow easy attachment to a stake or pole. The USB version (left) requires only one cable, but at the cost of shorter cable runs and the internal heating provided by the Ethernet version (right).
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The Ethernet enabled SQMs were installed at three locations: our measurement tower at the Institute for Space Sciences at the Freie Universität (52.4577°N, 13.3107°E), at the Leibniz-Institut of Freshwater Ecology and Inland Fisheries (52.4487°N, 13.6513°E), and on an island of the Spree river outside of the city (52.3681°N, 13.8049°E). The locations are approximately 10, 18, and 32 km from the center of Berlin, and can be classified as urban, suburban, and rural respectively. In order to protect the devices from rain and snow, the SQMs were installed in a protective housing produced by Unihedron. The housing consists of a short length of 3" PVC pipe fitted on the top and bottom with 3" PVC endcaps. The bottom endcap has a hole drilled in it to allow for entry of cables and to allow moisture to escape, and the top endcap has a hole to allow a window for observations. This window is covered with a glass top which is glued to the surface of the endcap. The attenuation of the glass cover has been measured to be 0.11 mag/arcsec^2 [40], and to correct for this effect we subtract this amount from the readings reported by the device. The internal web server of the SQM-LE produces enough heat to quickly melt snow and evaporate water from the glass surface.

The data were read out from the SQMs using a custom developed Perl script, partially based on sample code provided by the manufacturer. The devices were polled approximately once per second, and whenever the readout value changed, the time and sky brightness measurement were recorded to a file. These values were then averaged by our analysis program to create a minute-by-minute dataset. Despite the logarithmic scale, we directly averaged the measurements in mag/arcsec^2, as we expect measurement differences at very short time scales are more likely to be due to the device electronics rather than a physical change in the sky brightness.

Our cloud coverage figures were taken from synoptic measurements at a manned weather station (Berlin-Dahlem, World Meteorological Index 10381) located adjacent to our measurement location at the Freie Universität. The SYNOP data were retrieved from the OGIMET website, http://www.ogimet.com. In synoptic observations cloud coverage is reported in "oktas", which represent the fraction of the sky obscured by cloud in eighth's. Zero oktas corresponds to a cloud-free sky, while eight oktas corresponds to completely overcast conditions. The synop data were reported hourly, so the maximum time difference between any sky brightness measurement and the most recent cloud observation was 30 minutes. Berlin has several synop stations, and we have verified that using cloud data from a different station (e.g. closer to the rural site) has only a minor impact on the results. Because we are most interested in what is happening at the urban location we used the data from the adjacent weather station.

In natural ecosystems, the moon is the brightest source of light at night. The relationship between the intensity of moonlight (both direct and scattered) and the moon's position parameters (distance from Earth, phase, elevation above the horizon, and time of year) is computationally very complex (see e.g. the simulation presented in [28]). We eliminated the need to compensate for moon lighting in the cloud analysis by simply considering only moonless nights. To do this, it was necessary to calculate the position of the moon for each data point. This was accomplished using the "Astro::Coord::ECI" and "Astro::Coord::ECI::Moon" open source Perl scripts (v0.033), which were developed by Thomas R. Wyant, and are freely distributed by the Comprehensive Perl Archive Network (http://search.cpan.org/~wyant/Astro-satpass-0.033/). The algorithm is based upon calculations in [41], and has a quoted moon position uncertainty of 10 seconds of arc in latitude.

The moon positioning algorithm was initialized using the longitude, latitude, and elevation (91 m) of the measurement tower at the Freie Universität. The moon position was calculated at the 30 second mark of each minute, matching the median time of our sky brightness measurements. We define our data to be "moonless" when the moon's true position (i.e. ignoring any effects of refraction in the atmosphere) is 2° or more below the horizon.

The sky brightness data for the cloud analysis were taken during the period from April 22 to September 21, 2010, using wide field-of-view SQM-Es at our urban and rural measurement stations (10 and 32 km from the city center, respectively). Within this time span the data from six nights were rejected due to failures in the data acquisition chain (e.g. from a power interruption). The summer air in Berlin is relatively clean, and visibilities of 30–40 km were typical during this study. Because we expected the total amount of light produced by the city to decrease as the night progressed (from decreased auto, residential, and advertising lighting), we only considered data taken during the same time window each night. This considerably restricts the size of our dataset, but reduces the possibility of introducing systematic bias or larger variation into the observed sky glow.

The optimal duration of the data taking window depends upon the analysis that one wishes to pursue. For the cloud analysis our goal was to include as many different cloud coverage values as possible; getting a "snapshot" of the sky brightness at the same time as the cloud coverage measurement was taken, and for a variety of weather conditions, was more important than sampling unchanging skies over several hours. The large size of weather systems means that overcast or clear conditions often persist for several days, and for this reason we wished to use data from as many nights as possible. Due to the extremely short duration of the night at the time of the summer solstice in Berlin, this restricted us to using only data taken between 12:45 am and 1:15 am local time (UTC+2, Central European Summer Time). Berlin is near the center of its time zone, so the moment of "true" local midnight occurred during this half-hour period for each night in our dataset.

In the case of our moon analysis we were less concerned with including as many individual nights as possible. Instead, we preferred to use a longer time interval each night, which allowed the moon to move through a substantial range of elevation above the horizon each night. For this reason we only used data taken at least three weeks away from the summer solstice (i.e. April 22-May 30, and July 13-September 21). This allowed us to use a wider time window than that used in the cloud analysis, from 12:00 am to 2:00 am. To avoid the possible influence of clouds, we only included data for which the cloud coverage in the two synop reports nearest to the sky brightness measurement was 0 or 1 okta.

The computer reading out the data at the Freie Universität has access to an Internet connection, which allowed timing to be maintained to better than second accuracy throughout the data taking period. The computer collecting data at the remote location, however, was located in a non-climate controlled container, and experienced clock drift. This computer's time was periodically corrected manually, at intervals ranging from 5 to 38 days. When these corrections were made, the total drift since the last correction was noted. This allowed us to remove the linear portion of the clock drift in software, and pass the corrected data to our analysis program after the data was collected. Over the entire period of data taking, the average clock drift was +12.9 seconds/day, and we do not expect that the maximum deviation from true time at any period in our dataset was more than 5 minutes.

Results

The sky brightness values recorded on three representative nights (clear, partly cloudy, and overcast) at our three measurement locations are shown in Figure 3. In all weather conditions, the rural site was darkest (largest value of mag/arcsec^2) and the urban site was brightest. The plot at left shows the data for the clear (0–1 oktas) night of June 4–5, 2010, during which the half full moon rose at 1:21 am. The middle plot shows data for May 20–21, which was partly cloudy (3–4 oktas) until 3 am, when the sky cleared (to 1 okta). The right hand plot shows the data for May 13–14, which was overcast (8 oktas) the entire evening. A dotted line is drawn in the right hand panel to show the portion of the data from that night that contributes to the cloud analysis.

At midnight on the clear night in the left hand frame of Figure 3, the sky brightness at the rural site was on average about 1.85 mag/arcsec^2 darker than the urban site (2.4 mcd/m^2 compared to 0.43 mcd/m^2, ~1/5 the luminance), while on the overcast night it was 3.15 mag/arcsec^2 darker (26 mcd/m^2 compared to 1.4 mcd/m^2, ~1/20 the luminance). It is immediately apparent from these plots that the sky glow exhibits a strong

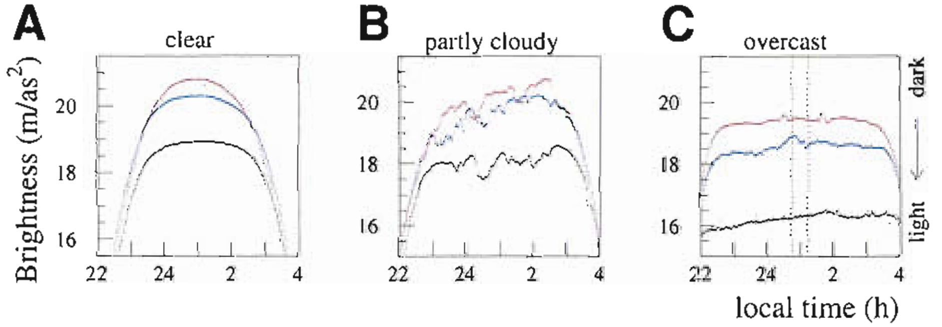

Figure 3. Examples of the sky brightness (in mag/arcsec^2) observed for different cloud conditions and at different locations. The minute by minute data for individual clear (A, June 4–5), partly cloudy (B, May 20–21), and overcast (C, May 13–14) nights at each of our rural (red), suburban (blue), and urban (black) measurement stations is shown. Larger values of mag/arcsec^2 indicate darker skies. The unit is logarithmic, with a 2.5 increase in mag/arcsec^2 corresponding to a sky that is ~10 times as dark. The dotted lines in the plot at right show the time window used in the cloud analysis.

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urban→rural gradient, and that clouds have a very significant impact on urban sky brightness. Note that the suburban data were taken with a narrow FOV SQM-LE, which we found tends to record darker values for clear and partly cloudy conditions. We included the suburban data in Figure 3 to emphasize the urban→rural transition, but we do not use the data from that location in our cloud or moon analyses.

While we would in principle prefer to have equivalent statistics for each level of cloudiness, in practice we must make use of the conditions that nature provides. Table 1 shows the number of nights in the dataset for which each degree of cloudiness was observed at 1 am. The table also shows the effective number of nights available for the cloud analysis. Fractional values occur because of occasional data loss, and because of nights during which the moon rose or set during the 30 minute analysis period. Clear or overcast conditions occurred much more frequently than partly cloudy (2–6 oktas) skies.

Our results for the cloud analysis using the full dataset are shown in the left panel of Figure 4, and numerically in Table 2. In the figure, the upper set of points represent the data at the rural location, while the lower set were taken inside of the city. For each value of cloudiness (in oktas) the median sky brightness observed is shown with a horizontal line. The variation in the observed data is shown by the thick and thin lines, which cover the ± 1 and 2 σ bands (containing ~ 68% and 95% of the observed data, respectively). The large separation between the distributions for clear and cloudy conditions at the urban site refutes the null hypothesis (i.e. that clouds do not amplify urban sky glow) with certainty.

We found that on the clearest nights around the time of the solstice, the sky at the rural location doesn't appear to get quite as dark as it might on an equivalent night in the spring or fall. As is shown in Figure 5, on these nights the ∩ shaped pattern of the sky darkening and then brightening doesn't include the typical broad plateau. However, due to both our narrow time window of 15 minutes around 1:00 am, the large number of clear nights, and the marked difference between the urban and rural measurements, the impact of this effect is a minor increase in the spread of the data for the darkest nights. As a test, we tried selecting data within 15 minutes of 1:08 am (which is a better approximation of local midnight), and found that this had a negligible impact.

The results of the moon analysis are shown in the right hand panel of Figure 4. The data are grouped in bins of 5° of moon elevation above the horizon, and the bars show the ± 1 and 2 σ bands, as in the plot at left. Negative values of elevation indicate that the moon was below the horizon, and are shown in individual bins as a consistency demonstration.

As discussed in the Materials and Methods section, the analysis uses only a small portion of the data from each night because the total amount of light produced by the city is expected to change as the night progresses. We tested this hypothesis by selecting a small number of nights with completely overcast skies. In order to guarantee overcast skies, data were only included if the cloudiness was 8 oktas in both of the adjacent hourly synop reports. Figure 6 shows how the sky glow over the Freie Universität changed during nights between April 26 and May 15. The left hand plot shows the data in mag/arcsec^2, the right hand plot shows the same data on a linear scale, using the approximate conversion to cd/m^2 (nit). Over the course of the night the sky brightness decreased from 15.95 to 16.55 mag/arcsec^2, a decrease in luminance of approximately 40%.

Table 1. Frequency of cloud coverage conditions over the course of data taking.

Oktas	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Total Nights	21.5	26.5	7	12.5	7	13	10	23	26
Moonless Nights	11.9	10.6	3	7	0	5	6	9.2	13.6

For each value of cloud coverage (0 is clear, 8 is overcast), the number of nights in the observation period is shown along with the effective number of nights that the moon was at least 2° below the horizon between 12:45 and 1:15 am. Fractional values occur due to occasional data loss due to power outages, and to nights during which the moon rose.

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The data on which these results are based is provided in supplemental File S1. The table's contents are: the date, time of observation in "hours after midnight" in the GMT+1 time zone (i.e. +0.5 is 12:30:00 am, and −0.0083 is 11:59:30 pm), the sky brightness value observed at the urban and rural sites (in mag/arcsec^2), the cloud coverage from the most recent SYNOP report in okta, the difference in oktas between the two adjacent SYNOP reports, the cloud base (an integer code number as per the SYNOP specifications, see e.g. http://weather.unisys.com/wxp/Appendices/Formats/SYNOP.html), the visibility (in meters), and finally the elevation (in degrees), illuminated fraction, and distance (in km) of the moon.

Discussion

Using two SQMs, we studied changes in the sky brightness of Berlin in a rural and urban location over a period of 152 calendar days. The degree to which Berlin's skies are polluted by light can be demonstrated by comparing the sky brightness measured here with that measured in a more natural setting. In a recent study of sky brightness at the Zselic Landscape Protection Area in Hungary (an International Dark-sky Park), the darkest measurements obtained on clear moonless nights using an SQM were 21.5–21.6 mag/arcsec^2 [38]. The very darkest observations for clear moonless nights in Berlin were ~21.2 mag/arcsec^2 at our rural location and ~19.3 mag/arcsec^2 at our urban location, a luminance greater by 38% and 690%, respectively. Typical nights at both locations, however, were far brighter even than this.

The left hand plot of Figure 4 demonstrates the significant degree with which clouds amplify the impact of light pollution. The data show a strong dependence on the cloudiness level, with very rapid brightening as the sky becomes fully overcast. The mean observed sky brightness for fully overcast skies at our urban measuring station was 16.5 mag/arcsec^2, a luminance approximately 10600% brighter than that observed for dark nights at the dark-sky park in Hungary.

We can see that this sky brightening is ecologically relevant by comparing the brightness at the urban station to the brightness observed on moonlit, cloud free nights at our rural station. The two panels of Figure 4 show that regardless of weather conditions, the night sky of Berlin is almost always as bright as that naturally experienced during a high elevation summer moon. (Although it should be kept in mind that the SQM-E effectively measures the integral amount of light incident on a plane parallel to the ground. The angular distributions of sky glow and direct moonlight, and therefore an organism's visual experience of the environment under the two, are very different.) This means that for light avoiding organisms that moderate their behavior in the presence of moonlight, for example zooplankton in a lake system [42], the light pollution from Berlin is expected to be a considerable stressor. It has been previously shown, in lake food webs, that light mediated diurnal vertical migrations of zooplankton may be

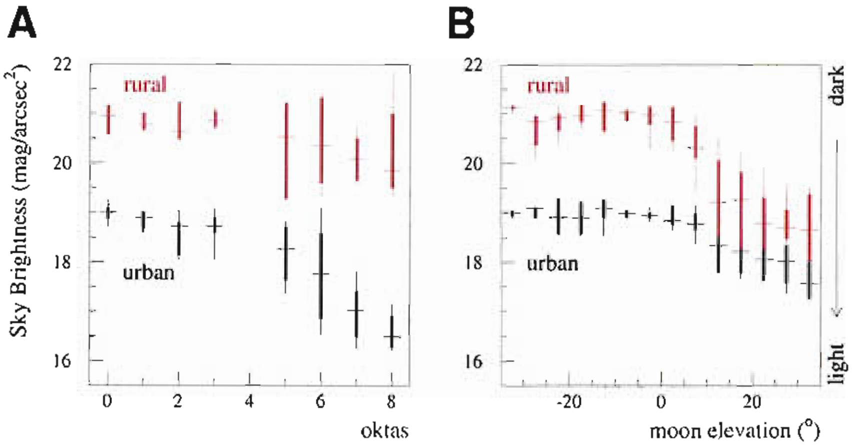

Figure 4. Profile histograms of the sky brightness data. Panel A shows the sky brightness observed as a function of cloud coverage. The bars show the ± 1 and 2 σ spread of the data. Panel B shows the sky brightness as a function of moon elevation for clear (0–1 okta) nights. Larger values of mag/arcsec^2 indicate darker nights.
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suppressed, decreasing the grazing pressure on phytoplankton [7,43].

The amplification of sky glow by clouds surely amplifies this stressor, since we observed that the sky glow typical on overcast nights within Berlin was 4.1 times as bright as that observed outside the city on clear nights with a high elevation moon. In pristine ecosystems at a similar latitude to Berlin, a sky glow brighter than 19 mag/arcsec^2 is likely only experienced for several hours on a few nights each summer, namely on cloud free nights when the moon happens to be high in the sky. This "worst case scenario" for some zooplankton species in their natural environment represents almost the most favorable conditions they can ever face in the urban waterways of Berlin. While it can be expected that some species will be genetically capable of adapting their behavior, physiology, growth, and reproduction to live in or take advantage of unnaturally lit environments, other species will not, and at least some light-sensitive species and genotypes will be lost in the long term [9].

The "error bars" shown in Figure 4 are not uncertainties, but rather represent the spread of the observed data. For the data in the cloud analysis there are three sources of variation. First, during a single night, changes in the local cloud coverage (i.e. the positions of clear and cloudy patches of the sky relative to the SQM) lead to changes in the measured sky brightness, in part due to the angular response of the SQM. This was shown in Figure 3. While only data taken within 15 minutes of the synoptical observation we considered, in some cases the cloud coverage changes during this time. Second, "oktas" are a relatively crudely spaced measure, and are determined by human observers, each of whom might have a slightly different idea of where the cutoff lies between, say, 3–4 oktas. Third, from night to night the baseline value for a given number of oktas is expected to be different, due to differences in the environmental conditions: cloud type (i.e. the cloud height, optical thickness, single scatter albedo, and asymmetry parameter), surface albedo, visibility, and atmospheric aerosol content. It is this second source of variation that gives rise to some of the "lopsided" distributions, where the upward and downward lengths of the 1 or 2σ bars differ considerably in length. For example, the large upward tail on the rural 8 okta measurement in Figure 4 is due to a night with exceptionally low clouds (100–200 meter ceiling). Finally, in the case of the rural data, the cloud condition at the rural site may be slightly different than at the urban site, where the synoptical observation was made.

We believe the largest source of the night to night variation, and the reason for the steep increase in brightness with cloud level at 4–5 oktas, is changes in cloud type and thickness. Scattering from aerosols is strongly forward peaked, so while light may be deflected as it propagates through a thin cloud it is not particularly likely to be scattered back towards the ground. Thick clouds on the other hand, are expected to be very efficient at scattering light back down to ground level, as the photons must undergo many scattering events before leaving the cloud top. The hypothesis that

Table 2. Amplification factor of clouds.

Oktas	0	1	2	3	4	5	6	7	8
Rural (mag/arcsec^2)	21.0	20.8	20.7	20.9	/	20.5	20.4	20.1	19.9
Urban (mag/arcsec^2)	19.0	18.9	18.7	18.7	/	18.3	17.8	17.0	16.5
Rural amplification	1	1.2	1.3	1.1	/	1.5	1.7	2.3	2.8
Urban amplification	1	1.1	1.3	1.3	/	2.0	3.1	6.1	10.1

For each value of cloud coverage (0 is clear, 8 is overcast), the median observed sky brightness over the course of data taking is shown in mag/arcsec^2. These data were used to calculate a sky brightness amplification factor for each level of cloudiness (relative to clear skies). Under clear conditions urban skies were 6.1 times brighter than at the rural site.
doi:10.1371/journal.pone.0017307.t002

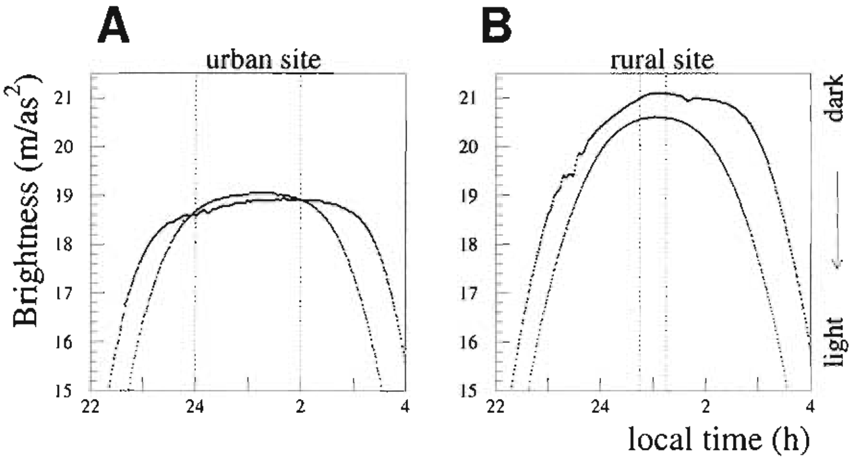

Figure 5. Nights are dramatically shorter around the time of the summer solstice. The minute by minute sky brightness data (in mag/arcsec^2) for the night of June 16–17 (red) is compared to July 20–21 (black) at our urban (A), and rural (B) locations. In the left plot the dotted lines indicate the time window used in the moon analysis, and in the right plot the time window used in the cloud analysis. Due to the shortening days we reject data taken within three weeks of the summer solstice from our moon analysis. The curve for July 20–21 at the rural site appears lopsided because the moon set shortly before 1am.
doi:10.1371/journal.pone.0017307.g005

the night to night variation is due to changes in cloud type could be easily tested by repeating this experiment in a location that has access to continuous LIDAR measurement of cloud properties.

We have demonstrated that in Berlin, and presumably in urban areas in general, cloud coverage has a strong amplification effect on light pollution. Due to this amplification, the luminance of the night sky in Berlin is 10.1 times brighter on overcast nights than on clear moonless nights, and 4.1 times brighter than that observed at our rural location on the brightest clear nights with a high elevation moon. Since many organisms are known to modify their behavior in the presence of moonlight, and because of the high frequency of overcast conditions, the cloud amplification effect has strong implications for the ecology of urban areas. The influence of cities extends over large areas: at 32 km from the city center the impact of clouds was still to brighten (by a factor of 2.8), rather than to darken, the night sky.

In contrast to the results reported here, a similar study undertaken in Hong Kong as part of a Master's thesis did not find a dependence of the night sky brightness on cloud coverage [28]. Although there were several methodological differences between that study and the present work, we believe that the primary reason for the different conclusions is that the studies were taken under completely different environmental conditions. The horizontal visibility measured by the synop station in Hong Kong was typically between 4 and 12 km. This is far shorter than that reported in Berlin, which was in almost all cases >10 km. A second important difference is that the data presented in [28] are for a site 15–20 km away from Hong Kong itself, a very large

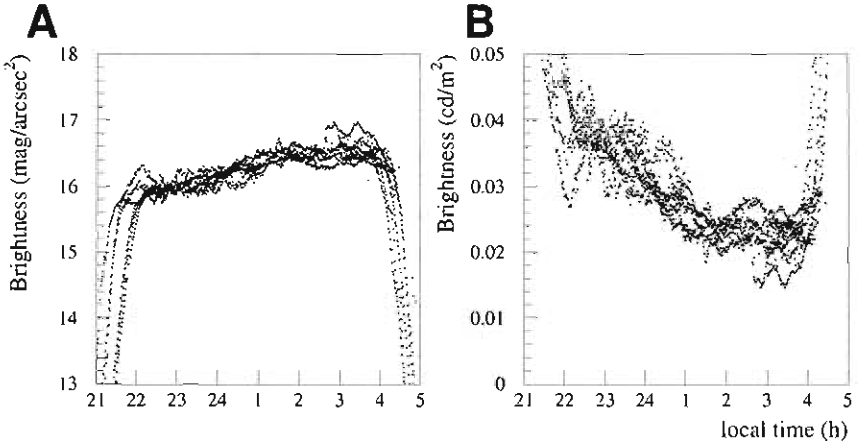

Figure 6. The sky brightness measured at the urban location is shown against local time for overcast skies in the April 26 - May 15 period. Data were included if the cloudiness was reported as 8 oktas in both the hourly report before and after the data was taken. Panel A shows the minute-by-minute data in the usual logarithmic scale (mag/arcsec^2), panel B shows the same data on a linear scale, using the approximate conversion to cd/m^2. The data shown were taken during the nights of April 26, May 2–3, May 6–7, May 9–10, May 11, and May 13–15, 2010.
doi:10.1371/journal.pone.0017307.g006

distance compared to the typical visibility. It may be that an examination of the data taken within Hong Kong itself would reveal a stronger relationship between cloud coverage and sky brightness. We agree with the suggestion in [44], that duplication of this study in other cities could help to elucidate the interaction between visibility, aerosols, clouds, and sky brightness, particularly if the site has access to LIDAR data.

The recent development of convenient sky brightness meters (both the Sky Quality Meter and the International Year of Astronomy Lightmeter) has made the continuous monitoring of ecological light pollution simple. The long term deployment of these devices by light pollution researchers in cities and dark sky parks, and by ecologists and physiologists in their research environments, will allow for both a quantitative understanding of the difference in night lighting across social-ecological systems, and for systematic, high precision, ground based tracking of year-to-year changes in sky brightness.

The well known map of world light pollution [14] includes by necessity only data from clear nights. Our analysis indicates that it is very important that biological conclusions based upon those results (e.g. [16]) consider the potential role that weather plays in enhancing the brightness of urban areas. Additionally, researchers performing *in situ* experiments in or near urban areas in which the presence or absence of the moon is known to affect the result (e.g. insect catches, [4,45]) should be aware that clouds and aerosols may play a larger role than the moon in determining ambient lighting.

It may be the case that the regional frequency of overcast nights is more important than population density in determining the threat posed to urban ecosystems by light pollution. By extending this analysis to include cities and towns of varying size, different regions, rural areas, and dark sky parks, we could test if this is the case. The development of a global dataset of continuous measurements from sky brightness meters would allow for rigorous evaluation of the results of [14], would provide strong constraints for verifying light pollution models, and would be beneficial to ecologists and light pollution researchers everywhere. We encourage anyone interested in participating in such a measurement to contact us.

Supporting Information

File S1
(TXT)

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Author Contributions

Conceived and designed the experiments: CCMK TR FH JF. Performed the experiments: CCMK FH TR. Analyzed the data: CCMK. Contributed reagents/materials/analysis tools: CCMK. Wrote the paper: CCMK FH JF TR.

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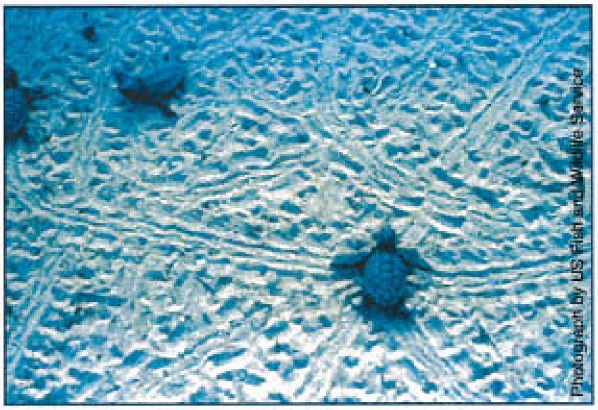
IDA Practical Guide


Photograph by Blair Witherington

Turtle trails that go straight to the ocean, as they should.


Photograph by US Fish and Wildlife Service

Turtles that are confused by light pollution (shown above with their erratic trails), are unable to find their way to the ocean.

Topic :

Effects of Artificial Light at Night on Wildlife

FROM THE BEGINNING OF EXISTENCE, humans have controlled their immediate environment, building shelters to keep out the elements and fires to banish the darkness. As civilizations continue to develop, humans are able to affect dizzying change on habitats in all corners of the globe. Though agreeable to us, many of the comforts of advanced society are devastating to the creatures that share the earth. A growing body of data suggests that artificial night lighting has negative and deadly effects on a wide range of creatures, including amphibians, birds, mammals, insects, and even plants.

Humans have evolved as diurnal animals, biased toward the daytime and dependant on visual cues, so illumination of our nightscapes seems comfortable and necessary. All animals, including humans, depend on a regular interval of daylight and darkness for proper functioning of behavioral, reproductive and immune systems. Many of these animals need the natural night to survive. For thousands of species, the natural dark night of the evolutionary past is an integral component of their continued existence.

Artificial night lighting harms species directly by triggering unnatural periods of attraction or repulsion that lead to disruptions in reproductive cycles, by fixation, by disorientation, or by interfering with feeding and sustenance. Light pollution has been shown to disorient migratory birds and hatchling turtles, disrupt mating and reproductive behavior in fireflies and frogs, and interfere with communication in species from glowworms to coyotes. Disruptions such as degradation of habitat, creation of artificial and dangerous habitat, and energy waste that may lead to climate change can all be linked to excessive artificial night lighting. Research biologists are warning that the negative synergy of such combinations can result in a cascade effect, with disastrous results for entire ecosystems around the world.

Diurnal— active during daylight
Photoperiod—duration of sunlight as determined by season (photoperiodic—internal clock governed by how long the day is)
Phototaxis—movement in response to light
Predation—predatory behavior in animal relationships

Climate characteristics vary from one year to the next; it is not uncommon to experience cool summers, dry springs, and slow falls. A season's photoperiod is the only consistent factor in the natural environment. Therefore, many species of plants and animals rely on the length of the day to indicate the proper season for mating, molting, and other life cycle activities. This photoperiodic sensitivity is often so acute that many species can detect discrepancies in natural light as short as one minute. Reproduction cycles are most often disrupted when artificial light at night interferes with species' natural detection systems. Trees have been known to bud prematurely; some flowers cease blooming. Artificial light also can cause animals such as squirrels and robins to mate out of season. Changes in plant and animal reproductive activity can create difficulty in finding food and increase chances of starvation.


Photograph by U.S. Fish and Wildlife Service

Pine Barrens tree frog

There is evidence that the use of high and low pressure sodium light in ecologically sensitive areas such as wetlands, woods, and coastal areas has less impact on habitat and life cycle behavior than use of other kinds of light. The relatively monochromatic wavelength emitted by the yellow tinted sodium vapor lights attracts fewer insects and can be more easily filtered to minimize negative effects.

Insects, frogs, toads, and salamanders have demonstrated both physical and behavioral disruptions as a result of artificial night lighting. A majority of frog and toad species are nocturnal and, because they must remain close to a water source, are less able to compensate for changes in the environment by relocating.

Like other amphibians, salamanders are currently suffering population declines around the world. Many species of pond-breeding salamanders show strong site fidelity to their home ponds, and studies to date have shown that artificial illumination can disrupt salamanders' ability to return to home ponds to breed.


Photograph by Alexei Pace

Insects are attracted to the white light of floodlights.

Artificial light at night contributes to lack of food (starvation) by interfering with predator/prey relationships. For instance, moths and other night-flying insects are attracted to lights. This involuntary phototaxis leads to their easy capture. Their incessant gravitation toward artificial points of light not only makes them vulnerable as prey and subjects them to increased predation, but disrupts the normal nocturnal patterns of predator species by creating an artificial feed concentration around points of light. For some species of predators, such as bats or birds that are not repelled by light, this disruption means a change in the concentration and location of their feed, which can lead to imbalances in predator/prey ratio. For species repelled by light, such as horseshoe bats, long eared bats, and mouse eared bats, feed becomes scarcer and difficult to procure, as many insects swarm around lights, leaving fewer to be caught as they fly free. The decreasing amount of available food due to


Photograph by Cameron Hansen

Visible for miles, squid boat lights unnaturally attract species of fish and migratory birds.


Photograph by www.offshorepictures.com

Relentless lights are common on offshore oil platforms.

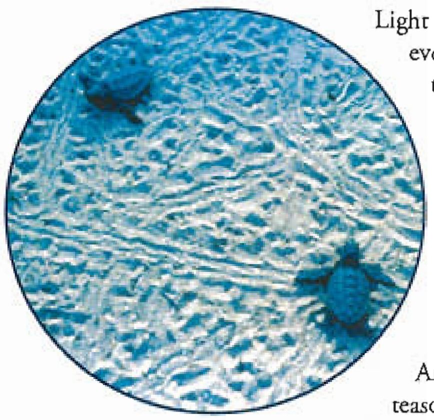
Upon discovering the magnitude of fatal bird collisions, some cities are initiating mitigation procedures. The Lights Out Toronto campaign, established in 2006 in Toronto, Canada calls for residents to turn out any unnecessary lights for the protection of migratory birds. In addition, the city has issued bird friendly development guidelines for all new buildings, which include the control of unnecessary artificial light. In September 2008, Boston, MA, USA began a two-month initiative to conserve electricity by shutting off lights at 34 city skyscrapers. A stated purpose of this project was the protection of migrating birds. Chicago, IL and New York, NY USA also participate in a "Lights Out" during migration season.

As awareness of the danger of artificial light to sea turtles grows, an increasing number of communities are restricting coastal illumination. Countries all over the world have passed ordinances that control the amount and type of light used in coastal environments. As the list grows, hatchling sea turtles are starting to be able to find the sea without the help of human volunteers to guide them. Learn more about local and regional action by visiting *www.seaturtle.org*.

a combination of habitat loss and life cycle disruption is causing many bat populations, such as Europe's horseshoe bat, to become threarened or endangered.

Since the eyes of nocturnal animals are specially evolved for foraging in low-light conditions, small changes in illumination can compromise strategies and profoundly alter their relationship with prey species. Even fish are affected by artificial light. Some species of fish, normally exposed only to natural light sources such as phosphorescence, can be temporarily blinded and left vulnerable by artificial light. Artificial light also inhibits normal anti-predation behavior such as schooling, and can affect migratory patterns in species such as salmon and sockeye fry.

Offshore, brightly lit oil and gas platforms and squid vessels that attract prey and affect numerous species of fish wirh lights pose both primary and secondary hazards to marine birds. The illumination and heat of offshore hydrocarbon platforms and squid fishing vessels also encourage algae growth, attracting fish and invertebrates. Marine birds are then killed around squid vessels by swallowing hooked prey or by feathet contamination in oil-fouled water at hydrocarbon platforms. Marine birds that feed on bioluminescent prey may be particularly sensitive to light source attraction, many threatened and endangered species at great risk ftom artificial ocean lighting. Many species are susceptible to fixation—also known as "capture"—on artificial lights at sea; exhausted birds will circle for hours or days until they fall into the sea. Off eastern Canada in 1998, tens of thousands of seabirds were observed circling the newly operational Hibernia platform, fixated by an unrelenting point of illumination.



Light fixation is a constant bird hazard that continues to kill thousands of birds in urban areas every year. Hundreds of terrestrial bird species fly and migrate under cover of night. While the mechanisms for birds' attraction to artificial night lighting are not well understood, its hazards to birds have been well documented. During the 1960s, it is estimated that over a million birds a year were killed in collisions with lighted television towers in the United States. Since that time, the number and height of communication towers has increased exponentially. Skyscrapers and other urban buildings also threaten birds, posing collision, fixation, and disorientation hazards.

Light and Sea Turtles

Artificial light at night is devastating sea turtle populations around the world for several reasons. Studies in Florida have shown that loggerhead, leatherback, and green turtle females choose the darkest beaches for their nest sites and will not nest at beaches lit by mercury vapor lights. On beaches subject to indirect light trespass, turtles will avoid the more brightly lit areas in preference to the dark. Nests are, therefore, more concentrated in the dwindling dark spaces, causing more hatchlings to succumb to predators and other site-specific hazards.

However, the most deadly problem facing these internationally protected sea turtles is disorientation from excessive and carelessly placed light. Many types of coastal illumination, including street, residential, and business lighting, confuses newly emerged hatchlings, which instinctively orient to the brightest light source. For thousands of years, this source was the reflection of moon and starlight on the sea. The turtles' natural programming allowed them to reach the water safely. Today, development along coastlines can cause hatchlings to head inland instead toward artificial lights, where they die of exhaustion, dehydration, predation, and road traffic. Each year, Florida alone loses hundreds of thousands of hatchlings.

Inappropriate artificial night lighting disrupts physiological as well as environmental functions. Hormone production in vertebrates, for example, is regulated by the circadian rhythm. Studies in humans and rats show a correlation between exposure to even low levels of illumination during normally dark hours and depressed levels of melatonin (a hormone produced in the retina), resulting in an increased risk of accelerated growth in breast cancer tumors. The effect of artificial night lighting on melatonin and other hormonal systems has yet to be studied in the wild, a study made more difficult by the scarcity of natural dark night conditions in most Western ecosystems.

While the wide range of potential damage caused by artificial light at night is still being discovered, steps to reset the natural balance between light and darkness are already being taken. To help preserve wildlife and minimize damage to ecosystems, start by following the steps listed in the Practical Actions to the right. A list of resources to increase knowledge of these topics and links to information on local and regional action groups can be found at the end of this practical guide.

Practical Actions:

Turn off unnecessary lights around your house and yard. Use timers and sensors to help put light only where and when it is needed.

Use fully shielded fixtures to direct the light ONLY WHERE NECESSARY FOR COMFORT AND SAFETY.

See red: Use red filters on house and street lights. Red lights emitting a low wavelength generally have less of an impact on wildlife. Sea turtles and other coastal creatures, as well as amphibians and many species of insects, react especially well to red light—by hardly reacting at all.

...or yellow: Yellow lights such as high pressure sodium (HPS) or low pressure sodium (LPS) lamps attract fewer insects and moths (think of your typical yellow front porch bug light). If light is required, advocate for their use in environmentally sensitive areas such as coastal regions or forest preserves.

Get educated: field guides and nature walks will help identify vulnerable species in your area.

Raise awareness: Most people are blind to the impact artificial light has on wildlife. A presentation to a social club or activist group could increase interest and win supporters.

Ask that any further development in your community include a report on ecological issues of light pollution in their environmental impact statement.

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Rich, Catherine, and Travis Longcore, eds. *Ecological Consequences of Artificial Night Lighting.* Washington: Island Press, 2006.

Related Practical Guides and Web Links:

Blair E. Witherington and R. Erik Martin. "Artificial Lighting and Sea Turtle Hatchling Behavior." *Florida Marine Research Institute Technical Reports.* TR-2 (1996)—*http://research.myfwc.com/features/view_article.asp?id=2156*

Cinzano, P., F. Falchi, and C.D. Elvidge. "The First World Atlas of the Artificial Night Sky Brightness." *Monthly Notices of the Royal Astronomical Society.* 328 (2001): 689-707. *Light Pollution in Italy.* 2006—*http://www.lightpollution.it/cinzano/download/0108052.pdf.*

FLAP—Fatal Light Awareness Program—http://www.flap.org

FWC—Florida Fish and Wildlife Conservation Commission— http://www.myfwc.com/WILDLIFEHABITATS/Seaturtle_Lighting.htm

seaturtle.org— http://www.seaturtle.org

For information on IDA membership and donations, visit our Web site at www.darksky.org.

http://www.darksky.org/light-pollution-topics/the-environment

A non-profit member organization that teaches others how to preserve the night sky through factsheets, law references, pictures, and web resources.

Light Pollution Topics

Light Pollution Matters
The Environment
Ill Health
Energy Waste
Lighting, Crime & Safety

- Night Sky Heritage
- Take Action!

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- Glossary

Materials and Outreach

- IDA Activity Book
- Star Parties
- IDA Displays
- IDA Annual Awards
- Education
- Dark Skies Awareness and IYA2009

Events

- Annual Conference
- European Symposium
- International Dark Sky Week
- Event Archives

Press Room

- Press Kit
- IDA Fact Sheet

Multimedia

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http://www.darksky.org/light-pollution-topics/the-environment

Dark Sky Ambassadors
Images
NeedLess Campaign and Lighting Design Simulator
Shop IDA
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THE ENVIRONMENT

"When we add light to the environment, that has the potential to disrupt habitat, just like running a bulldozer over the landscape can." — Chad Moore National Park Service

Light pollution is a threat to the environment

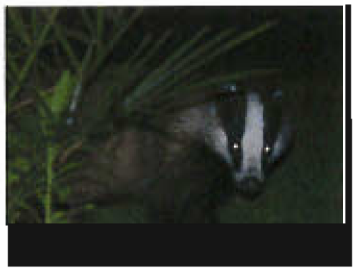
For billions of years, all life has relied on Earth's predictable rhythm of day and night. It's encoded in the DNA of all plants and animals. Humans have radically disrupted this cycle by lighting up the night.

Plants and animals depend on Earth's daily cycle of light and dark rhythm to govern life-sustaining behaviors such as reproduction, nourishment, sleep and protection from predators.

Scientific evidence suggests that artificial light at night has negative and deadly effects on many creatures including amphibians, birds, mammals, insects and plants.

Artificial lights disrupt the world's ecosystems

Credit: Michael Newton



Credit: Chris Parfitt

Nocturnal mammals sleep during the day and are active at night. Light pollution radically alters their nighttime environment by turning night into day.

According to research scientist Christopher Kyba, for nocturnal animals, "the introduction of artificial light probably represents the most drastic change human beings have made to their environment."

"Predators use light to hunt, and prey species use darkness as cover," Kyba explains "Near cities, cloudy skies are now hundreds, or even thousands of times brighter than they were 200 years ago. We are only beginning to learn what a drastic effect this has had on nocturnal ecology."

Glare from artificial lights can also impact wetland habitats — home to amphibians such as frogs and toads, whose nighttime croaking is part of the breeding ritual. Artificial lights disrupt this nocturnal activity, interfering with reproduction and reducing populations.

Artificial Lights Can Lead Baby Sea turtles to their Demise

Sea turtles live in the ocean but hatch at night on the beach. Hatchlings find the sea by detecting the bright horizon over the ocean. Artificial lights draw them away from the ocean. In Florida alone, millions of hatchlings die this way every year.

Glare from artificial lights can also impact wetland habitats — home to amphibians such as frogs and toads, whose nighttime croaking is part of the breeding ritual. Artificial lights disrupt this nocturnal activity, interfering with reproduction and reducing populations.

Migratory birds depend on cues from properly timed seasonal schedules. Artificial lights can cause them to migrate too early or too late and miss ideal climate conditions for nesting, forgaing and other behaviors.

Artificial Lights have Devastating Effects on Many Bird Species

Birds that migrate or hunt at night navigate by moonlight and starlight. Artificial light can cause them to wander off course and toward the dangerous nighttime landscapes of cities. Every year millions of birds die colliding with needlessly illuminated buildings and towers.

Migratory birds depend on cues from properly timed seasonal schedules. Artificial lights can cause them to migrate too early or too late and miss ideal climate conditions for nesting, forgaing and other behaviors.

http://www.darksky.org/light-pollution-topics/the-environment

Ecosystems: Everything is Connected

Many insects are drawn to light, but artificial lights can create a fatal attraction. Declining insect populations negatively impact all species that rely on insects for food or pollination. Some predators exploit this attraction to their advantage, affecting food webs in unanticipated ways.

Resources

- **IDA Light Pollution & Wildlife brochure**
- **IDA Light Pollution & Wildlife Practical guide**
- **Audubon Bird-Safe Building Guidelines**
- **Wildlife Research**

For Kids

Nighttime Activity Book

Videos

Dark Ranger, Kevin Poe, explains how light pollution affects baby sea turtles and provides ways in which we can help them successfully make their journey from the shore to the ocean.

Learn in one minute what you can do to protect birds.

http://www.darksky.org/light-pollution-topics/the-environment

Learn in one minute what you can do to protect wildlife

Watch this video from the Sea Turtle Conservancy on the effect of light pollution on sea turtles.

http://www.darksky.org/light-pollution-topics/the-environment

Watch this Science in Seconds video to learn how light pollution negatively affect all types of wildlife.

Recent News Items on Light Pollution & the Environment

'Lights Out' seeks to stem bird carnage caused by city skylines (Washington Post)

Lights Out Baltimore, an organization that started in 2008, scours the streets in the predawn hours to collect birds — dead or stunned — that have collided with windows in the city's corporate canyons. **Read more.**

Light pollution 'affects bats' tropical seed dispersal' (BBC News)

Light pollution could affect the regeneration of tropical rainforests because it disrupts the behavior of seed dispersing bats, a study suggests. **Read more.**

Birds Killed By Skyscrapers: An Oddly Life-Affirming Photo Essay (FastCompany)

Nine years ago, artist Lynne Parks got into birdwatching. The Baltimore-based artist, who has suffered from cancer since childhood, found something life-affirming in the birds' energy. **Read more**.

Artificial lighting and noise alter biorhythms of birds (Science Daily)

Noise from traffic and artificial night lighting cause birds in the city center to become active up to five hours earlier in the morning than birds in more natural areas. **Read more**.

Night light pollution affect songbirds' mating life, research suggests (Science Daily)

http://www.darksky.org/light-pollution-topics/the-environment

In today's increasingly urbanized world, the lights in many places are always on, and according to a new study, that's having a real impact on the mating life of forest-breeding songbirds. **Read more**.

Light at night, melatonin and bird behavior (Science Daily)
Low light levels, similar to those found in urban areas at night, can have a significant effect on melatonin production in birds at night. This suggests that melatonin could be mediating changes in bird behavior at night. **Read more**.

Submission #___
Subject Cedar River Predation

Cedar River Rention, WA Poster - used as display and introduction

The Effect of Light Intensity on Predation of Sockeye Salmon Fry By Cottids in the Cedar River
Roger Tabor, Gayle Brown, Aaron Hird and Stephen Hager, April 2001

Saving Salmon On The Cedar River - derived from Washington State Department of Transportation Bulletin March 23, 2001 No. 01-12

Signals Maintenance Shapes Salmon Solution - Washington State Department of Transportation Bulletin March 23, 2001 No. 01-12

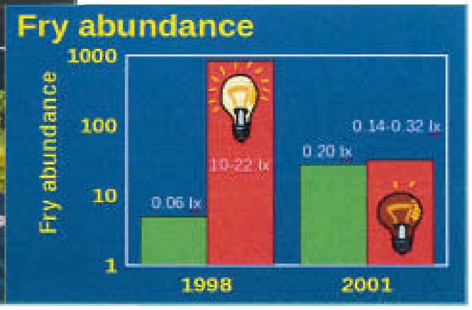
The Effect of Light Intensity on Sockeye Salmon Fry Migratory Behavior and Predation by Cottids in the Cedar River, Washington
R. Tabor, G. Brown, V. Luiting, North American Journal of Fisheries Management 24:128-145, 2004

The Effect of Light Intensity on Predation of Sockeye Salmon Fry By Prickly Sculpin and Torrent Sculpin
Roger Tabor, Gayle Brown, Victoria Luiting, May 1998

Cedar River Renton, WA

The Cedar River is where the largest run of sockeye salmon in the lower 48 states begins.

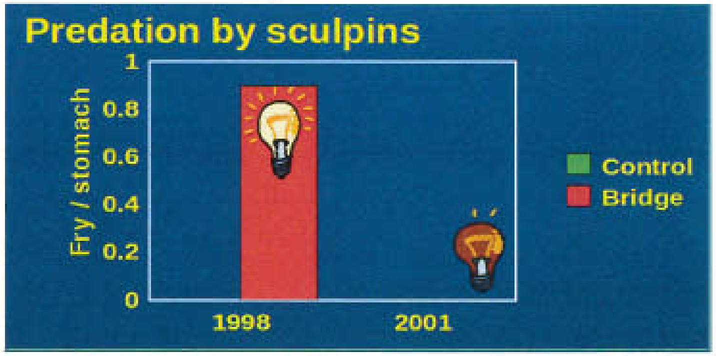
That is, it was before lighting was installed on the Cedar River Trail where it crosses the river below the I-405 bridge.



Light is basically a big stop sign. Sockeye like to migrate at night in the fastest part of the river channel and move to low velocity waters along riverbanks and river bottoms during the day. This way they avoid becoming the prey of fully-grown trout and sculpin, which like to forage at night. But the lights above the trail made the sockeye fry think it was daylight.

The result of shielding the lighting in 1998

The 2000 run was one of the biggest in recent memory, but the year before that was one of the worst, according to Roger Tabor, a fishery biologist with the U.S. Fish and Wildlife Service.



Ref. 1. The Effect of Light Intensity on Sockeye Salmon Fry Migratory Behavior and Predation by Cottids in the Cedar River, Washingtion, Taabor, Brown, Luiting, 2004
2. Effects of Artificial Lighting on Juvenile Salmonids: A Review of Research in the Lake Washington Basin, Roger Tabor, Mark Celedonia, USFWS , Gayle Brown, USGS

THE EFFECT OF LIGHT INTENSITY ON PREDATION OF SOCKEYE SALMON FRY BY COTTIDS IN THE CEDAR RIVER

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April 2001

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ABSTRACT

In the Cedar River, we examined the relationship between light intensity level and migratory behavior of sockeye salmon fry (*Oncorhynchus nerka*) and predation by cottids. Additionally, light intensity readings were taken to document the location of high artificial light intensity levels and determine what atmospheric conditions affect those light levels. The effect of light intensity on sockeye salmon fry was examined with two methods: 1) comparison of lighted and non-lighted areas in the City of Renton; and, 2) experimental trials with standardized amounts of light added to the river.

Within the lower 2.9 kilometers of the Cedar River, there were several locations with high light intensity levels. Most were next to street bridges. The highest light readings recorded were at the I-405 Bridge and the Renton Library. In the lower Cedar River, artificial lighting appeared to come from two major sources: direct lighting and reflected lighting off of the clouds. At locations with minimal direct lighting, the highest light intensity levels occurred on overcast nights due to reflected light. The lowest levels occurred during clear, moonless nights. As far upstream as river kilometer 9.8, we recorded readings during overcast nights that were higher than during a clear night with a full moon.

Experimental trials were done at two locations away from any lights, Lion's Club Park and Elliot Park. Two trials were done at the Lion's Club Park, both following a release of hatchery sockeye salmon fry. Most trials at Elliot Park were conducted below a sockeye salmon spawning channel. At the Lion's Club Park, light intensity treatments were done in two habitat types, gravel shore and rip-rap shore.

At all City of Renton sites examined, the abundance of sockeye salmon fry was substantially higher at sites with high light intensity levels than at nearby sites with low light. Correspondingly, most predation of fry by cottids was observed in the bright light areas. Higher predation rates were observed along the shoreline as well as in the mid-channel area. In relation to other sampling conducted by the U.S. Fish and Wildlife Service, the I-405 Bridge lighted area was the only location we have ever seen any significant predation of fry by cottids in a mid-channel area of a riffle in the Cedar River.

In the experimental trials, we found that the abundance of fry and predation by cottids was related to light intensity levels. In one bright light treatment, we were able to slow the migratory behavior of over 550 sockeye salmon fry within an 8-meter (m) shoreline section. At the Lion's Club Park, gravel shores had five times as many fry as rip-rap shores for a given light intensity level. Gravel shores had a larger low-velocity area than did rip-rap shores. In two experimental trials, we also examined the abundance of fry shortly after the lights were turned off. In all lighted experimental units, the number of fry declined dramatically after the lights were turned off, however, in control units (no light added), the number of fry remained about the same or actually increased slightly. In the experimental trials, we also monitored the abundance of juvenile chinook salmon

(*O. tshawytscha*). Small numbers of chinook were observed. No relationship between chinook salmon abundance and light intensity was detected. In conclusion, our results indicated that any estimation of predation loss needs to assess the light intensity level, as well as fry abundance and shoreline and mid-channel habitat.

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INTRODUCTION

After emerging from their redds, most sockeye salmon (*Oncorhynchus nerka*) fry immediately emigrate downstream to a lake environment where they reside for the next year. They reduce their vulnerability to predators by emigrating at night. Results of recent lab experiments indicated that increased light appears to slow or stop emigration of sockeye salmon fry which makes them more vulnerable to capture by predators (Tabor et al. 1998a). The Lake Washington sockeye salmon occur within a large urban area. In some river sections that sockeye salmon fry must migrate through, artificial lighting is present. As part of the mitigation for the recent flood control project, light intensity levels were reduced or proposed to be reduced in some areas of the lower Cedar River to reduce predation. Although reduced lighting appears to benefit sockeye salmon fry, little work has been done to quantify its effect on predation in a field situation. Most earlier work was done under laboratory conditions and results can be difficult to apply to field conditions. In 1998 and 1999, we attempted to quantify the effects of increased light under field conditions in the Cedar River. In 2000, we also took light intensity readings in the lower Cedar River to identify areas with high artificial light levels.

STUDY SITE

The Cedar River is the main tributary for the Lake Washington basin. The lower 35.1 kilometers are accessible to anadromous salmonids. Landsburg Dam (Figure 1), a water diversion structure, prevents fish from migrating further upstream. The Cedar River is the major spawning area for a large population of sockeye salmon. Runs in excess of 300,000 fish have occurred in some years.

The lower 3 kilometers of the Cedar River occurs within a large flood plain that was the historical Black River flood plain and Lake Washington delta. Presently, the area is the City of Renton (Figure 1) and has numerous artificial light sources due to urban and residential development. Upstream of river kilometer (Rkm) 3, the river is confined in a relatively narrow canyon with some residential development but substantially less artificial light than the Renton area.

METHODS

We examined the effect of light intensity on sockeye salmon fry with two methods: 1) comparison of lighted and non-lighted areas in the City of Renton; and, 2) experimental trials with standardized amounts of light added to the river. Additionally, we took light intensity readings in the lower Cedar River to document light levels. All light intensity measurements were made with an International Light Inc. model IL1400A radiometer/photometer. Light intensity was measured as lumens/ft^2.

PREDATION AND SALMONID FRY BEHAVIOR

Renton City lights

Four sites were selected in Renton; 1) I-405 Bridge (Rkm 2.7), 2) Renton Library (Rkm 2.5) Williams Avenue Bridge (Rkm 2.0), and South Boeing Bridge (Rkm 1.2). Each had a high light intensity area and a nearby area with similar habitat and substantially lower light intensity levels. Two sites were done in 1998 and the other two were done in 1999. Fry abundance was estimated at each site except the South Boeing Bridge. In 1998, we used a small 2.5-m long by 1-m high beach seine to compare fry abundance. Fry at the 1999 sites were counted by slowly moving along the shoreline using a flashlight. To be consistent between treatments, we only counted fry within the beam of the flashlight. We assumed that the counting had a minimal effect on fry abundance because it was done within a short period of time, approximately 1 minute per shoreline section. Sockeye salmon fry as well as chinook salmon fry (*O. tshawytscha*) were counted. The two species could be easily distinguished based on parr marks and relative size. Chinook salmon fry were considerably larger than sockeye salmon fry. Light intensity measurements (lumens/ft^2) were taken at the surface of the water in the middle of the area sampled. At three of the four sites, cottids were collected for stomach analysis to compare predation rates. Fish were collected with backpack electrofishing equipment. Cottids were collected along the shoreline and/or in the mid-channel area. Cottids along the shoreline were collected visually with the aid of dip nets. Cottids in the mid-channel area were collected passively with the aid of block nets. After capture, cottids were identified to species and total length (TL) was measured. Afterwards, their stomachs were flushed and salmonid fry were counted. We sampled cottids that were > 49 millimeters (mm) TL. Smaller cottids rarely consume sockeye salmon fry. We assumed that cottids had captured fry in the same general area that they were captured. A Mann-Whitney *U* test was used to compare differences in predation rates between a lighted site and the control site. Data were log-transformed because the data was multiplicative rather than additive (Zar 1984).

Experimental Trials

Experimental trials were done at two sites in 1999, the Lion's Club Park at Rkm 18.3 and the Elliot Park at Rkm 7.4 (Figure 1). Sites were divided into shoreline sections that had uniform habitat. Two experimental trials were conducted at the Lion's Club Park along a 112-m shoreline section. The upper 56 m had a rip-rap shoreline while the lower 56 m was a gravel shoreline. Both trials were conducted on a night when hatchery sockeye salmon fry were released upstream at Rkm 21.7. On March 31, 1999, 135,000 fry were released, and on April 5, 1999, 57,000 fry were released. The other site at the Elliot Park consisted of three 40-m shoreline sections: 1) main channel, 2) braided channel; and, 3) side channel at the outlet to the spawning channel. Within each section, three experimental light intensity levels were tested. The main channel and braided channel section were only done once due to the low numbers of fry. The side channel was done five times because good numbers of fry were migrating through this section during the study period. Most of the fry in this section were probably migrants from a nearby spawning channel.

Each shoreline section was divided into 8-m long units. Lights were only added to every other unit to insure light from one experimental unit did not affect another one. Treatments were randomly assigned within each shoreline section. Two lights were used for each experimental unit. Lights were mounted at the top of a 2-m pole, placed 1 m from both edges of each unit, and lights were directed towards the middle of the unit. An individual light system consisted of a 60-watt light bulb, a deflector to focus the light, and a dimmer switch to control the light intensity. We used five light intensity levels: 1) control (no lights): 0.0006-0.010; 2) dim: 0.015-0.025; 3) low: 0.045-0.055; 4) medium: 0.10-0.14; and, 5) bright: 1.0-1.4 lumens/ft^2.

Light intensity measurements were taken at the surface, 2 meters from shore. Generally three measurements were taken, one in the middle and one each from just inside of the upstream and downstream edges. The middle of each experimental unit was the brightest and the upstream and downstream edges were the dimmest. Light intensity was slowly attenuated across the river channel. Lights were turned on shortly after dusk and adjusted to get the appropriate light intensity. Fry were counted with a flashlight, similar to the City of Renton sites. For some experimental trials, we turned off the lights and recounted the number of fry 20 minutes later.

In most experimental trials, we used backpack electrofishing equipment to collect cottids to determine the predation rate. After capture, cottid stomachs were flushed and the number of ingested fry was counted. Fry were categorized as freshly ingested or well digested. Only counts of freshly ingested fry were used. We assumed that freshly ingested fry were consumed during the experiment and well digested fry were consumed the prior night or sometime before the experiment. Since we started the experiments shortly after sunset and cottids are primarily nocturnal, we felt this was a valid assumption.

Differences in fry abundance were tested with a two-way analysis of variance (ANOVA) without replication. A Mann-Whitney *U* test (two samples) or a Kruskal-Wallis test (more than two samples) was used to compare differences in predation rates. Data were log-transformed because the data was multiplicative rather than additive (Zar 1984).

LIGHT INTENSITY READINGS

Readings of light intensity in the lower Cedar River were done under three scenarios: 1) overcast skies; 2) clear skies, no moon; and, 3) clear skies, full moon. Light reading were taken every 50 m from Rkm 0.9 to 2.9. Below Rkm 0.9 access to the river was limited in many areas. However, additional readings were done at Rkm 0.0, 0.2, 0.3, and 0.7. We also included one site at Rkm 9.8. Additional readings were also taken at major light sources to determine peak light levels. For safety reasons, light readings were taken close to the river bank, approximately 1-5 m from shore. In most locations, the mid-river light reading would be lower than readings taken close to shore because the light source is located on the river bank. At some locations, such as I-405 Bridge and Renton Library, light sources span the entire channel width. At a few sites, we took light readings on the opposite bank from the light source. All readings were taken at the surface of the water. Most readings were taken from the right bank except between the Renton Library (Rkm 2.5) and Houser Way Bridge (Rkm 2.6), where the right bank was difficult to access.

RESULTS

SOCKEYE SALMON FRY

Renton City Lights

Fry abundance. At all three sites examined, the abundance of sockeye salmon fry was substantially higher at sites with high light intensity levels than at a nearby site with low light (Figure 2). This was particularly apparent at the I-405 site where large numbers of fry were present under the bridge but 180 m upstream we were unable to collect a single fry. Both sites had a large amount of shallow, low velocity water where numerous fry could reside. In contrast, few sockeye salmon fry were observed at the Renton Library. Light levels were lower and there was little shallow, low velocity water along the shoreline. However, all sockeye salmon fry observed were present in the lighted area (Figure 2). The Williams Bridge site was counted on two nights, both having similar results. Most fry were nearest the bridge where the light intensity levels were the highest. At 35 m from the bridge, light levels were greatly reduced (0.012 lumens/ft^2) and only a couple of fry were observed (Figure 2).

Predation. At both the I-405 Bridge and Renton Library, little predation was observed in control areas with little light, while relatively high predation rates were observed in lighted areas (Figure 2). Fifty-three percent of the cottids in the mid-channel area of the lighted I-405 site had consumed fry (0.9 fry/stomach), while no predation occurred at the control. Predation rates were significantly higher in the lighted area (Mann-Whitney U test = 58.5; P = 0.002). Preliminary sampling was also done on February 23, 1998, at the I-405 Bridge (the control was not sampled). From 15 cottids collected, a total of 18 sockeye salmon fry were present in the stomach samples (1.2 fry/stomach). At the Renton Library site, cottids were sampled at both the shoreline and mid-channel areas on the same night (March 18, 1999). In the control, no predation was observed in the shoreline area and 1 sockeye salmon fry was observed out of 18 stomach samples from the mid-channel. In the lighted shoreline area, 33% of the cottids had consumed fry (0.6 fry/stomach) but no predation was observed in the lighted mid-channel area (Figure 2). Predation rates were significantly higher in the shoreline of the lighted area than the control area (Mann-Whitney U test = 63; P = 0.03). Of the cottids (> 49 mm TL) collected at both sites, 95% were coastrange sculpin (*Cottus aleuticus*) and 5% were torrent sculpin (*C. rhotheus*). Predation was observed in both cottid species.

At the South Boeing Bridge site (including control), we collected 105 cottids but only three were > 49 mm TL. No fry was observed in their stomachs. We also flushed the stomachs of four cottids that were 45-49 mm TL. Of these, one torrent sculpin (47 mm TL) that was collected at the bridge had consumed a sockeye salmon fry. No predation was observed at the control site. Light intensity at the South Boeing Bridge was 0.28 lumens/ft^2 and 0.12 lumens/ft^2 at the control.

Experimental Trials

Fry abundance. At Lion's Club Park on March 31 (Figure 3) and April 5, few sockeye salmon fry were observed in all units for the first 45 to 60 minutes. However, within the next 20 minutes the number of fry increased dramatically. For example, in the bright-light experimental unit, the number of fry changed from 27 at 2025 hours, to 577 at 2045 hours. The increase in the number of fry was due to the large number of hatchery fish that had been released earlier that evening. The fry were released at Rkm 21.7 at approximately 2008 hours (90 minutes after sunset). Experimental units with higher light levels had significantly more fry in both experimental trials (ANOVA; March 31, $P = 0.02$; April 5, $P = 0.005$; Figures 4,5). Within each light intensity level, higher numbers of fry occurred in the gravel shore than the rip-rap shore (ANOVA; March 31, $P = 0.04$; April 5, $P = 0.03$; Figures 4,5). On average, gravel shores had five times as many fry as rip-rap shores for a given light intensity level.

Overall, fry abundance results at Elliot Park followed similar patterns as at Lion's Club Park. On April 7, low numbers of fry were observed in every experimental unit. However, the highest numbers of fry occurred in the units with the highest light levels for each channel type (Figure 6). Analysis of variance revealed a significant difference ($P = 0.003$) in fry abundance between light intensity levels. Fry abundance was done on four additional dates in the side channel, however, on May 3, the light system for the medium-light experimental unit malfunctioned, thus we were unable to get a count for that experimental unit (Figure 7). Between the fives dates that the side channel was sampled, the abundance of fry varied greatly. Most fry were probably migrants from the spawning channel. Peak outmigration appeared to be around May 3. Analysis of variance revealed a significant difference ($P < 0.001$) in fry abundance between light intensity levels. The highest number of fry was always in the medium light unit (Figure 7). On every date, the dim light unit had more fry than the control unit.

In two experimental trials, we also examined the abundance of fry shortly after the lights were turned off. In all lighted experimental units, the number of fry declined dramatically after the lights were turned off (Figure 3). In control units (no light added), the number of fry remained about the same or actually increased slightly (Figure 3).

Predation. In general, predation rates of cottids showed the same trend as fry abundance. The highest predation rates recorded were from experimental units with increased light. This trend was particularly noticeable during the March 31 trial at the Lion's Club Park. No predation was detected in the control units. In contrast, large numbers of fry were found in the stomach samples of cottids collected from the bright-light experimental unit (Figure 4). Three torrent sculpin were collected from this unit with 10 or more fry in their stomachs. The maximum number of sockeye salmon fry consumed by an individual fish was 13 (92 mm TL, torrent sculpin). Differences in predation rates were marginally significant (Kruskal-Wallis test = 5.7, $P = 0.058$) between experimental units but not significant between medium and bright experimental units (Mann-Whitney U test = 3.5, $P = 0.23$). Predation rates in both lighted rip-rap experimental units were lower than in units with gravel shores. Differences were significant between the two bright experimental units (Mann-Whitney *U* test = 8.0, *P* = 0.03) but not the medium light experimental unit (Mann-Whitney *U* test = 3.5, *P* = 0.66).

Predation rates on April 5 were low for all experimental units. Only three out of 42 cottids had consumed sockeye salmon fry. No differences between treatments were detected. However, four of the five fry consumed were from the medium-light experimental units and no predation was observed in the control units (Figure 5).

On April 5, one riffle sculpin (89 mm TL; *C. gulosus*) was collected with 14 yolk-sac sockeye salmon fry. Because these fish were yolk-sac fry, we assumed these were not migrating fish but instead they probably were captured in the substrate. Additionally, many were well-digested and thus were not consumed on the night of our experiment. None of these fry were included in our estimate of predation. Some sculpins such as reticulate sculpin (*C. perplexus*), have been shown to be able to move into the substrate to consume recently-hatched salmonid fry (Phillips and Claire 1966). Additionally, we have collected several riffle sculpin that consumed yolk-sac fry in another location of the Cedar River (R. Tabor, unpublished data).

During the April 7 experimental trial, few predators were collected along the shore in the main channel and braided channel. However, 23 cottids were collected in the side channel. The only experimental unit to have any predation of fry was the medium-light unit. In addition to April 7, side channel predators were sampled two other times. In each trial, the highest predation rates were observed in the medium-light unit; however, there was no significant differences detected between the light intensity levels.

At Lion's Club Park, torrent sculpin made up 91% of the cottids captured, while riffle sculpin made 8% and shorthead sculpin 1% (*C. confusus*). No coastrange sculpin were observed at this site. In the side channel at Elliot Park, 50% of the cottids were torrent sculpin, 26% coastrange sculpin and 24% riffle sculpin.

In addition to cottids, we also collected a few salmonids. The number and species collected included five juvenile coho salmon (*O. kisutch;* range, 74-112 mm FL) , eight unidentified trout (range 76-103 mm FL), one cutthroat trout (*O. clarki*; 160 mm FL), and one rainbow trout (*O. mykiss*; 146 mm FL). Almost all were collected at the Lion's Club Park site. The only salmonids observed to have freshly-ingested fry in their stomachs were three juvenile coho salmon. One juvenile coho salmon (109 mm FL) was collected with five freshly ingested sockeye salmon fry. The fish was captured in the bright experimental unit on March 31, 1999. The other two juvenile coho salmon had one fry each in their stomachs. These fish were collected from experimental units with dim and low light intensity levels. Therefore, salmonid predation rates show the same general trend as with cottids but because the sample sizes are small it is difficult to say anything conclusive. Additionally, salmonids are far more mobile than cottids and thus there is a greater chance that they may have consumed their prey at a different location. However, most of the salmonids collected were small and thus, may have a small home range.

CHINOOK SALMON FRY

Small numbers of chinook salmon fry were also observed along the shoreline. There was no apparent pattern between different light intensity levels (Figure 8). In some cases, chinook salmon were more abundant in treatments with little or no light. For example, at the I-405 bridge site, we collected 3.4 chinook salmon/seine in the control area but only 0.3 chinook salmon/seine in the lighted area. Only one chinook salmon was seen from all the cottid stomachs examined. The cottid was a riffle sculpin (95 mm TL) captured in the bright section at the Lion's Club Park during the March 31 experiment.

LIGHT INTENSITY READINGS

Most high light intensity sites were next to street bridges (Figure 9). The Renton Library and a Boeing building at Rkm 1.6 also had high light readings. The highest light readings were at the I-405 Bridge and the Renton Library. Some light sources are typically shut off during the night. The Renton Library closes at 2100 hours. Peak light levels changed from 1.90 to 0.05 lumens/ft^2. Many of the lights along the Cedar River Trail are turned off at 2300 hours. Most of our readings were taken while the lights were still on.

Near strong light sources, such as street lights near bridges, light intensity levels did not appear do vary greatly between different sky conditions because the artificial lights were far more intense than other lighting sources such as the moon. However, away from these lights, light intensity levels appear to vary greatly depending on cloud cover and the moon. For example, at locations close to the City of Renton, overcast nights had higher light readings than during a full moon. Reflected light off of the clouds from nearby urban areas appears to be the main light source during overcast nights. The lowest readings were during a clear, moonless night.

We examined past readings of light intensity at Rkm 0.3. In addition to readings taken in 2000, readings were also taken in 1997 and 1999. The highest light intensity readings were recorded on overcast nights (Figure 10). Light readings as high as 0.040 lumens/ft^2 were recorded on an overcast night, whereas during clear, moonless nights readings ranged from 0.003-0.005 lumens/ft^2. Even at upstream locations, reflected light appears to be a major source of lighting. At Rkm 9.8, we detected little or no light on a clear, moonless night, on a full moon night light intensity was 0.008, and on an overcast night it was 0.012 lumens/ft^2 (Figure 10). Upstream of Rkm 10, we did not take any light readings, but we expect that the amount of reflected light would be substantially less due to the lower amount of urban development. In this area, the highest light intensity readings would probably occur during nights with a full moon.

Light intensity readings at Rkm 0.3 were quite variable between overcast nights (Figure 10). Most likely, the thickness of the clouds and the level of the clouds influence to amount of light that is reflected. On March 27, 2000, the clouds appeared to be very thick and low. Light intensity levels on that night were the highest that we have observed.

DISCUSSION

SOCKEYE SALMON FRY BEHAVIOR

Results for field observations in Renton and field experiments corroborated results from earlier lab experiments. Increasing light intensity levels have a profound effect on the behavior of sockeye salmon fry. Fry appear to move out of the thalweg and move to low velocity water where they are vulnerable to predators such as cottids. Even small increases in light intensity levels appeared to affect fry behavior. For example, at the Elliot Park side channel we observed differences in fry abundance consistently between the control (0.010 lumens/ft^2) and the dim light experiment unit (0.020 lumens/ft^2). Our results suggest that any reductions in light level can be beneficial and the impact of lighting should be considered for any future development project.

We were surprised by the large number (> 550 fry) of sockeye salmon fry that were present within the bright-light experimental unit (sand/gravel shoreline) during the March 31 experiment. Approximately 120,000 fry were released on that date. Assuming a similar per kilometer survival rate as hatchery releases from Landsburg Dam (Seiler and Kishimoto 1997), we estimate that 110,000 fry moved past our experimental site (assumes that the number of wild fry was minimal). Therefore, we were able to delay 0.5% of the release group within a 8 m shoreline section with two small lights. This suggests that several large lights spread out over a long section of shoreline and across the channel with sand/gravel substrate and a low sloping bank could have a strong effect on the behavior and survival of the entire run of out-migrating fry. McDonald (1960) was able to experimentally stop the nightly movement of sockeye salmon fry with artificial lighting of 3.0 lumens/ft^2, however, other levels of light intensity levels were not tested. Our bright-light experimental unit was 1.0 - 1.4 lumens/ft^2.

Experiments at the Lion's Club Park demonstrated that habitat can have an important effect on the number of sockeye salmon fry attracted to the lights. The effect was probably due in part to the amount of low velocity habitat as well as to substrate size. Light causes sockeye salmon fry to move to low velocity areas. The rip-rap banks were steeper and had a narrower area of low velocity water than did the gravel shoreline. Differences in substrate size between the two habitat types may also have resulted in differences in predator abundance, which could influence the number of sockeye salmon fry. Typically, the number of large cottids is higher in larger substrates than smaller substrates (Tabor et al. 1999b). Other predators such as rainbow trout were probably higher near the rip-rap. The presence of predators has also been shown to increase the downstream movement of sockeye salmon fry (Ginetz and Larkin 1976; Tabor et al. 1998a) and brown trout fry (*S. trutta*; Gaudin and Caillere 1985; Bardonnet and Heland 1994).

In all of our experimental trials, we only examined the abundance and predation of fry along the shoreline. Results indicate that lights cause fry to delay their migration and move to the shoreline to an area of low velocity. Another area of low velocity water is typically very close to the substrate across the entire channel. Results from the I-405 bridge site suggest that fry move to the shore as well as move to the substrate in mid-channel areas. The I-405 bridge site has strong lights all the way across the channel. Although, we have never directly observed sockeye salmon fry close to the substrate in the mid-channel, we did observe much higher predation rates than in similar areas with little or no light. Following 1998 and 1999 hatchery releases, we sampled a total of 10 mid-channel sites with little or no light. Out of 109 cottid stomachs examined, only one salmonid fry was seen. At the I-405 bridge site, a total of 33 fry were observed from 33 cottid stomach samples.

The use of the mid-channel substrates in lighted areas by sockeye salmon fry may be more common in areas with boulders and cobble than areas with smaller substrates. Larger substrates will create a more roughened river channel and have low velocity locations for sockeye salmon fry. Unfortunately these same sites will probably have a higher abundance of cottids > 49 mm TL. At South Boeing Bridge, the substrate was mostly small gravel and few cottids > 49 mm TL were collected and those that were > 49 mm TL were much smaller than those from the I-405 bridge which had some cobble and large gravel. Little predation was documented at the South Boeing Bridge. In the Cedar River, the number of cottids > 49 mm TL was shown to be related to the substrate size (Tabor et al. 1998b).

An important factor that probably affects the impact of artificial lighting is streamflow. The survival of hatchery sockeye salmon fry has been shown to be profoundly affected by streamflow conditions (Seiler and Kishimoto 1997). At lower flows, fry migration time is increased (Seiler and Kishimoto 1996) and they become more vulnerable to predators (Tabor et al. 1998). Fry typically migrate in the thalweg or the fastest part of the channel. During low streamflow conditions, mid-channel velocities are reduced and fry will move through a lighted area slower and thus they may be more likely to be influenced by light. In fact, at streamflow levels over 1,500 cubic feet per second (cfs), approximately 10% of the sockeye salmon fry will migrate during the day (Seiler and Kishimoto 1997). Streamflow levels at Renton for the March 31 and April 5 experiments were 800 and 670 cfs, respectively (USGS, unpublished data). Base streamflow levels are 375 cfs during the fry outmigration period. Thus, we would predict that at lower streamflows more fry would be delayed in our experimental units.

Turbidity will have a large effect on light intensity levels in the water column. Light will not penetrate as well during turbid conditions. Turbidity is often related to streamflow, particularly after rain events. Fry may migrate faster during turbid conditions and visual predators such as trout will have reduced foraging success (Barrett et al. 1992; Vinyard and Yuan 1996).

PREDATION

The size of the experimental units (8 m shoreline length) appeared to work well for detecting differences in fry abundance, but it may have been too small for estimating predation rates. We were able to detect differences between lighted areas and control areas but we were often unable to detect differences between light intensity levels. Few or no predators were collected in some experimental units. Also, the diets of cottids can vary between individual fish. Even when fry are abundant, many cottids will not consume them. Each site will have a variety of other prey types such as aquatic insects or oligochaetes. Also, many of the male cottids may be guarding egg nests and probably will not be actively searching for prey. In most areas, a 20-30 m shoreline would probably be adequate to collect enough cottids to get an accurate estimate of predation. Additionally, our experiments only lasted for a few hours. Had we extended the experiments over the entire night we may have seen more predation and thus better able to detect differences between treatments. Similarly, for City of Renton light comparisons, large numbers of cottids may be needed to detect differences between light levels.

Based on earlier lab experiments, increased light levels have a profound effect on the behavior of sockeye salmon fry (Tabor et al. 1998a), however, the effect on predator behavior is not well understood. In the Cedar River, cottids appear to exhibit a functional response due to an increase in the abundance of fry but we did not observe any type of numerical response. However, our experiments were done over a short period of time and a numerical response may take several days or weeks. In Lake Iliamna, cottids exhibited a strong numerical response in relation to the abundance of sockeye salmon eggs but cottid movements to the spawning sites takes place over a period of three weeks (Foote and Brown 1998). Therefore, cottids may exhibit a numerical response to an increase in fry availability near permanent light structures. However, there are several alternative prey types in the Cedar River and cottids may not show a strong numerical response such as in Lake Iliamna, which is an oligotrophic system and alternative prey may be limited. Additionally, cottids may naturally avoid lighted areas because they may become more vulnerable to predators. Movement into lighted areas may be a tradeoff for cottids and thus they must balance increased predation risk with increased prey availability.

Cottids are generally considered nocturnal fish; they appear to hide during the day and move out from cover at night to feed. The distance they move away from their daytime cover and the relationship to light levels is not known. If they only move a short distance on a given night then the only cottids that can take advantage of the increase in fry abundance are those that have nearby cover. The number of cottids > 49 mm TL increases as the substrate size is increased (Tabor et al. 1998b). Therefore, in sand or gravel areas where fry may be abundant, cottids may have low abundance.

CHINOOK SALMON FRY

Like sockeye salmon, many chinook salmon out-migrate to the lake as fry (D. Seiler, WDFW, unpublished data), however, while sockeye salmon fry typically use the river channel only as a migratory corridor, chinook salmon fry and juveniles may inhabit the shoreline habitat for an extended period of time (R. Peters, U.S. Fish and Wildlife Service, unpublished data). Chinook salmon may avoid lighted areas while they are inhabiting the shoreline but may become more vulnerable to predation as they move downstream through lighted areas. Nevertheless, given the low number of chinook salmon fry observed, it is problematic to make any conclusions concerning the effect of lights on chinook salmon. Further work directed at chinook salmon is needed to reach any conclusions.

LIGHT INTENSITY READINGS

The location with the most potential for predation appeared to be the area between the I-405

Bridge and the Renton Library. The highest light levels were recorded in this area. There was also good pool habitat where fry could be consumed by large trout as well as cottids. Additionally, the mid-channel substrate is composed of cobble and gravel which was inhabited by cottids > 49 mm TL. Downstream of the Renton Library between Rkm 2.5 and 0.9 there was little pool habitat and the mid-channel substrate was predominantly gravel. Cottids may be abundant but few are > 49 mm TL.

In the lower Cedar River, artificial lighting appears to come from two major sources; direct lighting and reflected lighting off of the clouds. Direct lighting is intense lighting that occurs in a relatively small area and occurs every night and usually all night. Whereas, reflected light is not very intense but spread out over a much larger area and varies greatly with the weather. Direct lighting probably have strong localized effects on sockeye salmon fry and reflected lighting probably has weak effects over a large area. Which has more overall effect of sockeye salmon fry is difficult to assess. However, reducing direct lighting is much easier to address than reducing reflected light. Direct lighting can be turned off, redirected, or perhaps shielded (such as by trees). Reducing reflected light would be a much larger and far more difficult management objective.

ACKNOWLEDGMENTS

This study was funded in part by the U.S. Army Corps of Engineers (MIPR W68MD983512421) and the City of Renton. The project was administered by Merri Martz, USACOE. and Gary Schimek, City of Renton. We thank USFWS employees: H. Gearns, M. Mizell, R. Peters, D. Low, F. Mejia, and B. Missildine for their assistance with the field work. D. Seiler, WDFW, provided information on sockeye fry abundance and migration timing. R. Little, Seattle Water Department, provided information on streamflow conditions.

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Saving Salmon On The Cedar River

Signals Maintenance Shapes Salmon Solution

Washington State Department of Transportation

Northwest Region, March 23, 2001 BULLETIN No. 01-12

They hung on the light fixtures above the Cedar River Trail southwest of downtown Renton like black rubber lampshades. Users of the trail, which crosses above the river and under I-405, may wonder about the purpose of the pieces of rubber matting. The simple answer is that they are what they appear to be - black rubber lampshades. The more complex answer is in the river below. What does this have to do with WSDOT? Find out below.

The Ceder River is where the largest run of sockeye salmon in the lower 48 states begins. Each year between January and June, several million salmon fry migrate form their spawning grounds east of Maple Valley to Lake Washington. The 2000 run was one of the biggest in recent memory to Roger Tabor, a fishery biologist with the U.S. Fish and Wildlife Service. Tabor has been working with federal, state, local and tribal governments to determine the reason for the decline in the sockeye run. His research brought him to the Cedar River underneath I-405, where he noticed a problem. The light that WSDOT installed to help keep trail users safe posed a threat to the sockeye salmon fry.

"Light is basically a big stop sign,"Tabor said. *Sockeye like to migrate a night in the fast part of the river channel and move to low velocity waters along riverbanks and river bottoms during the day. This way they avoid becoming the pray of fully-grown trout and sculpin, which like to forage at night. But the lights above the trail make the sockeye fry think it was daylight.*

"We were doing a great job of lighting the stream and an inadequate job of lighting the walkway," seid Northwest Regin Signals Superintendent Kurt Schleichart.

The end result was that thousands of sockeye moved to shallow areas along the riverbank, making them easy prey for trout and scuplin looking for a late-night snack. Tabor estimated the lighting on the river resulted in several thousand salmon fry being eaten at this location in each spring migration period.

Word of the problem reached Gary Davis, a biologist at Northwest Region headquarters i Shoreline who has been working to coordinate WSDOT's salmon recovery efforts with other agencies in King, Pierce, and Snohomish counties. Davis said the agency wanted to help in whatever way it could.

Schleichert, Tabor, Davis and a representative from the city of Renton visited the site last June. Ti was immediately obvious that the lighting system wouldn't work as it was set up - too much light was shining on the river. One solution, a complete retrofit of the lighting system, wasn't feasible. Schleichert estimates the retrofit would have cost in excess of $100,00, mainly because it would have required drilling holes in the concrete pathway above the environmentally-sensitive river.

Another solution, at the extreme opposite end of the cost spectrum, beckoned to Schleichert as he examined the light fixtures above the pathway. Why not equip the fixtures with some kind of shield so the light would shine down on the path, but not on the river? Schleichert set South Signal Supervisor John Merryman to work on the task. Merryman enlisted the help of Rich Loucks, a Traffic Signal Technician 3 and Mark Wolff a Traffic Signal Technician 2, who fabricated shields out of rubber matting. The shield had to be custom made for each fixture, because the lights where mounted in different locations in reference to the walkway and the river. Loucks and Wolff installed six shields in late January and two more just this week for a total cost of less than $100!

After the first six shields were mounted, it was necessary to see if they were doing the job for which they were designed. In early February Tabor and Loucks measured light levels on the river in the area of the trail ligh fixtures. The results were dramatic. Light readings showed that levels were similar to other nearby areas of th Cedar River that have no direct lighting.

The next evaluation was to see if the reduction of light led to a reduction in salmon fry on the riverbank. Again, the results were remarkable. In fate February, Tabor and others counted salmon fry along the shoreline. In one location they counted only 23 fry where there had been more than 1000 in 1998. The 2001 and 1998 counts were conducted under similar conditions and on similar dates and time of the day. Tabor said the shields that WSDOT mounted on the light fixtures likely made the difference.

The Northwest Region is committed to being a responsible environmental partner. Our effort to reduce lighting along the Cedar River is a small, but important example of this commitment. Sockeye salmon is not an endangered or even threatened species, but as the challenges posed by the Endangered Species Act loom, solutions like the one used on the Cedar River will become more common and more necessary.

By - Greg Phipps

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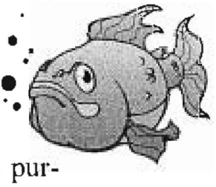
Northwest Region
Washington State Department of Transportation
March 23, 2001 BULLETIN No. 01-12

SIGNALS MAINTENANCE SHAPES SALMON SOLUTION



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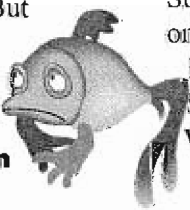

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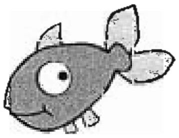
The end result was that thousands of sockeye moved to shallow areas along the riverbank, making them easy prey for trout and sculpin looking for a late-night snack. Tabor estimated the lighting on the river resulted in several thousand salmon fry being eaten at this location in each spring migration period.



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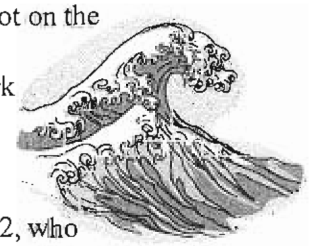

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(Continued on Page 2)

Washington State Department of Transportation

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"The fry moved through the bridge quickly and were not delayed by the lights," he said. "Fry counts along the shore are usually related to the light intensity level."

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—Greg Phipps

BUILDING TRUST 2001

On Monday, March 12, the Northwest Region hosted an all-day session with the staff from northwest regional offices of the Washington State Department of Ecology and the Washington State Department of Fish and Wildlife. Dubbed "Building Trust 2001", the meetings presented major 2001 construction projects with potential substantial erosion control and storm water issues. The strategic objective of this meeting was to jointly develop approaches to best address environmental issues that may emerge during the delivery of 2001 construction program. This gathering was in line with the region's business plan to deliver its products and services in such a way that it acts and is recognized as a responsible environmental partner.

WSDOT provided an overview of 32 projects and their unique challenges to the agencies. The meeting was also an opportunity for the department to listen to resource agencies' concerns about WSDOT projects and erosion control issues. Project offices and field staff heard firsthand management commitment to environmental compliance.

The session was a big hit with the two resource agencies. Reprinted below are excerpts from rave reviews they sent to Regional Administrator John Okamoto:

- John—The joint meeting between our staffs went very well I thought. Thank you for hosting it and all the work your crew put into the preparations. Our biologists were impressed with the discussion and really appreciated the heads up on each districts work plan. Please express my gratitude to Dave (Dye) and the rest of your staff for creating a very productive session. We are already looking forward to a follow up this fall.
  Bob Everitt, Regional Director, WSDFW
- Thanks to you and DOT for hosting the gathering, John. And thanks to Dave (Dye) and Lorena (Eng) for setting the stage for a very open, inviting and positive meeting. Our staff appreciated the chance to meet with so many of your

(Continued on Page 3)

North American Journal of Fisheries Management 24:128–145, 2004

The Effect of Light Intensity on Sockeye Salmon Fry Migratory Behavior and Predation by Cottids in the Cedar River, Washington

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Abstract.—We examined the relationship between light intensity, migratory behavior of sockeye salmon *Oncorhynchus nerka* fry, and predation by cottids *Cottus* spp. We tested the hypothesis that above-natural intensities of nighttime light would increase cottid predation of sockeye salmon fry. In circular tank experiments under controlled laboratory conditions, we tested the ability of cottids to prey on sockeye salmon fry under six different light intensities using minimal water circulation to separate the effect of the migratory behavior of fry from the ability of cottids to capture them. We found that cottids preyed most effectively in complete darkness, whereas the lowest predation occurred at the brightest light intensity. We next tested the predation ability of cottids at four light intensities in a pair of artificial streams to simulate more natural conditions. In experiments without cottids, the majority of fry passed quickly through the artificial streams under complete darkness, but as light intensity was increased, fewer fry emigrated and did so at a slower rate. With cottids present and increased light intensity, even fewer fry emigrated but they did so at a faster rate than did those in the stream without cottids. We determined that cottids probably consumed about 5% of the sockeye salmon fry under complete darkness and ate about 45% of the fry at the brightest light intensity tested. In experimental field trials, the shoreline abundance of fry and predation by cottids increased as light intensities increased. Using two small lights within an 8-m shoreline section on the Cedar River, Washington, we delayed as many as 550 sockeye salmon fry and observed predation of as many as 7.6 fry/cottid. At the end of the experiment, we turned the lights off and noted that the shoreline abundance of fry declined dramatically. At two locations on the Cedar River lit by city lights, the abundance of sockeye salmon fry and predation by cottids was substantially greater than at nearby sites with low light. Also, we demonstrated at one site that reducing light intensity substantially reduced predation on sockeye salmon fry. Overall, we conclude that increased light intensity appears to slow or stop out-migration of fry, making them more vulnerable to capture by predators such as cottids.

After emerging from their redds, most sockeye salmon *Oncorhynchus nerka* fry immediately emigrate downstream at night to a lake environment, where they reside for the next year. However, during this brief (usually one or two nights) out-migration period, predation by other fishes can be an important source of mortality (Foerster 1968; Beauchamp 1995). Fry presumably reduce their vulnerability to predators by emigrating at night and selecting areas of the river channel with the fastest current velocities (McDonald 1960). The downstream migration of sockeye salmon fry is closely related to light intensity (McDonald 1960). The nightly downstream migration is initiated after the light intensity is less than 0.1 lx. Therefore, increased light intensity from artificial lighting may alter the migration patterns of sockeye salmon fry and change their vulnerability to predation.

The few studies that have examined predation

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on juvenile salmonids under different light intensities have had variable results. Ginetz and Larkin (1976) found that predation of sockeye salmon fry by rainbow trout *O. mykiss* in artificial streams increased as light intensity was increased under low light conditions (<0.1 lx); at high light intensities (0.5–3.0 lx), however, predation decreased as the light intensity was increased. Predation of chum salmon *O. keta* fry by staghorn sculpin *Leptocottus armatus* increased with increased light intensity at night but decreased with increased light intensity during the day (Mace 1983). Patten (1971) found that predation on coho salmon *O. kisutch* fry was greater on moonlit nights than on moonless nights; their results may have been biased, however, by differences in water temperature between treatments. In contrast, Petersen and Gadomski (1994) found that predation on chinook salmon *O. tshawytscha* smolts by northern pikeminnow *Ptychocheilus oregonensis* increased as light intensity decreased from 215 to 0.01 lx.

With increased urbanization and development of the Pacific Northwest, the amount of artificial lighting has increased on many streams. The effects of artificial lighting on salmonid populations is poorly understood. In Washington, the Lake Washington sockeye salmon are found within a large urban area. The major spawning tributary to Lake Washington is the Cedar River, some sections of which are exposed to artificial lighting and also present migration routes for sockeye salmon fry. In recent years, sockeye salmon production has declined in the Cedar River; increased predation on migrating sockeye salmon fry as a result of increased nighttime lighting may be one factor in the decline of the Cedar River sockeye salmon population.

The objective of this study was to determine the effect of light intensity on the migratory behavior of sockeye salmon fry and on the predation of fry by cottids *Cottus* spp. in the Cedar River.

Study Site

The Cedar River, the main tributary for the Lake Washington basin (Figure 1), is the major spawning area for sockeye salmon. The lower 35.1 km are accessible to anadromous salmonids. Landsburg Dam, a water-diversion structure, prevents fish from migrating farther upstream. The lower 3 km of the Cedar River flows through a large, heavily urbanized floodplain. This river section is within the City of Renton, Washington, and has numerous sources of artificial light from urban and residential development. Upstream of river kilometer (rkm) 3, the river valley has some residential development but artificial light is substantially less than in the Renton area. Historically, the Cedar River did not flow into Lake Washington but flowed south as part of the Duwamish River. In 1917, however, the Cedar River was diverted into Lake Washington and a ship canal was constructed to connect the lake to Puget Sound. The historical abundance of sockeye salmon in the Cedar River is poorly understood, although the current sockeye salmon population in the Cedar River appears to be derived principally from introductions between 1937 and 1945 of fry from Baker Lake, Washington (Hendry et al. 1996).

Lake Washington, a large monomictic lake with a total surface area of 9,495 ha and a mean depth of 33 m, sits within a large urban area that includes both Seattle and Renton. More than 78% of the shoreline is given over to residential land use. The lake supports a large run of sockeye salmon. Some years have seen adult returns in excess of 350,000 fish, with most of the adult fish spawning in the Cedar River.

After emerging from the gravel, sockeye salmon fry immediately migrate downstream to Lake Washington, where they reside for the next year. They migrate primarily at night but some daytime migration can occur, particularly during high-flow events with increased turbidity (Seiler and Kishimoto 1997; Hensleigh and Hendry 1998). Fry generally take one or two nights to reach the lake (Seiler and Kishimoto 1997). In the Cedar River, sockeye salmon fry are vulnerable to predation from rainbow trout (both resident and steelhead; Beauchamp 1995), cutthroat trout *O. clarki*, juvenile coho salmon, and four cottid species: coastrange sculpin *Cottus aleuticus*, prickly sculpin *C. asper*, riffle sculpin *C. gulosus*, and torrent sculpin *C. rhotheus* (Tabor et al. 1998).

Prickly sculpin is the largest cottid in Lake Washington and the Cedar River, reaching more than 225 mm total length (TL). Prickly sculpin that prey on sockeye salmon fry in the Cedar River are generally 50–150 mm TL (R. Tabor, unpublished data). Larger prickly sculpin mostly consume larger prey such as lamprey (adults and ammocoetes) *Lampetra* spp., adult longfin smelt *Spirinchus thaleichthys*, other cottids, and signal crayfish *Pacifastacus leniusculus*. Found in quiet areas of the lower 5 km of the Cedar River, prickly sculpin are also the dominant cottid in the benthic areas of Lake Washington (Eggers et al. 1978).

Torrent sculpin and riffle sculpin are widespread

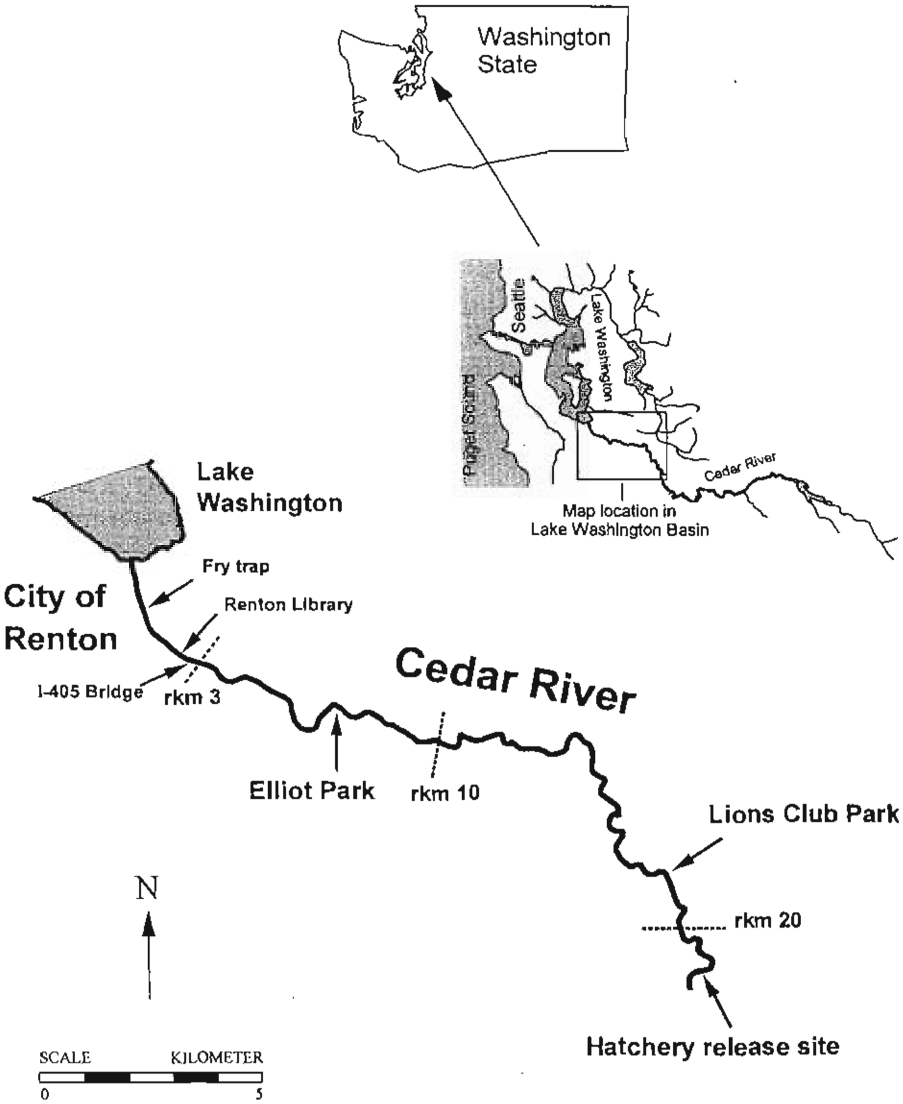


FIGURE 1.—Map of the lower Cedar River, showing the two experimental field trial sites (Lions Club Park and Elliot Park) and the two Renton city light sites (Renton Library and I-405 bridge). The locations of the release site for hatchery sockeye salmon fry and the fry enumeration trap are also shown. rkm = river kilometer.

in the Cedar River, inhabiting the lower 55 km of the river and several small tributaries. Coastrange sculpin occur primarily in the lower 21 km of the river. Torrent sculpin as large as 150 mm TL have been found in the Cedar River. Because of their high abundance and relatively high predation rates, torrent sculpin appear to be the most important cottid predator of sockeye salmon fry in the Cedar River (Tabor, unpublished data). Sizes of riffle sculpin and coastrange sculpin in the Cedar River are generally similar, both reaching approximately 120 mm TL. Riffle sculpin are typically found in low-velocity areas along the shore of the Cedar River. Coastrange sculpin are usually found in riffles; however, large individuals are often found in pools.

Methods

To determine the effect of light intensity on the migratory behavior of sockeye salmon fry and on the predation of fry by cottids, we conducted several laboratory experiments and field studies (Table 1). We also measured light intensity at sites along the Cedar River to document the amount of

TABLE 1.—List of various study components used to examine the relationship between light intensity and sockeye salmon fry migratory behavior and predation by cottids. All field studies were conducted on the Cedar River. The cottid species of the field studies are listed in order of abundance; river km is distance from the mouth of the river.

Study component	River km	Dates	Cottid species
Laboratory experiments			
Circular tank experiments		May 1997	Prickly and torrent sculpin
Artificial stream experiments		May, Jun 1997	Prickly sculpin
Field Studies			
Experimental field trials			
Lions Club Park	18.3	Mar, Apr 1999	Torrent and riffle sculpin
Elliot Park	7.4	Apr, May, Jun 1999	Torrent, coastrange, and riffle sculpin
Renton city lights			
Renton Library	2.4	Mar 1999, Feb 2001	Coastrange sculpin
I-405 bridge	2.7	Feb 1998, Feb 2001	Coastrange and torrent sculpin
Light intensity readings			
City of Renton	0.0–2.9	Mar, Oct 2000	
Non-lighted areas	0.5–13.2	Feb, Apr 2001	

artificial lighting present and to assess how much the moon and cloudy nights affect light intensity levels. We used cottids to test the effect of increased light intensity on predation of sockeye salmon fry because cottids readily adapt to laboratory conditions, are abundant, and are important predators of sockeye salmon fry in the Cedar River (Tabor et al. 1998). Prickly sculpin and torrent sculpin were used in the laboratory experiments; torrent sculpin, coastrange sculpin, and riffle sculpin were collected at the field study sites.

Laboratory Experiments

We took a dual experimental approach to determine whether cottids prey more effectively at the light intensities generated by standard artificial light sources. Because cottids and sockeye salmon fry may alter their behavior in relation to light intensity, the sensory abilities of one to detect the other may be differentially affected by light intensity. We first tested predation of cottids in the simplistic environment of circular hatchery tanks with minimal water flow, to allow us to separate the effect of the changes in fry migratory behavior that might occur under different light intensities from the ability of cottids to prey on them. To assess the effect of light intensity on sockeye salmon fry behavior, we performed a second experiment, using artificial streams under more natural conditions that allowed fry to migrate downstream. The sockeye fry released upstream in these trials could behave more naturally in this environment than in a hatchery tank in relation to the light intensities used in our treatments; that is, they could migrate quickly through the artificial stream or delay their passage by stationing in eddies or burying in the gravel substrate.

During May–June 1997, we conducted experiments at the Western Fisheries Research Center, U.S. Geological Survey, Seattle, Washington. Prickly sculpin (74–103 mm TL) and torrent sculpin (74–98 mm TL) collected from the Cedar River and Lake Washington by electrofishing were transported to the laboratory, where they were maintained in circular holding tanks in size-sorted (small: 70–79 mm TL; medium: 80–89 mm TL; and large sculpin: 90–99 mm TL) and species-specific groups. The sizes of cottids collected are representative of those that commonly consume sockeye salmon fry in the Cedar River (Tabor, unpublished data). 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. The mean fork length (FL) of the fry was 28.4 mm ($N = 90$; SE, 0.18; range, 26–34 mm FL). The fry were presumably both migration- and predator-experienced. After transport to the laboratory, the fry too were held in circular holding tanks. Fry were fed commercial fry food daily throughout the experimental period. Most fry were used in experiments within 5 d after they were collected; however, some fry used in the last experiments were held as long as 14 d. Sculpin were fed available salmonid fry before the experiment.

The light intensities used in the experiments represent the range of values observed during field measurements in the lower Cedar River. All light intensity measurements were made with an International Light, Inc., model IL1400A radiometer/

photometer. The light source consisted of one or two strings of small ornamental lights (small, clear, holiday tree lights) taped to the underside of the lids of the tanks and the artificial streams and 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.—The tank experiments were conducted in three 1.2-m-diameter circular tanks. Water depth was maintained at 30 cm and water temperature was approximately 12°C. We tested six light intensities (0.00, 0.03, 0.06, 0.11. 1.08, and 10.8 lx) during the predation experiments. For each trial, we randomly selected one of these treatment light intensities. We carefully adjusted the lights to maintain that intensity in each of the three replicate test tanks before each experimental trial. In each trial we used single-species groups of 20 sculpin (three large, nine medium, and eight small fish randomly sampled from the size-sorted holding tanks) and 100 fry. We performed six replicate trials for each light intensity with both prickly sculpin and torrent sculpin. The fry were given 15 min to adjust to the experimental setup before the sculpin were added. Two black Plexiglas shelves within each tank served as a refuge/hiding place for the sculpin during the experiments. After addition of the sculpin, each trial lasted 40 min. Trial starting times were staggered for the three test tanks to allow sufficient time for recovery of all fish with a small aquarium net and flashlight. Predation was determined as the number of sockeye salmon fry lost during a trial. 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.

Prickly and torrent sculpin were used on alternate days to allow adequate digestion time between trials. The stomach contents of three replicate groups of cottids from both the 0.00 and 10.8 lx light intensities (N = 60 for each light treatment and cottid species combination) were removed by gastric lavage to confirm consumption of fry, determine the percent of sculpin that consumed fry, and confirm the absence of previously consumed fry. Light et al. (1983) found gastric lavage was 100% effective for removing stomach contents of slimy sculpin *C. cognatus*.

Artificial stream experiments.—Sockeye salmon fry migration/behavior experiments were done in two identical artificial streams containing natural river gravel substrate. Each stream was 9 m long by 1.5 m wide and was contained within a fiberglass trough. We used only a 3-m section of each stream to allow enough space downstream to set up a fish trap for collecting the fry. Each experimental section consisted of a 2.5-m-long pool and a short riffle section. The riffles had a 2% gradient and 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 intensity was measured approximately 10 cm below the surface of the water in both streams. For the predator trials, 20 prickly sculpin (mean, 86.5 mm TL; range, 75–99 mm TL) were placed in each artificial stream, where they remained throughout the duration of the experiment. We performed trials once every 2–3 d to allow the sculpin enough time to digest fry from the previous trial.

At the start of each trial, 125 fry were transferred from the laboratory, where they had been held in low light intensity, and were released at the upstream end of each experimental section. Trials started immediately with the addition of fry, and the fry traps were checked with a flashlight at 20 min and after 2, 4, and 6 h. Any fry caught in the fry trap were removed with a small aquarium net and counted. After 6 h, all lights were turned off and the fry were given 12–16 h (overnight) to migrate through the streams to the trap. Again, any fry in the trap were removed and a final count was made. We did not try to collect any fry possibly remaining in the artificial streams because preliminary work had indicated the fry were extremely difficult to locate and capture. In nonpredator 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 that next trial. Consequently, the results are presented as a cumulative percentage of the total fry in each stream that 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 few fry migrated overnight in the predator trials when the streams were darkened, this appears to be a valid assumption.

The artificial stream trials were conducted in two parts. No predators were used in the first part, in which two replicates of each of three light intensities (0.00, 1.08, and 5.40 lx) were tested. In the second part, predators were present in one stream and absent in the other, and four light intensities were tested (0.00, 0.22, 1.08, and 5.4 lx). Two replicates of each level were tested except that time constraints allowed only one trial at 0.22 lx. On each trial date, the same randomly selected light intensity treatment was used in both the predator and nonpredator artificial stream.

Field Studies

Experimental field trials.—We performed experimental field trials at two sites on the Cedar River, the Lions Club Park at rkm 18.3 and the Elliot Park at rkm 7.4 (Figure 1). The Lions Park site, with a 112-m shoreline section, had two distinct habitat types: The upper 56 m had a riprap shoreline (steep sloping banks), whereas the lower 56 m had a gravel shoreline with gradually sloping banks. The Lions Club Park was the site of two experimental trials, both conducted on nights when hatchery sockeye salmon fry had been released upstream at rkm 21.7. On March 31, 1999, 135,000 fry were released at approximately 2015 hours and on April 5, 1999, 57,000 fry were released at approximately 2115 hours. Most of the fry appeared to reach the fry trap at rkm 1.2 between 2300 and 0000 hours on March 31 and between 0000 and 0100 hours on April 6 (D. Seiler, Washington Department of Fish and Wildlife, unpublished data).

The other site, at Elliot Park, consisted of a side channel immediately downstream from the outlet of a spawning channel. We sampled the side channel five times from April 7 to June 14, 1999, during the fry out-migration period. Fry observed at this site most likely originated from the spawning channel, because no hatchery fry were released during these dates. The Elliott Park site consisted of one 40-m-long sand/gravel shoreline section.

Shoreline sections at both sites were divided into 8-m-long units. Lights were added only to every other unit to ensure that light from one experimental unit did not affect the adjacent units. Treatments were randomly assigned within the alternate shoreline sections. Two lights were used for each experimental unit, each mounted at the top of 2-m-tall poles that were placed at the far ends of each unit; there, the lights were directed toward the middle of the unit. Each light was set up as an individual light system consisting of a 60-W light bulb, a deflector to focus the light, and a dimmer switch to control the light intensity. We used different combinations of five light intensities: (1) control (no lights), 0.01–0.11 lx; (2) dim, 0.16–0.27 lx; (3) low, 0.48–0.59 lx; (4) medium, 1.08–1.51 lx; and (5) bright, 10.80–15.10 lx. Light intensity was measured at the surface of the water, 2 m from shore. Generally, we took three measurements, one in the middle and one each from just inside the upstream and downstream edges. The middle of each experimental unit was the brightest, and the upstream and downstream edges were the dimmest; moreover, light intensity attenuated across the river channel. We turned on the lights shortly after dusk and adjusted their settings to get the appropriate light intensity.

Experiments lasted 2–3 h. At both sites, sockeye salmon fry abundance was estimated by counting fry along the shoreline. Fry were counted by an observer using a flashlight, who slowly walked along the shoreline in a systematic pattern to ensure that the area out to 2 m from shore was completely covered. To be consistent between treatments, we counted only fry within the beam of the flashlight. Preliminary observations indicated that fry were in shallow water and close to the surface of the water, tended to hold their position facing into the current, and did not move appreciably. Thus, fry could be easily counted and fish counts between different shoreline types (gravel shore and rip-rap) could be compared. In subsequent electrofishing after the experimental trials, we found no evidence that sockeye salmon fry were hidden within the riprap. We assumed that the counting had a minimal effect on fry abundance because it took only a short time, approximately 1 min per shoreline section. Fry were counted every 15 min at the Lions Club Park. At Elliot Park, we only did two counts, one shortly after the experiment was started and another at the end of the experiment. For some experimental trials, we recounted the number of fry present 20 min after the lights had been turned off.

After the lights had been turned off, we used backpack electrofishing equipment to collect cottids along the shoreline to determine the level of predation. We assumed there was little movement of sculpin between sections because of the relatively short duration of each experiment (approximately 2 h) and the 8-m gap between sections. We also considered it unlikely that a sculpin from one section could flee into another section because there was a gap between sections and because we sampled in an upstream direction, from the downstream end to the upstream end. Stunned fish were collected with the aid of dip nets and a spot light. After capture, cottids were identified as to species and measured for total length. Cottids of 50 mm TL or larger were anesthetized and their stomach contents were removed by gastric lavage. Because smaller cottids rarely consume sockeye salmon fry (Tabor, unpublished data), we did not check the contents of their stomachs. Ingested fry were counted and categorized as freshly ingested or well digested. Only counts of freshly ingested fry were used in the analyses. We assumed that freshly ingested fry were consumed during the experiment, whereas well-digested fry had been consumed the previous night or sometime before the experiment. Because we started the experiments shortly after sunset and because cottids are primarily nocturnal and sockeye salmon fry migrate primarily at night, we deem this a valid assumption.

We tested differences in fry abundance with a two-way ANOVA without replication. Data were log-transformed because the data were multiplicative rather than additive (Zar 1984). The two factors paired for testing were light intensity and habitat type for the Lions Club Park data and light intensity and date for the Elliot Park data. Several cottids did not consume any fry, meaning that the predation data were not normally distributed; therefore, we used nonparametric procedures to compare predation, a Mann–Whitney *U*-test (two samples) or a Kruskal–Wallis test (more than two samples).

TABLE 2.—River conditions and the number of emigrating sockeye salmon fry on three dates used to examine the difference in predation of sockeye salmon fry by cottids before and after lights at the I-405 bridge were shielded. Streamflow and water temperature data were taken by U.S. Geological Survey at rkm 2.2. Fry abundance estimates were obtained from fry trap data (D. Seiler, Washington Department of Fish and Wildlife, unpublished data). The fry trap was located at rkm 1.6 (from the mouth of the river). Catch efficiency of the fry trap on the dates listed ranged from 9.6% to 10.2%.

	Fry abundance			
Date	Sample night	Prior night	Streamflow (m^3/s)	Temperature (°C)
Feb 23, 1998	296,800	318,000	16.7	7.3
Feb 25, 1998	537,900	434,000	18.6	7.2
Feb 21, 2001	684,000	557,000	10.0	7.7

Renton city lights.—Two sites were selected in Renton, the Renton Library and the I-405 bridge (Figure 1), as having an area of high light intensity and a nearby area with similar habitat and substantially lower light intensity. Abundance of sockeye salmon fry and predation of fry by cottids were monitored on nights when hatchery sockeye salmon fry were released so we could ensure that a large number of fry were available. The Renton Library sits 5 m above the Cedar River, spanning the entire width of the river and covering a 28-m-long section of the river. We compared the findings for a 22-m-long river section under the library, where no artificial lights were present, with those for a 22-m-long river section 3 m downstream of the library and characterized by several artificial lights spanning the width of the river. The library site was sampled once in 1999 and once in 2001. The I-405 bridge had several lights under the bridge to illuminate a walkway that spans the river. The control site for this location was 180 m upstream from the bridge, where no direct lighting was present. Both sites were 20 m long. Sampling was conducted once in 1998 and again in 2001. Sampling in 2001 was conducted after artificial lights had been shielded and light intensities along the river had been substantially reduced from 9.7–21.5 lx in 1998 to 0.14–0.32 lx in 2001. In the 2001 sampling, streamflow was lower, water temperature was slightly higher, and fry abundance was greater than during the 1998 sample (Table 2). Therefore, predation in 2001 was expected to be as high or higher than during sample dates in 1998. Sockeye salmon fry abundance at all sites was estimated by counting fry along the shoreline, similar to the experimental field trials. Light intensity was measured at the surface of the water in the middle of the area sampled.

At both sites, cottids were collected with backpack electrofishing equipment and analyzed for stomach content to compare the extents of predation of fry. At Renton Library, cottids were sampled along the shoreline and were collected visually with the aid of dip nets and a spot light. At the I-405 bridge site, cottids were collected in the mid-channel area because few cottids were present along the shore of the control site. Stunned cottids in the mid-channel area were collected passively with the aid of block nets. After capture, cottids were identified to species and TL was measured. Afterwards, their stomach contents were removed by gastric lavage and consumed sockeye salmon fry were counted. We assumed that cottids had consumed fry in the same general area where we captured them. We included counts of all sockeye salmon fry ingested because the artificial lighting was consistent from night to night. A Mann–Whitney *U*-test was used to compare differences in predation between the lighted site and the control site.

Light intensity readings.—In 2000 we assessed the artificial lighting along the lower 3 km of the Cedar River, taking light readings every 50 m over rkm 0.9–2.9. Below rkm 0.9, access to the river was limited in many areas, so additional readings were only made at rkm 0.0, 0.2, 0.3, and 0.7. All

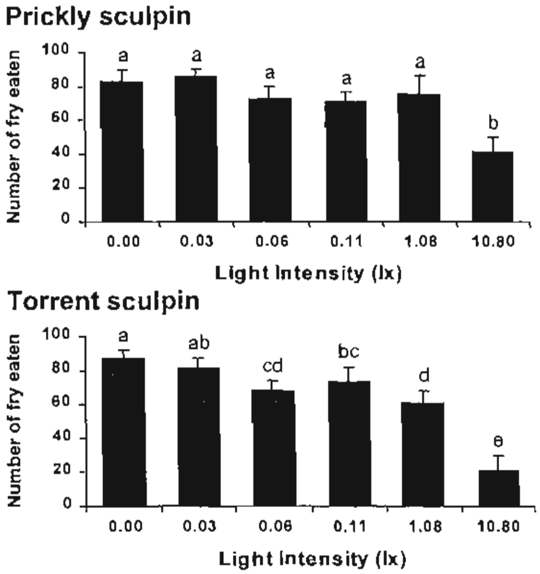


FIGURE 2.—Number of sockeye salmon fry eaten (±SD) by prickly sculpin and torrent sculpin in 40-min trials in circular tanks at different light intensities. Each bar is the mean of six trials. Groups of bars with different letters are significantly different (ANOVA and Tukey's HSD; $P < 0.05$).

readings were taken close to the riverbank, approximately 1–5 m from shore, and at the surface of the water. At major light sources, we took an additional reading to determine the maximum light intensity. Besides identifying sources of direct lighting, we also measured light intensity in other natural lighting conditions—(1) overcast skies; (2) clear skies, no moon; and (3) clear skies, full moon—at five locations without artificial lighting: rkm 0.5, 3.1, 6.9, 9.8, and 13.2.

Results

Laboratory Experiments

Prickly sculpin and torrent sculpin displayed similar amounts of predation with respect to increasing light intensity in tank experiments. Both species captured more fry under low light conditions than under the highest light intensity (Figure 2). Prickly sculpin captured a mean of 82.3 fry (SD = 7.4) at 0.00 lx compared with a mean of 41.5 fry (SD = 8.7) at 10.80 lx. Torrent sculpin captured a mean of 86.8 fry (SD = 5.3) at 0.00 lx and a mean of 21.3 fry (SD = 8.3) at 10.80 lx. A separate one-way ANOVA was performed on untransformed data of number of fry eaten for the two sculpin species. The ANOVA tests indicated significant differences among the six light intensities tested for both prickly sculpin ($P < 0.001$) and torrent sculpin ($P < 0.001$). Results from a post hoc Tukey's HSD test for prickly sculpin showed significantly less fry consumption at the highest light intensity but no difference among the other five light levels (Figure 2). Torrent sculpin indicated more differences among the six light intensities although, as with prickly sculpin, predation at the highest light intensity differed from that at the other five. The other five levels showed significant differences between treatments ($P < 0.05$), but there was no consistent trend from the lowest intensity to the highest one. In general, however, the number of fry eaten by torrent sculpin decreased as the light intensity increased.

Gastric lavage of three replicate trials of 20 sculpins each (total, 60 sculpin per species) from the trials at 0.00 and 10.80 lx 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 0.00 lx, whereas only 87% consumed fry at 10.80 lx. Thirty-eight percent of the prickly sculpin had consumed more than four fry at 0.00 lx, but only 5% had consumed more than four fry at 10.80 lx. The maximum number consumed by a prickly sculpin was nine fry (0.00 lx). Ninety-two percent of the torrent sculpin had consumed at least one fry at 0.00 lx, but only 68% had consumed fry at 10.80 lx. Fifty-two percent of the torrent sculpin had consumed more than four fry at 0.00 lx, whereas only 7% had consumed more than four fry at 10.80 lx. The maximum number of fry consumed by a torrent sculpin was 12 fry (0.00 lx).

We also verified that 2 d was sufficient time for digestion of previously consumed fry (and therefore, resumption of predatory motivation) in these experiments because only freshly consumed fry were recovered in the gastric lavage contents.

Artificial Stream Experiments

The first set of experimental trials, conducted with no predators present, indicated that sockeye salmon fry migrated through the stream at a faster rate under complete darkness (0.00 lx) than in the other two light intensities (1.08 and 5.4 lx). Under complete darkness, 74% (SD = 4.5%) of the fry migrated downstream within the first 20 min of the trials, and an additional 25% migrated downstream over the course of the next 24 h. Results were similar for the two treatments with light present but differed from those with light absent. In the 1.08 and 5.40 lx trials, 32% (SD = 8.6%) and 34%

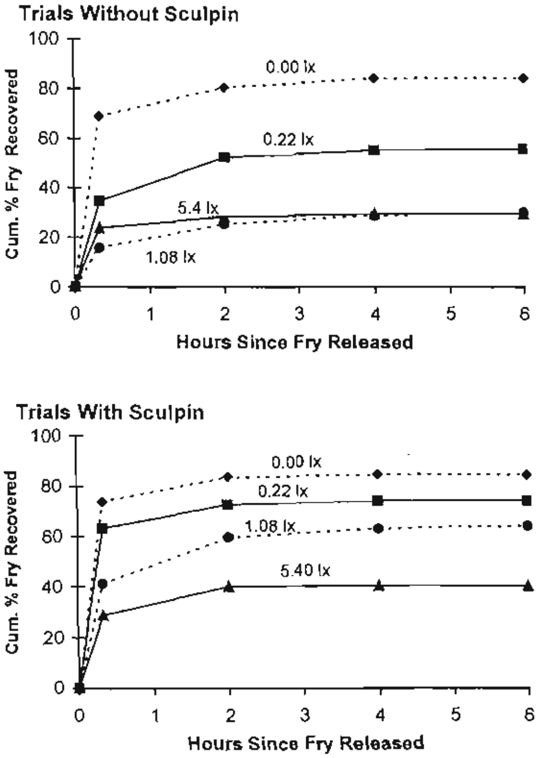


FIGURE 3.—Cumulative percent of total sockeye salmon fry recovered after release in artificial streams under four different light intensities. Each line is the mean of two trials, except that only one trial was conducted for the 0.22-lx experiment. The top and bottom panels show the results for trials when fry emigrated in the absence or in the presence of prickly sculpin, respectively.

(SD = 7.8%), respectively, of the fry migrated downstream within the first 20 min, and an additional 52% and 56%, respectively, migrated downstream within the next 24 h.

The second set of experimental trials was conducted with sculpin present in one stream and not in the other. These predation plus out-migration trials showed several strong patterns, even with only two trials completed at each of four light levels (Figure 3). First, as in the earlier trials, fry readily emigrated through the artificial streams under complete darkness but increasingly delayed passage as the light increased. Second, fry emigrated faster in all nondark trials when sculpin were present. Third, and most crucial, a greater proportion of fry were never recovered in the stream trials with sculpin present and the proportion missing was related directly to the light intensity (Table 3). Even though fry migrated more quickly with sculpin present than when the predators were absent, the fry were apparently more vulnerable to predation with increasing light intensity. At the most intense light tested (5.4 lx), subtracting the average number of fry unaccounted for in all trials with no sculpin present (10%) indicates that about 45% of the fry in the trial were probably consumed by sculpin. At 0.22 lx, about 28% of the fry became prey, and only about 5% were likely prey to the sculpin in the dark trials. Finally, our results consistently showed that fry not recovered in the first 2 h of a trial including sculpin were never recovered.

TABLE 3.—Percentage of sockeye salmon fry not recovered from outmigration trials in the artificial streams in the presence or absence of prickly sculpin under different light intensities. Estimates of the percent eaten were 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.

	Percent fry not recovered (SD)			
Light level (lx)	Sculpin abseut	Sculpin present	Estimated percent eaten	Number of trials
0.00	8.1 (2.2)	15.2 (2.3)	5.2	2
0.22	13.4	38.4	28.4	1
1.08	10.0 (1.7)	34.0 (6.2)	24.0	2
5.40	8.5 (1.5)	55.2 (13.6)	45.2	2

Field Studies

Experimental field trials.—At Lions Club Park on March 31 and April 5, 1999, few sockeye salmon fry were observed in all units for the first 45 min to 1 h. Within the next 20 min, however, the number of fry increased dramatically. For example, in the brightest light experimental unit, the number of fry changed from 27 at 2025 hours to 577 at 2045 hours. This increase in the number of fry most probably resulted from the large number of hatchery fish released earlier that evening. Experimental units with greater light intensities had significantly more fry in both experimental trials (ANOVA; March 31, $P = 0.02$; April 5, $P = 0.005$; Figure 4). Moreover, within each light intensity trial, more fry were found in the gravel shore than on the riprap shore (ANOVA; March 31, $P = 0.04$; April 5, $P = 0.03$; Figure 4). On average, gravel shores had 5 times as many fry as riprap shores for a given light intensity.

Overall, fry abundance results at the Elliot Park side channel followed patterns similar to those at Lions Club Park. Fry counts were conducted on five dates; on May 3, 1999, however, the light system for the medium-light experimental unit

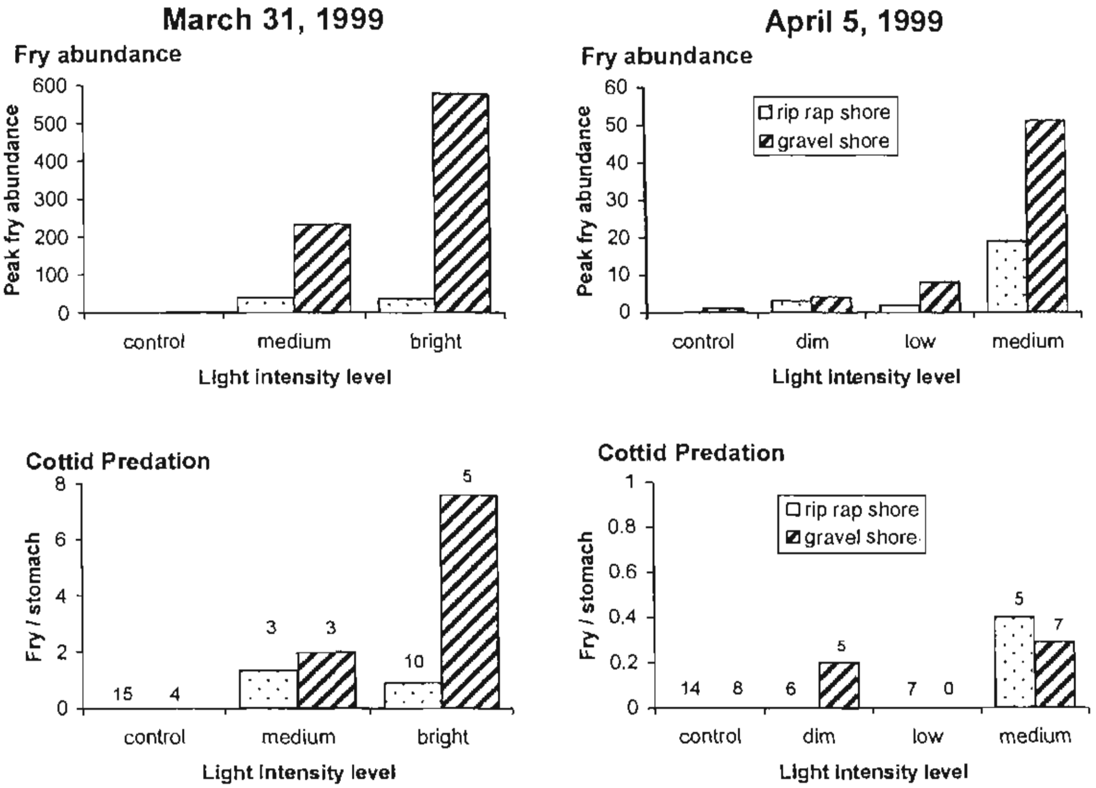


FIGURE 4.—Sockeye salmon fry abundance and cottid predation of fry at various light intensities and two habitat types from two experimental trials at Lions Club Park (rkm 18.3) on the Cedar River in 1999. Numbers above the bars indicate the number of cottid stomachs examined. Only freshly ingested sockeye salmon fry were counted as indicators of recent ingestion.

malfunctioned, and we were unable to get a fry count for that part of the experiment (Figure 5). The abundance of fry in the side channel varied greatly on the five dates sampled and most probably consisted of migrants from the spawning channel. Peak out-migration appeared to occur around May 3. An ANOVA revealed a significant difference ($P < 0.001$) in fry abundance between light intensity values and between sampling dates ($P < 0.001$). The most fry were always in the medium-light unit, the dim-light unit always had the second most numerous fry, and the control unit always had the least (Figure 5).

In two experimental trials, we also examined the abundance of fry shortly after the lights were turned off. In all the lighted experimental units, the number of fry decreased dramatically after the lights were turned off (Figure 6). In control units (no light added), the number of fry decreased slightly or actually increased. The lighted shoreline sections averaged a 93% reduction in fry abundance at Lions Club Park and a 88% reduction at Elliot Park.

In general, predation of fry by cottids showed the same trend as fry abundance. The most predation took place in experimental units with increased light. This trend was particularly noticeable during the March 31, 1999, trial at the Lions Club Park. Whereas no predation was detected in the control units, large numbers of fry were found in the stomach samples of cottids collected from the bright-light experimental unit (Figure 4). Three torrent sculpin collected from this unit had 10 or more fry in their stomachs. The maximum number of sockeye salmon fry consumed by an individual fish was 13 (92 mm TL, torrent sculpin). Differences in predation were marginally significant (Kruskal–Wallis test = 5.7, $P = 0.058$) between experimental units but were not significant between medium and bright experimental units (Mann–Whitney U-test = 3.5, $P = 0.23$). Predation in both of the lighted riprap experimental units

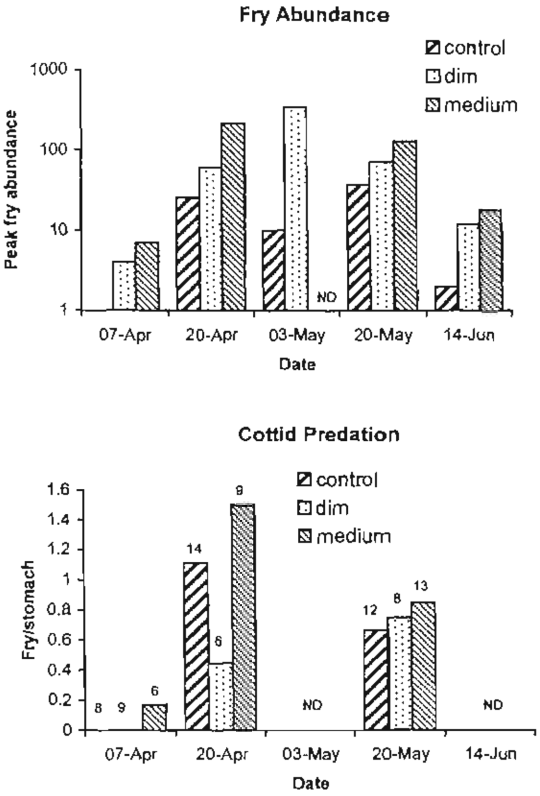


FIGURE 5.—Abundance of sockeye salmon fry (log scale) and extent of cottid predation of fry at three light intensity values on five nights in 1999 at the Elliot Park side channel (just below a spawning channel). Numbers above the bars indicate the number of cottid stomachs examined. Only freshly ingested sockeye salmon fry were counted as indicators of recent ingestion. ND = no data.

was less than in units with gravel shores; these differences were significant between the two bright experimental units (Mann–Whitney *U*-test = 8.0, $P = 0.03$) but not in the medium-light experimental unit (Mann–Whitney *U*-test = 3.5, $P = 0.66$).

Predation of fry on April 5, 1999, was low for all experimental units. Only 3 of the 42 cottids analyzed had consumed sockeye salmon fry. Although we detected no differences between treatments, four of the five fry consumed were from the medium-light experimental units and no predation was observed in the control units (Figure 4).

Cottids were collected on three occasions at the Elliot Park side channel. In each trial, the most predation was observed in the medium-light unit (Figure 5); however, no significant differences between the light intensity units were detected.

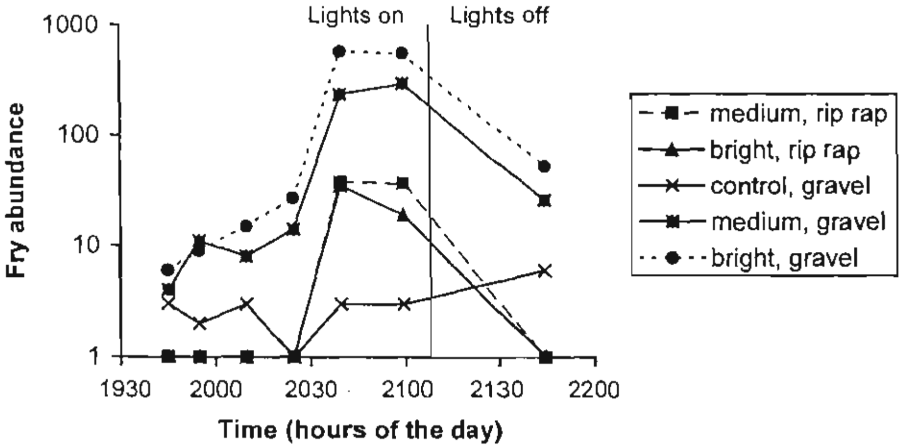
At Lions Club Park, torrent sculpin made up 92% of the cottids captured, riffle sculpin 8%. At the Elliot Park side channel, 50% of the cottids were torrent sculpin, 26% were coastrange sculpin, and 24% were riffle sculpin. Predation was observed in all cottid species present at both sites.

Renton city lights.—At both locations examined, the abundance of sockeye salmon fry along the shoreline was substantially greater at sites with high light intensity than at a nearby site with low light (Figures 7 and 8). Additionally, little predation was observed in control areas with low light intensity, whereas relatively high predation was observed in lighted areas. At the Renton Library, predation on both sample dates was significantly higher in the lighted area than in the control area (Mann–Whitney *U*-tests: March 18, 1999, $U = 63$, $P = 0.03$; February 21, 2001, $U = 247$, $P = 0.002$). Combined, 53% of the cottids in the lighted area had consumed sockeye salmon fry, whereas only 3% had in the control site. All of the cottids collected at the library location were coastrange sculpin.

At the lighted I-405 site on February 25, 1998, 53% of the cottids had consumed fry (0.9 fry/stomach), but no predation had occurred at the control site. Predation was significantly greater in the lighted area (Mann–Whitney *U*-test = 58.5; $P = 0.002$) than in the control area. Preliminary sampling was also done at the I-405 bridge on February 23, 1998 (the control site was not sampled). From 15 cottids collected, a total of 18 sockeye salmon fry was found in the stomach samples (1.2 fry/stomach). Shielding lights under the I-405 bridge greatly reduced light intensities in the river, consequently greatly decreasing the shoreline abundance of fry and the predation of fry. In 2001, in contrast to the sampling in 1998, the number of fry at the bridge was similar to the number at the control site (Figure 8). We sampled 22 cottids from the I-405 bridge site and 14 cottids from the control site and observed no predation at either site. Predation of fry was significantly less at the I-405 bridge site when the lights shielded than on two dates in 1998 when the lights were shining directly on the river (Mann–Whitney *U*-test = 319; $P < 0.001$). Of all the cottids collected at the bridge and control site, 96% were coastrange sculpin and 4% were torrent sculpin; both species were observed to have ingested sockeye salmon fry.

Light intensity readings.—Surveys of the lower 3 km of the Cedar River indicated that most of

Lions Club Park, March 31, 1999



Elliot Park side channel, April 21, 1999

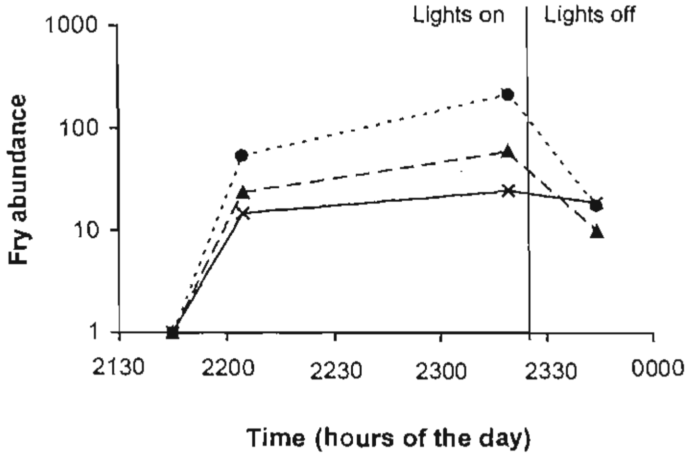


FIGURE 6.—Abundance of sockeye salmon fry (log scale) at three light intensity values in two experimental trials in the Cedar River, 1999, in which artificial lights that were on at dusk were later turned off. Vertical lines indicate when the lights were turned off. The March 31 trial was done at two habitat types, riprap and gravel shore. No fry were seen in the control riprap unit, so that site is not plotted on the graph.

this area has light intensity values (>0.2 lx) exceeding natural amounts (0.0 lx). Within the lower Cedar River, nine locations had light intensity greater than 1.1 lx. At six of these sites, the light was from street lights at bridges; at the other three, the light was associated with a building adjacent to the river. The highest light readings recorded were at the I-405 bridge (21.5 lx) and the Renton Library site (20.4 lx). Between rkm 0.9 and 2.9, the median light intensity level was 0.37 lx on a clear, moonless night but 0.94 lx on a cloudy night.

Light readings of areas with no direct lighting in the lower 13 km of the Cedar River indicated that light reflected off clouds was greatest near the mouth of the river and gradually decreased at upstream locations (Figure 9). Light intensities on cloudy nights in the lower 9 km of the river exceeded those on a clear night with a full moon. As expected, light intensity readings during clear skies were similar between locations. Observations from a plane at night suggest that most of the reflected light comes from the City of Renton

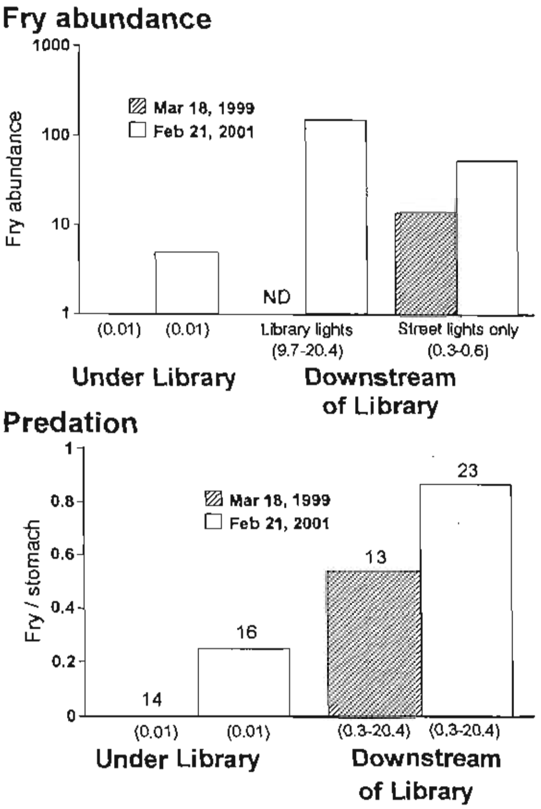


FIGURE 7.—Abundance of sockeye salmon fry (log scale) and extent of predation of fry by cottids at the Renton Library, City of Renton, Washington. The library lights were on for approximately 3 h after sunset and then turned off, whereas the street lights remained on all night. The abnndance of fry was the number along a 22-m shoreline section at each site. Light intensities (in lux) are indicated in parentheses. The number of cottids examined for fry consumption is given above each bar. ND = no data.

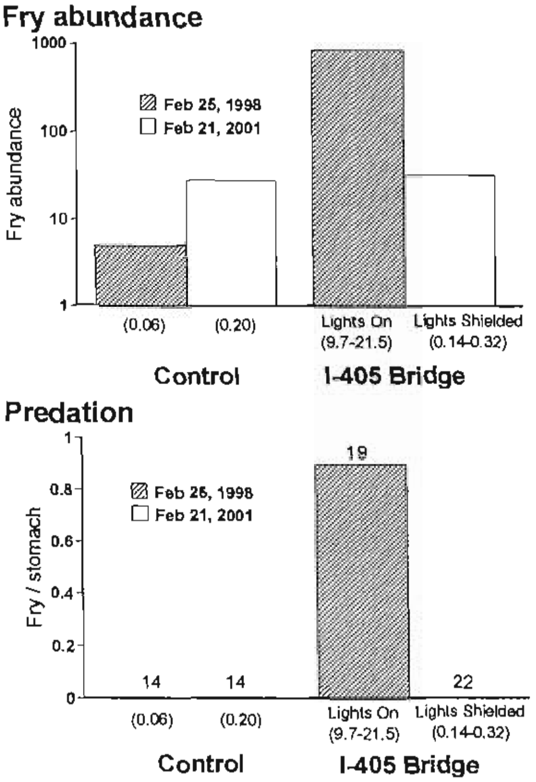


FIGURE 8.—Abundance of sockeye salmon fry (log scale) and predation of fry by cottids at two Cedar River sites with various light intensity values near the I-405 bridge, City of Renton, Washington. The abundance of fry was the number counted along a 20-m shoreline section at each site. Light intensities (in lux) are indicated in parentheses. In 1998, the lights under the I-405 bridge shone directly on the river; in 2001, the lights were shielded so that they shone primarily on a walkway and not on the river. The control site was located 180 m upstream of the bridge. The number of cottids examined for fry consumption is given above each bar.

and from a large industrial area just south of Renton. Upstream of the City of Renton, no significant lighting sources were apparent that would increase the amount of reflected light along the river during cloudy nights.

Discussion

Fry Behavior

Increasing light intensity appeared to affect greatly the behavior of sockeye salmon fry. Sockeye salmon fry usually emigrate at night, when light levels are less than 0.1 lx, and select areas of the river channel that have the fastest current velocities (McDonald 1960). Our experimental field trials demonstrated that if fry encounter lighted areas, many will hold their position in low-velocity water and delay their migration. McDonald (1960) also observed that sockeye salmon fry stopped swimming downstream when they encountered a light. Shoreline observations in the Cedar River indicated that fry were in shallow water close to the surface of the water and tended to hold their position facing into the current without moving appreciably. Our behavioral observations at lighted areas were similar to daytime observations of Hartman et al. (1962), who found that sockeye salmon fry accumulate and hold along the stream edges and invariably remain in the top 0.15 m of the water. Hensleigh and Hendry (1998) experimentally found that most fry moved down-

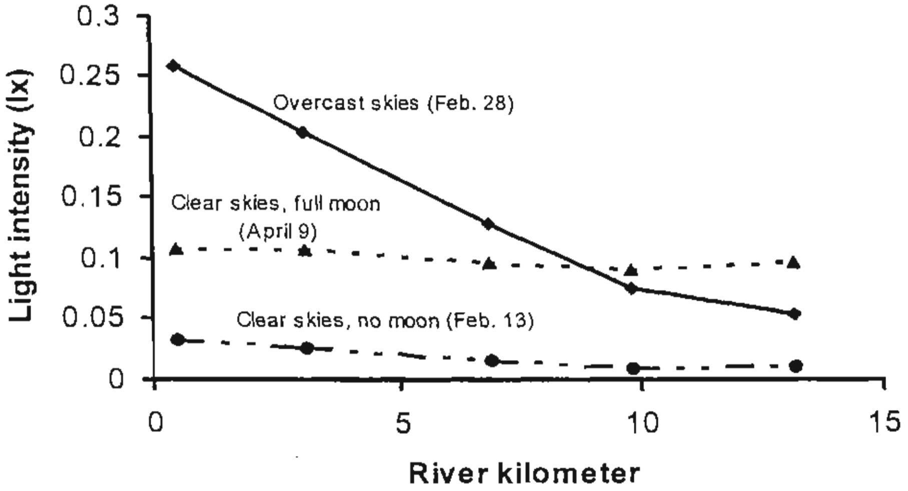


FIGURE 9.—Nighttime light intensities at five locations on the lower Cedar River as determined in 2001 under three different scenarios. Light readings were taken close to the surface of the water at locations with no direct lighting. The dates on which the light readings were taken are indicated in parentheses.

stream in the dark but tended to hold their positions or move slightly upstream in the light.

As shown by counts of fry along the shoreline of the Cedar River, the abundance of sockeye salmon fry that were delayed appeared to be positively related to the light intensity. Even small increases in light intensity seemed to affect fry behavior. At Elliot Park, for example, we consistently observed differences in fry abundance between the control (0.11 lx) and the dim-light experimental unit (0.22 lx). In the Cedar River, other variables such as total number of nightly migrants, water velocities, shoreline type, substrate type, streamflow, and turbidity will probably also influence the number of fry delayed. If these other variables could be held constant the number of fry delayed will probably be closely related to light intensity values.

We were surprised by the large number (>550 fry) of sockeye salmon fry present within the bright-light experimental unit (sand and gravel shoreline) during the March 31, 1999, experiment. Approximately 120,000 fry had been released on that date. Assuming a similar per kilometer survival rate as those in hatchery releases from Landsburg Dam (Seiler and Kishimoto 1997) and if the number of wild fry was minimal, we estimate that 110,000 hatchery fry moved past our experimental site. Therefore, we were able to delay 0.5% of the release group within an 8-m-long shoreline section with two small lights. Near the shoreline, the light intensity level was 11–15 lx, but in the middle of the channel, where most fry would be, we would expect the light intensity to be only 0.1 lx. This suggests that several large lights spread out over a long section of shoreline and across the river channel could strongly affect the behavior of outmigrating fry.

The duration of delay for an individual sockeye salmon fry is unclear. We assumed that once a fry is delayed in a lighted area, it may be delayed for a considerable period of time. At the I-405 bridge site (before the lights were shielded), we routinely observed large numbers of fry at different hours of the night, from shortly after dusk to shortly before dawn. Although there may have been some level of turnover of individnals, we think it reasonable that many were delayed for several hours. Because fry only take one or two nights to reach Lake Washington, a delay of a few hours may markedly increase their risk to predation. McDonald (1960) was able to completely stop the nightly movement of sockeye salmon fry with artificial lighting (30 lx) that was kept on all night. In other experimental trails, McDonald (1960) turned the lights off at different times of the night and observed that immediately afterwards the migration of fry commenced. In our experimental field trials, the fry appeared to resume their migration shortly after the lights were turned off. Further experiments are needed to determine how long fry are delayed.

In addition to increased shoreline abundance of sockeye salmon fry, increased light intensity may also cause fry to move into low-velocity areas along the bottom of the river channel. Once fry encounter artificial lighting, they reverse their direction and face upstream into the current (McDonald 1960); they will either stay in fixed position above the substrate or seek cover in the substrate. Given the high current velocities in the Cedar River, the only locations where fry could easily maintain their position in the current would be along the shore or on the bottom of the river channel. We were able to directly estimate the number of fry along the shoreline but not the number of fry along the bottom of the river channel. However, we were able to measure this number indirectly by examining predation by cottids in the midchannel area of a riffle at the I-405 site. Because of the high incidence of predation at this lighted site, we believe many sockeye salmon sought cover in the substrate and became vulnerable to predation by cottids. In all, we found 33 fry in 33 cottid stomach samples. Under similar conditions at a nearby control site, as well as at nine other sites further upstream with little lighting, only one salmonid fry was found in the stomachs of 109 cottids examined (Tabor, unpublished data). Similarly, in 2001, after the lights at the I-405 site were shielded, we observed no predation.

Predation of Fry

Under natural nighttime light intensity, sockeye salmon fry and cottids are probably spatially segregated because the fry occupy areas of faster water velocity (McDonald 1960), whereas cottids stay in close contact with the substrate and thus occupy areas with substantially slower water velocities. By selecting fast-flowing water areas, fry are able to move quickly downstream and reduce the likelihood of encounter with predators (Ginetz and Larkin 1976). Increased light causes fry to delay migration and to move to low-velocity water, where one would expect more frequent rates of encounter with cottids. Other research on predation of fry by cottids in the Cedar River has indicated that predation occurs primarily in low-velocity habitats such as pools and side channels (Tabor et al. 1998). Also, predation rates appear to be negatively related to streamflow. In addition, investigators have found that survival of juvenile salmonids is positively related to streamflow, which is probably related to reduced amounts of predation (Cada et al. 1997; Seiler and Kishimoto 1997)

Predation of fry by cottids appeared to be closely related to fry density at all field sites. As light intensity increased, the shoreline density of fry increased and subsequently the amount of predation increased. Cottids appeared to exhibit some type of functional response related to an increase in the abundance of fry. Because we conducted a variety of different field studies, it would be difficult to determine the exact type of functional response. Cottids may have a lesser ability to consume fry as light intensity increases, as demonstrated in the circular tank experiments, but the number of fry available to them at brighter light intensities will be substantially higher and thus overall predation should be greater, as was observed at field sites. Woodsworth (1982; prickly sculpin and sockeye salmon fry), Mace (1983; staghorn sculpin and chum salmon fry), and Jones (1986; prickly sculpin and chum salmon fry) studied the functional response of cottids feeding on salmonid fry. They all found that the functional response appeared to reach an asymptote at intermediate prey densities and then increase again at high prey densities. This may explain why we did not detect any differences in predation at Elliot Park. Jones (1986) also described a gorging behavior by prickly sculpin at high prey densities, wherein they would consume substantially more fry than the expected maximum ration. This may be similar to what we observed at high-light conditions at Lions Club Park, where fry were abundant and torrent sculpin of 90, 92, and 102 mm TL consumed 10, 13, and 12 fry, respectively.

Based on results from the artificial stream experiments and the Cedar River, increased light intensities greatly affect the behavior of sockeye salmon fry; however, the effect on predator behavior is not well understood. In field experiments, cottids appeared to exhibit a functional response in relation to an increase in the abundance of fry but did not exhibit any type of aggregative response (Sutherland 1996). However, our experiments were done over a short time and an aggregative response may take several days or weeks. In Lake Iliamna, Alaska, cottids exhibited a strong aggregative response in relation to the abundance of sockeye salmon eggs, but cottid movements to the salmon spawning sites took place over 3 weeks (Foote and Brown 1998). Therefore, cottids may exhibit an aggregative response to an increase in fry availability near permanent light structures. However, several alternative prey types exist in the Cedar River and cottids may not show a strong aggregative response such as that seen in Lake Iliamna, which is an oligotrophic system and perhaps limited in alternative prey. Jones (1986), in experimental studies with prickly sculpin, found that the abundance of alternative prey (amphipods and isopods) appeared to have almost as much influence as the abundance of the principal prey (chum salmon fry). In addition, cottids themselves may naturally avoid lighted areas because they too may become more vulnerable to predators. Movement into lighted areas may be a tradeoff for cottids, such that they have to balance increased risk of predation with increased prey availability.

Besides cottids, sockeye salmon fry in the Cedar River are also vulnerable to predation by salmonids, including rainbow trout (Beauchamp 1995), cutthroat trout, and juvenile coho salmon (Tabor et al. 1998). How increased light intensity affects predation of fry by salmonids is unclear. We used cottids for our laboratory experiments and field studies because they are an abundant predator in the Cedar River, are easy to collect, adjust readily to laboratory conditions, and are not as mobile as salmonids. Because salmonid predators are primarily visual predators, the effect of light intensity may be more pronounced when salmonids are present. Unlike cottids, salmonids may forage more effectively at higher light intensities. Predation of sockeye salmon fry by rainbow trout in artificial streams increased with increasing light intensity at intensities of less than 0.1 lx (Ginetz and Larkin 1976). Alternatively, salmonids are typically nocturnal during this time of the year (Riehle and Griffith 1993; Contor and Griffith 1995) and thus may avoid lighted areas. Additional field sampling needs to be undertaken to understand how increased light intensity would change the predation rate of fry by salmonid predators.

Tank and artificial stream experiments produced contrasting results. Tank experiments indicated that predation of sockeye salmon fry increased as light intensities decreased, whereas artificial stream experiments indicated the opposite. The reason for this large discrepancy is probably differences in current velocities. The artificial stream experiments were done in a flow-through system with strong current velocities (midchannel surface velocities ranging from 0.37 to 0.12 m/s), which created a fast-water refuge from cottids. In contrast, the tank experiments were done with little flow and no opportunity for the fry to emigrate downstream. In the tank experiments, predator and prey both occupied the same habitat and the reduction in predation with increased lighting probably reflects both the foraging ability of the sculpin and the ability of the fry to avoid them. The circular tank experiment made clear that both prickly sculpin and torrent sculpin can be highly effective predators in complete or near-complete darkness and that increased ambient light does not necessarily enhance their ability to prey on sockeye salmon fry. Hoekstra and Janssen (1985) demonstrated that blinded mottled sculpin *C. bairdi* were able to feed on mobile prey just by using their lateral line system.

In contrast to our results, Ginetz and Larkin (1976) found that predation of sockeye salmon fry by rainbow trout in artificial streams decreased as light intensity increased from 0.5 to 3.0 lx. Discrepancies between their experiments and this study are probably attributable to the predators used, the current velocities, and the size of the artificial stream. Ginetz and Larkin (1976) used a 0.6-m-wide experimental stream and rainbow trout, a highly mobile predator. Our experimental stream was 1.5 m wide and the predator we used was prickly sculpin, a substantially less mobile species. The current velocities used by Ginetz and Larkin were 0.12 m/s, which means there was probably no location where rainbow trout could not forage effectively. McDonald (1960) found that most sockeye salmon fry migrate in current velocities greater than 0.65 m/s, which may be too high for rainbow trout and other predators to forage effectively. Other researchers have also conducted light experiments with juvenile salmonids in which there is little or no current velocity (Patten 1971; Mace 1983; Petersen and Gadomski 1994). Their results may not apply to emigrating fish in natural situations if high current velocities are available. In those controlled experiments, predators usually had easy access to prey and the experiments may not have adequately simulated natural conditions, where high current velocities are available that create a fast-water refuge. In our artificial stream, current velocities were probably high enough to create such a refuge from prickly sculpin.

The size of the experimental field units (8 m shoreline length) appeared to work well for detecting differences in fry abundance but may have been too small for estimating predation rates. We could detect differences in predation between lighted areas and control areas at Lions Club Park, but we were often unable to detect differences in results between different light intensities. In some experimental units few predators were collected. Also, the diets of cottids can vary between individual fish; even when fry are abundant, many cottids will not consume them, and each site will include a variety of other prey types such as aquatic insects or oligochaetes. If many of the male cottids are guarding egg nests, they may not be actively searching for prey. In mottled sculpin, the male may spend 8 weeks fanning and protecting eggs and young (Downhower and Brown 1980). In most areas, a 20–30 m shoreline would probably be adequate to collect enough cottids to get an accurate estimate of predation. Additionally, had we extended the experiments—which lasted for only a few hours—over the entire night we may have seen more predation and thus been better able to detect differences between treatments.

Experiments at the Lions Club Park demonstrated that shoreline habitat type can have an important effect on the number of sockeye salmon fry delayed in their emigration and the subsequent predation that ensues. This effect was probably in large part attributable to water velocities as well as substrate type. Light caused sockeye salmon fry to move to low-velocity areas. The riprap banks were steeper and had a narrower area of low-velocity water than did the gravel shoreline. The two habitat types may also have had differences in predator abundance, which could influence the number of sockeye salmon fry. The results of our laboratory experiments and other studies (Ginetz and Larkin 1976; Gaudin and Caillere 1985; Bardonnet and Heland 1994) have demonstrated that the presence of predators increases the downstream movement of salmonid fry. Typically, large cottids are more numerous in larger substrates such as riprap than in smaller substrates (Tabor et al. 1998). The abundance of other predators such as rainbow trout may also be greater near a riprap bank (Lister et al. 1995).

The substrate type across the channel width may also have an important effect on predation in a lighted area. Larger substrates will create a rougher river channel and may have more abundant low-velocity locations for sockeye salmon fry. However, these same sites will probably also have more large cottids. In riffles of the Cedar River, the abundance of cottids larger than 50 mm TL was greatest in areas with large substrates such as cobble (Tabor et al. 1998). At the I-405 bridge site, the substrate consisted primarily of cobble and large gravel; there we were able to collect several cottids larger than 50 mm TL. At another lighted bridge site in the Cedar River, however, the substrate was mostly small gravel, and few cottids larger than 50 mm TL were collected; thus, the overall predation at that site was probably minimal (Tabor, unpublished data).

Management Implications

In the lower Cedar River, nighttime lighting appears to come from three major sources: direct artificial lighting, the moon, and reflected lighting off of clouds. Direct lighting is intense lighting that occurs in a relatively small area every night and usually all night. In contrast, reflected light and moonlight are not very intense but they are spread over a much larger area and vary greatly with the weather and moon phase. Direct lighting probably has strong localized effects on soekeye salmon fry, whereas reflected lighting and moonlight probably have weak effects over a large area. Which of these has more overall effect on sockeye salmon fry is difficult to assess. However, it is much easier to reduce direct lighting than to address reducing reflected light. Direct lighting can be turned off, redirected, or shielded. Reducing reflected light would be a much larger and far more difficult management objective.

Overall, our results suggest that reductions in light intensity can be beneficial for emigrating sockeye salmon fry and that the impact of lighting should be considered for any future development project. For example, by reducing the lighting at the I-405 bridge site, we substantially reduced predation on sockeye salmon fry. Attempting to keep light values below 0.1 lx appears to be a prudent management goal.

Acknowledgments

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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.

Acknowledgments

We thank Liz Warman and Paul Crane of The Boeing Company for financial support of this study. We also thank John Lombard, King Co. Dept. of Natural Resources for financial support and encouragement, and Dave Seiler, Washington Dept. of Fish and Wildlife, for permission to obtain sockeye fry from the Cedar River fry trap. Tim Eichler, Paul Lorenz and Chuck Ridley, WDFW, helped collect and transfer fry to us from the fry trap. Steve Hager, U.S. Fish and Wildlife Service, assisted with the field collection of sculpin. Brian Footen, Muckleshoot Indian Tribe, assisted with the gastric flushing. Bob Wunderlich, U.S. Fish and Wildlife Service, reviewed an earlier draft of this report.

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Tabor, R.A. and J. Chan. 1996b. Predation on sockeye salmon fry by piscivorous fishes in the lower Cedar River and southern Lake Washington. Miscellaneous report. U.S. Fish and Wildlife Service, Western Washington Fishery Resource Office, Olympia, Washington.

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/ft²)	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.

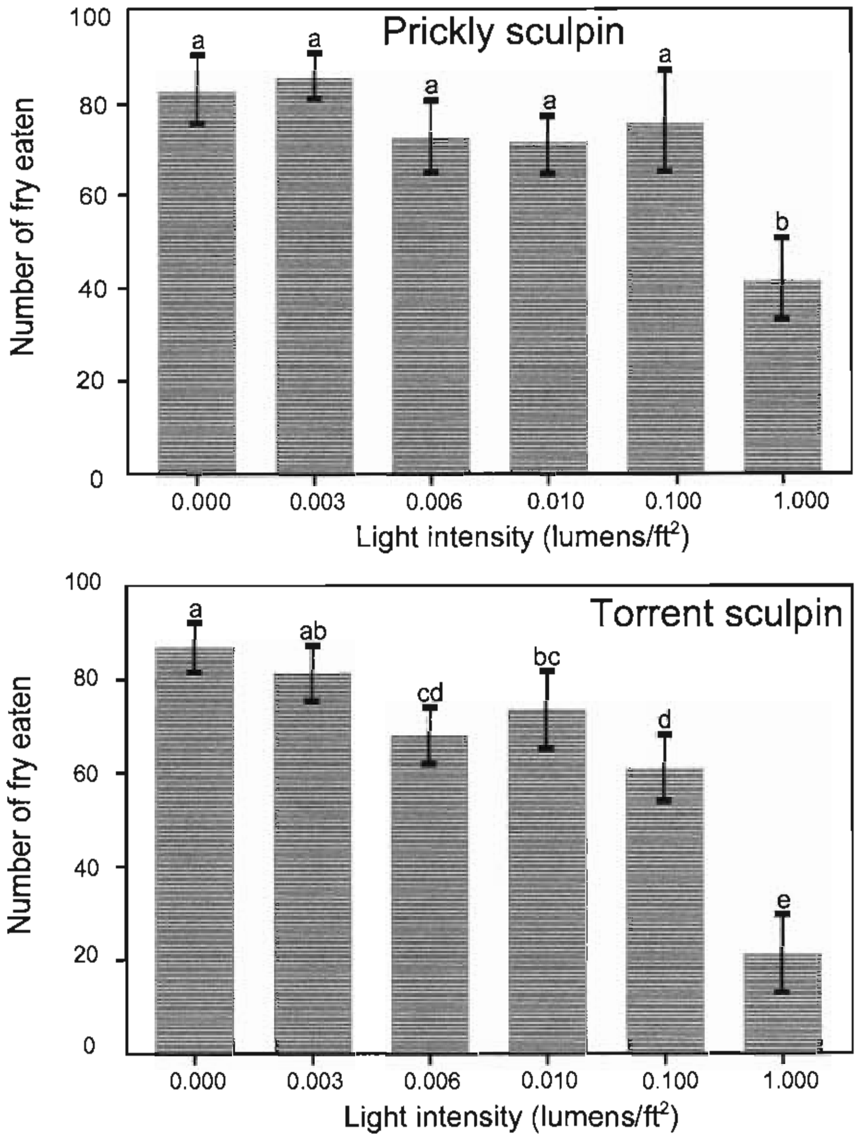


Figure 1. Number of sockeye salmon fry eaten by prickly sculpin and torrent sculpin in 40 min trials in circular tanks at different light intensities. Each bar is the mean of 6 trials. Error bars represent the standard deviation. Groups of bars with different letters are significantly different (ANOVA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

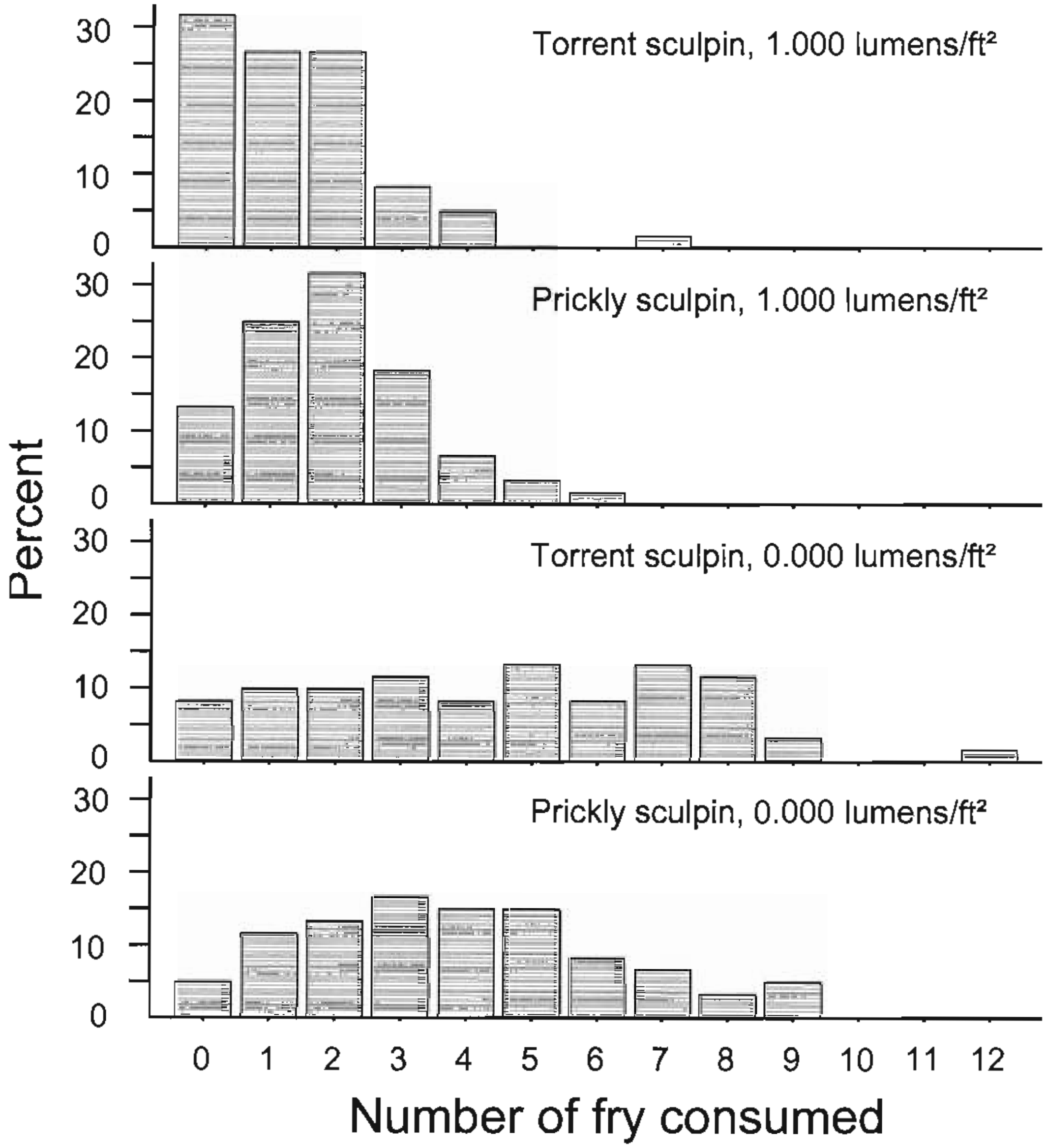


Figure 2. Frequency of occurrence (percent) of the number of sockeye salmon fry consumed by prickly sculpin and torrent seulpin in circular tanks at two light intensity levels. Numbers for each graph are based on a total of 60 sculpin from three replicates (20 sculpin each).

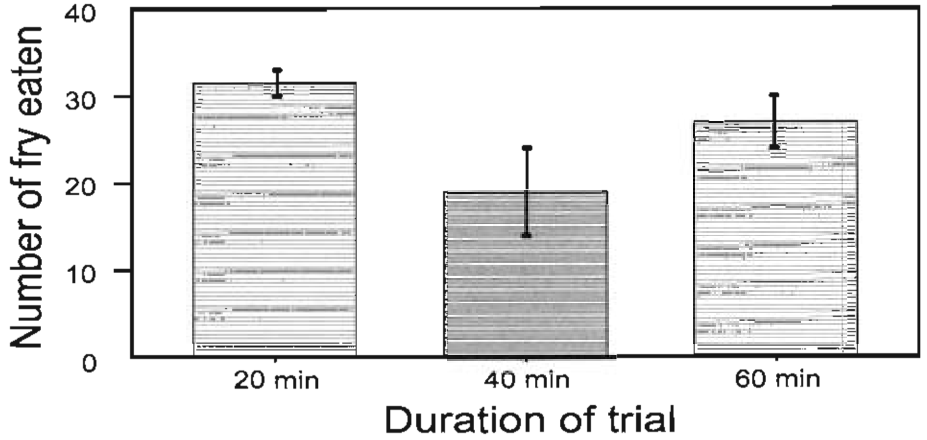


Figure 3. Mean number of sockeye salmon fry eaten by torrent sculpin in circular tank trials of different duration. Numbers are based on two replicates. Trials were all done with 100 fry and 20 sculpin; light intensity was 1.000 lumens/ft². Error bars represent the range of observations.

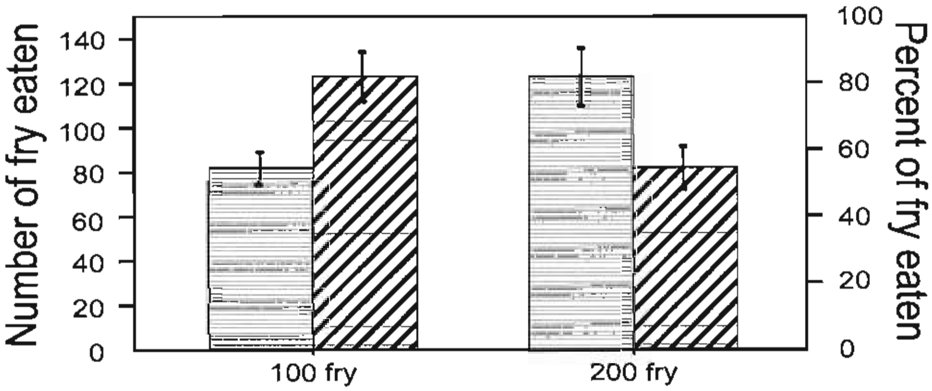


Figure 4. Mean number (shaded bars) and percent (hashed bars) of sockeye salmon fry eaten by prickly sculpin in circular tank trials of two densities of fry. Numbers for 100 fry density are based on six replicates and 200 fry density are based on three replicates. Trials were all done with 20 sculpin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

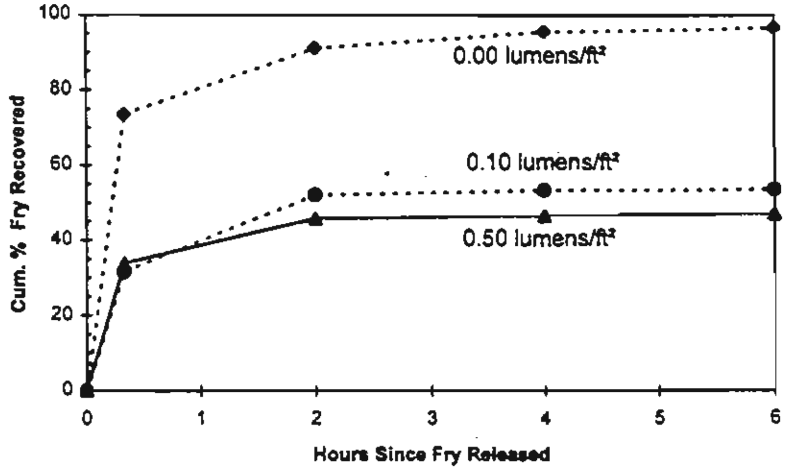


Figure 5. Cumulative percent of total sockeye salmon fry recovered after release in the artificial streams for three light intensity levels (lumens/ft^2), May 24-29, 1997. Each line is the mean of two trials. All trials were done in the absence of predators.

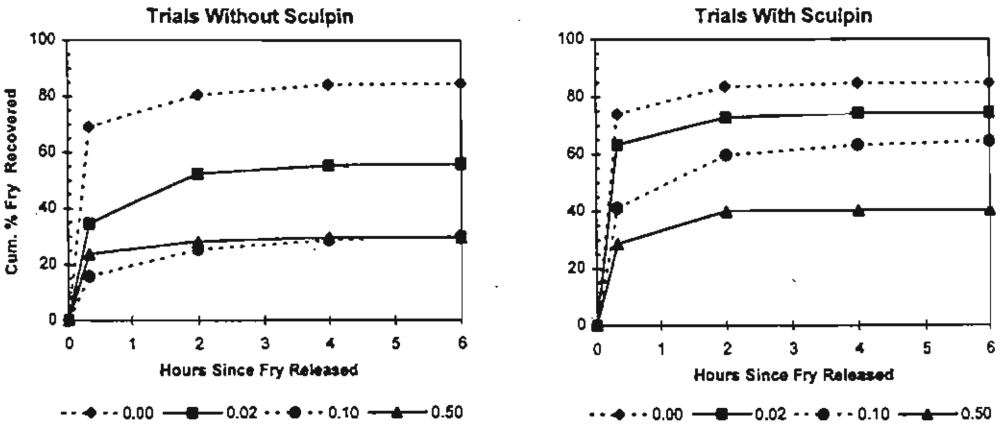


Figure 6. Cumulative percent of total sockeye salmon fry recovered after release in the artificial streams, June 4-23, 1997. Each line is the mean of 2 trials. The left and right panels show the results for trials when fry emigrated in the absence or presence of prickly sculpin, respectively. Trials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

Submission #____
Subject Lake Washington, Poster - used as display and introduction

Effects of Artificial Lighting on Juvenile Salmonids A Review of Research in the Lake Washingtonian Basin
Roger Tabor, Mark Celedonia, USFWS, Gayle Brown, USGS (PDF of Power Point) Oregon AFS Meeting October, 2010

Chinook Salmon Smolt Behavior in Lake Washington and the Ship Canal: 2004-2008 Acoustic Tracking Studies
Roger Tabor, Mark Celedonia, USFWS   Power Point Slide 1 and Slide 31

Movement and Habitat Use of Chinook Salmon Smolts in the Lake Washington Ship Canal 2007-2008 Acoustic Tracking Studies May 2011
Roger Tabor, Mark Celedonia, et el USFWS   (Selected pages referencing "lighting")

Movement and Habitat Use of Chinook Salmon Smolts, Northern Pikeminnow, and Smallmouth Bass Near the SR 520 Bridge 2008 Acoustic Tracking Study December 2011
Roger Tabor, Mark Celedonia, et el USFWS   (Selected pages referencing "lighting")

Lake Washington

Lake Washington is a rearing area and migratory path for salmon runs that include Cedar and Sammamish Rivers, Kelsey, Bear Creek, Issaquah, Ebright, and Pipers Creeks All these runs must also funnel through the Ballard Locks.

Acoustic tracking has been used extensively in research on these salmon runs. *While not the primary focus, these studies have shown conclusively that light on the waterway slows or stops outward migration of juvenal salmon, thus increasing predation.*

"*Light is basically a big stop sign" Roger Tabor USFWS*

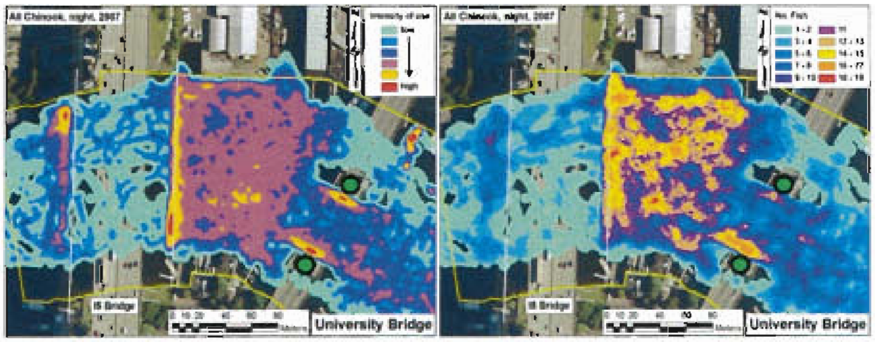


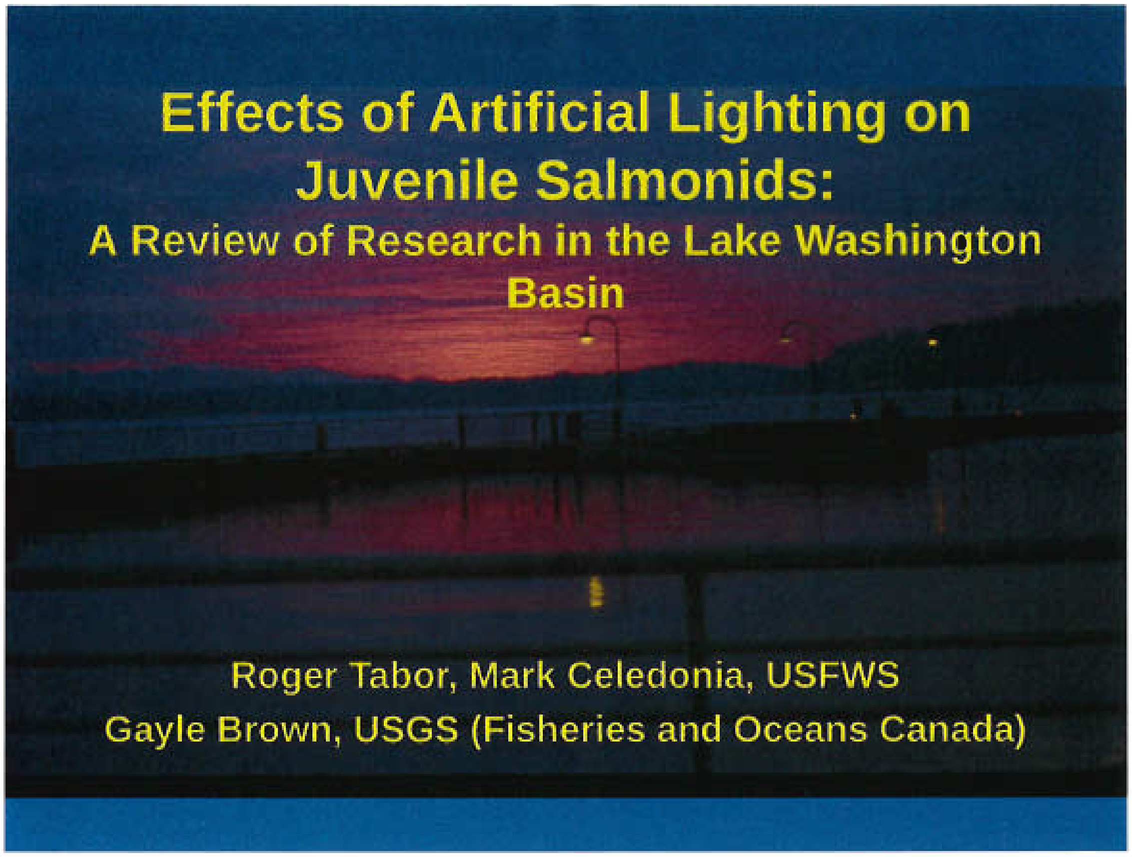
FIGURE 47. Distribution of tagged Chinook salmon at night at the University Bridge study site, June-July, 2007. Density plot (left) shows intensity of fish use for all tracked fish (weighted by time), and spatial frequency distribution (right) shows number of fish tracked by area. The white lines parallel to the I-5 bridge show the location of the light/shadow edge created by artificial lighting on the I-5 bridge deck (see Figure 48). Light levels were 1.6-2.0 lx (measured at 3 points) within 1 m of this line on the light side, and were 0.2-0.5 lx (measured at 6 points) in the shadow area between the lines. Green circles show approximate locations of lights beneath the University Bridge (see Figure 50).

FIGURE 48. Artificial lighting on the I-5 bridge deck spanning the Lake Washington Ship Canal (looking north).

FIGURE 50. Artificial lighting under the University Bridge. Lighting is directed down onto the water surface. Light on the north bridge support structure is pictured. Light on the south support structure is similar. These lights correspond with green circles in Figure 47.

Madison Park Condos 43rd Ave

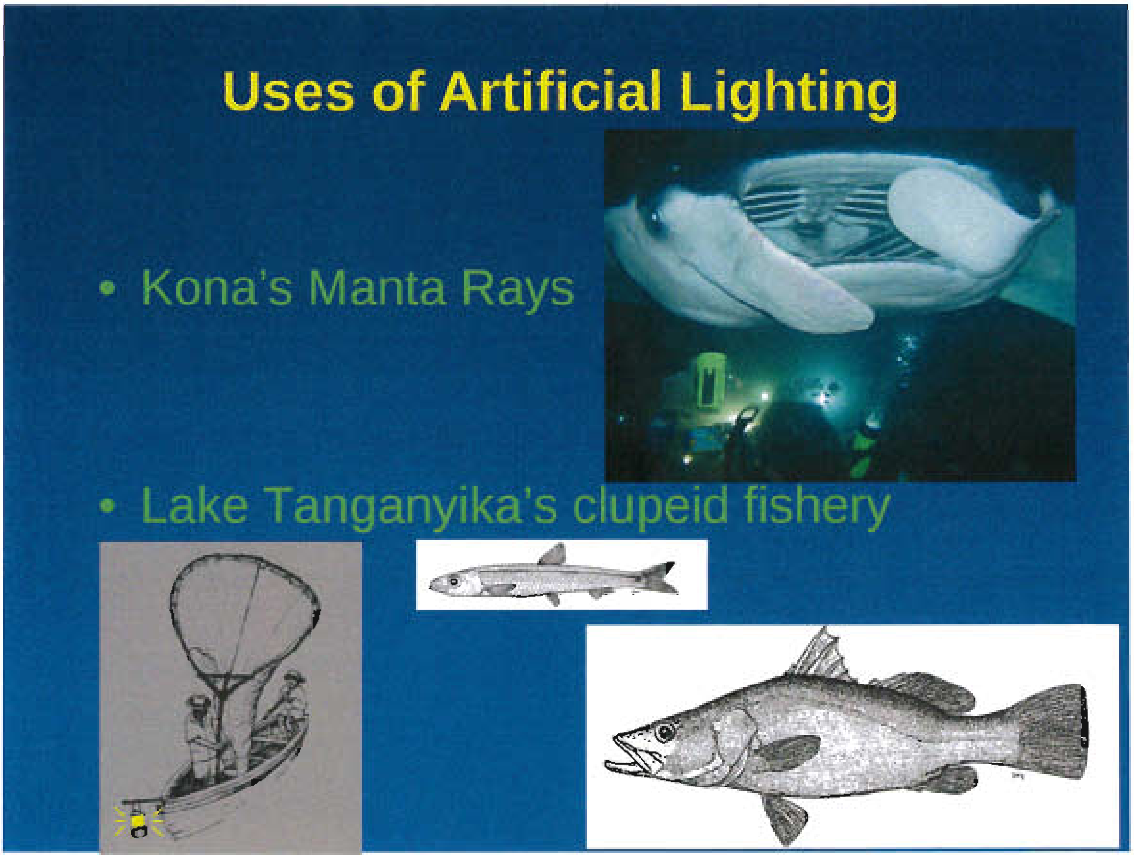
Ref. 1. Movement and Habitat Use of Juvenile Chinook Salmon Smolts in the Lake Washington Ship Canal: 2007-2008 Acoustic Tracking Studies Celedonia, M. T., Z. Li, S. Sanders, R. Tabor, S. Damm, D. Lantz, and B. Price, 2011
2. Effects of Artificial Lighting on Juvenile Salmonids: A Review of Research in the Lake Washington Basin, Roger Tabor, Mark Celedonia, USFWS , Gayle Brown, USGS



Effects of Artificial Lighting on Juvenile Salmonids:

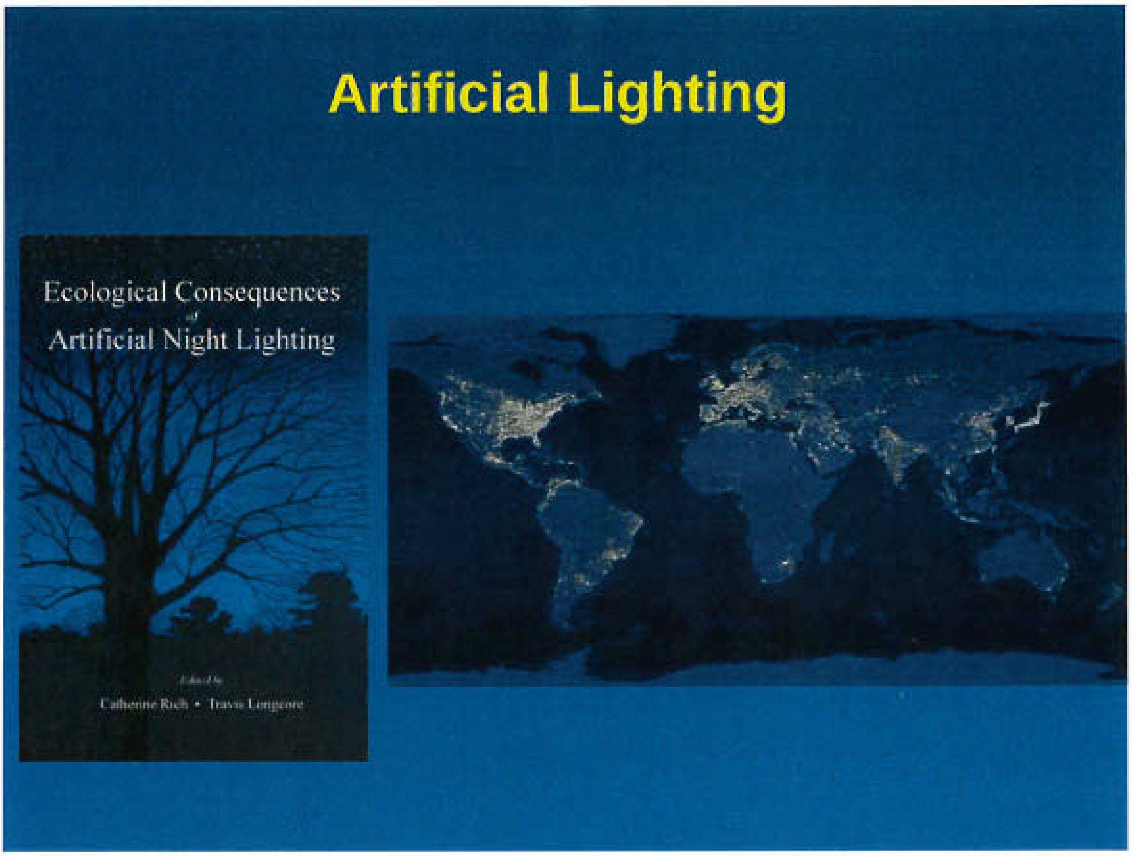
A Review of Research in the Lake Washington Basin

Roger Tabor, Mark Celedonia, USFWS
Gayle Brown, USGS (Fisheries and Oceans Canada)



Uses of Artificial Lighting

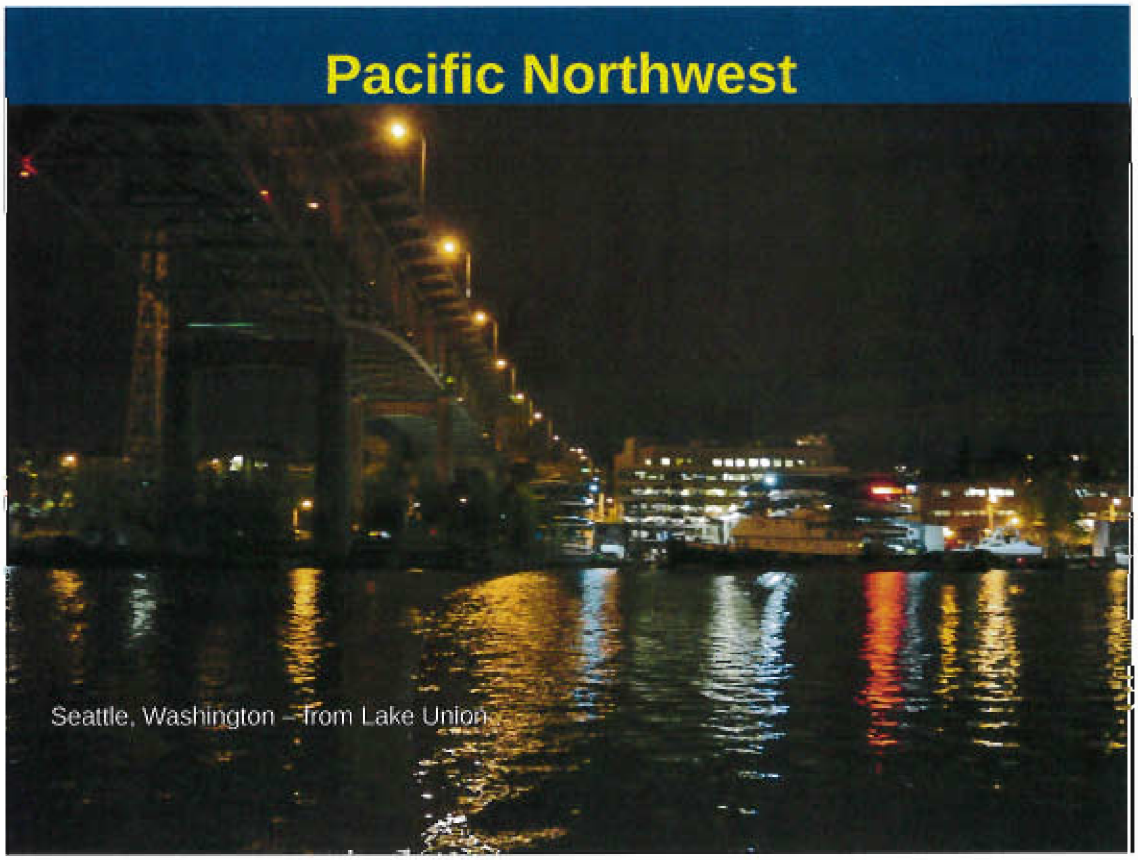
- Kona's Manta Rays
- Lake Tanganyika's clupeid fishery



Artificial Lighting

Ecological Consequences
of
Artificial Night Lighting

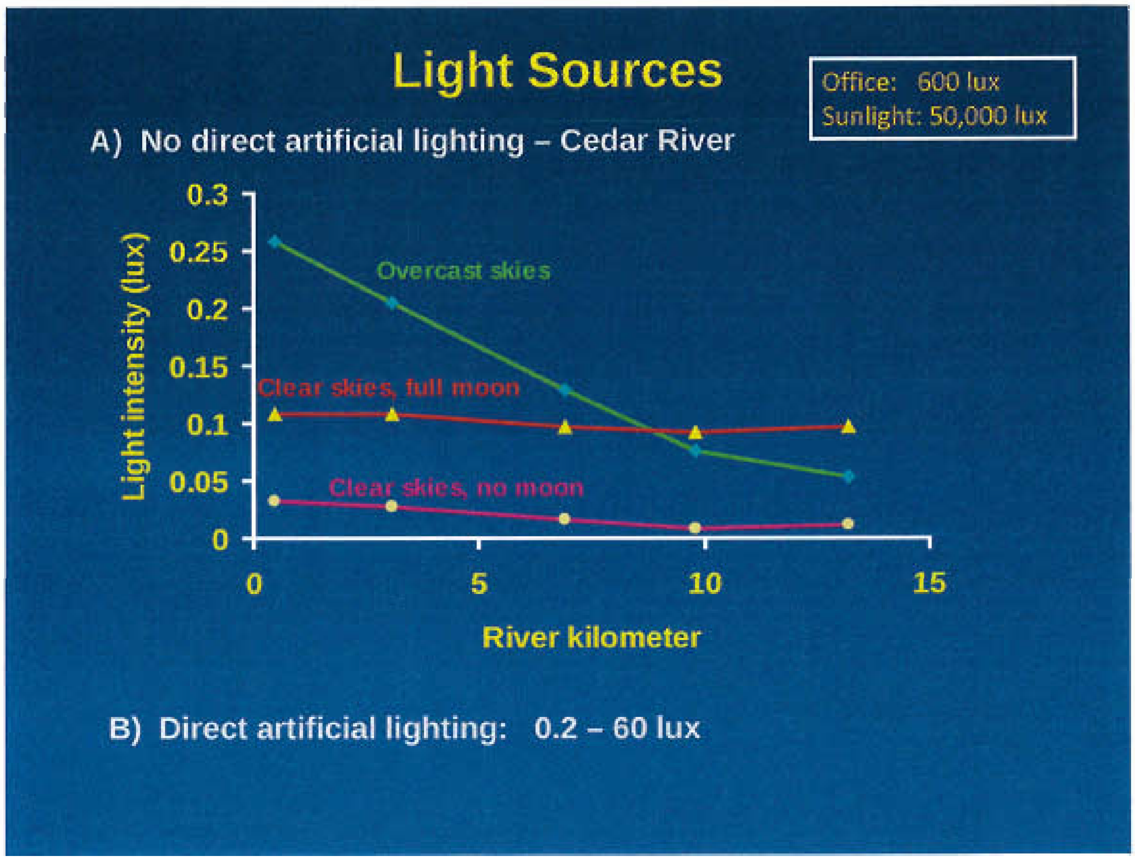
Edited by
Catherine Rich • Travis Longcore



Pacific Northwest

Seattle, Washington – from Lake Union

Lake Washington Basin

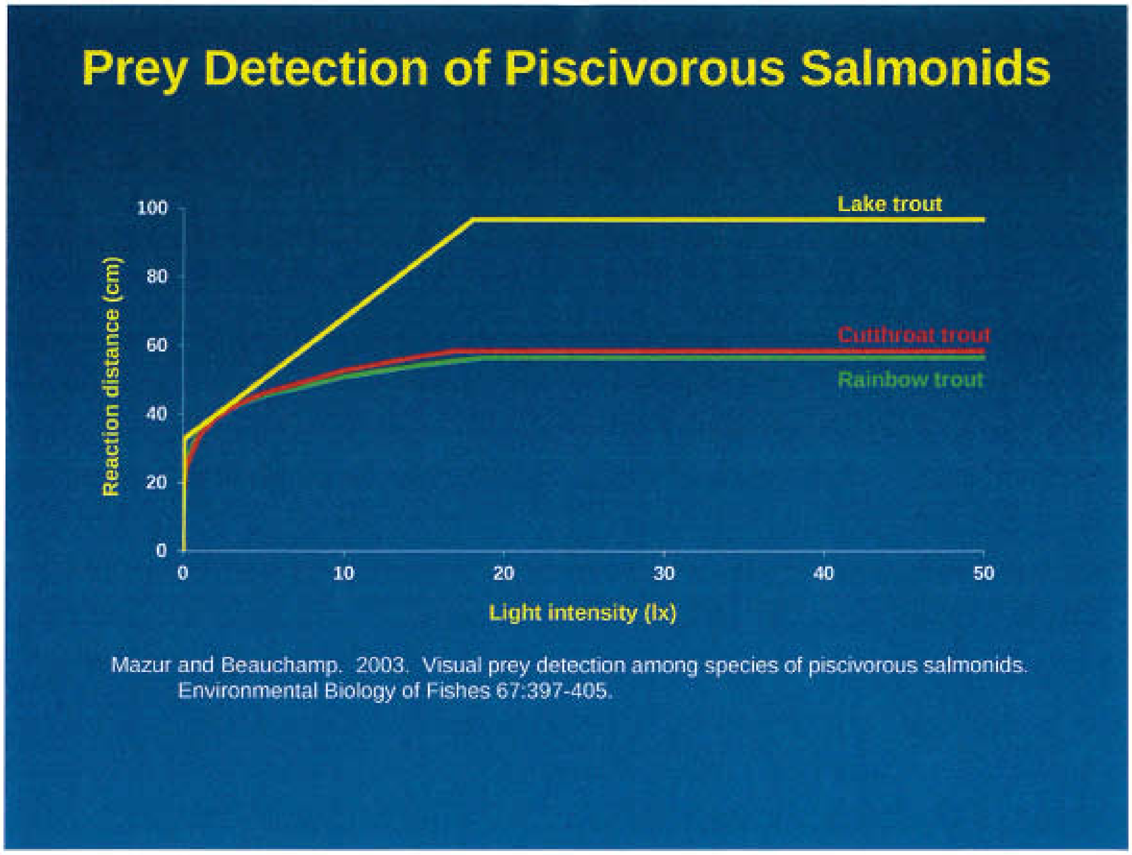


Light Sources

Office: 600 lux
Sunlight: 50,000 lux

A) No direct artificial lighting – Cedar River

B) Direct artificial lighting: 0.2 – 60 lux



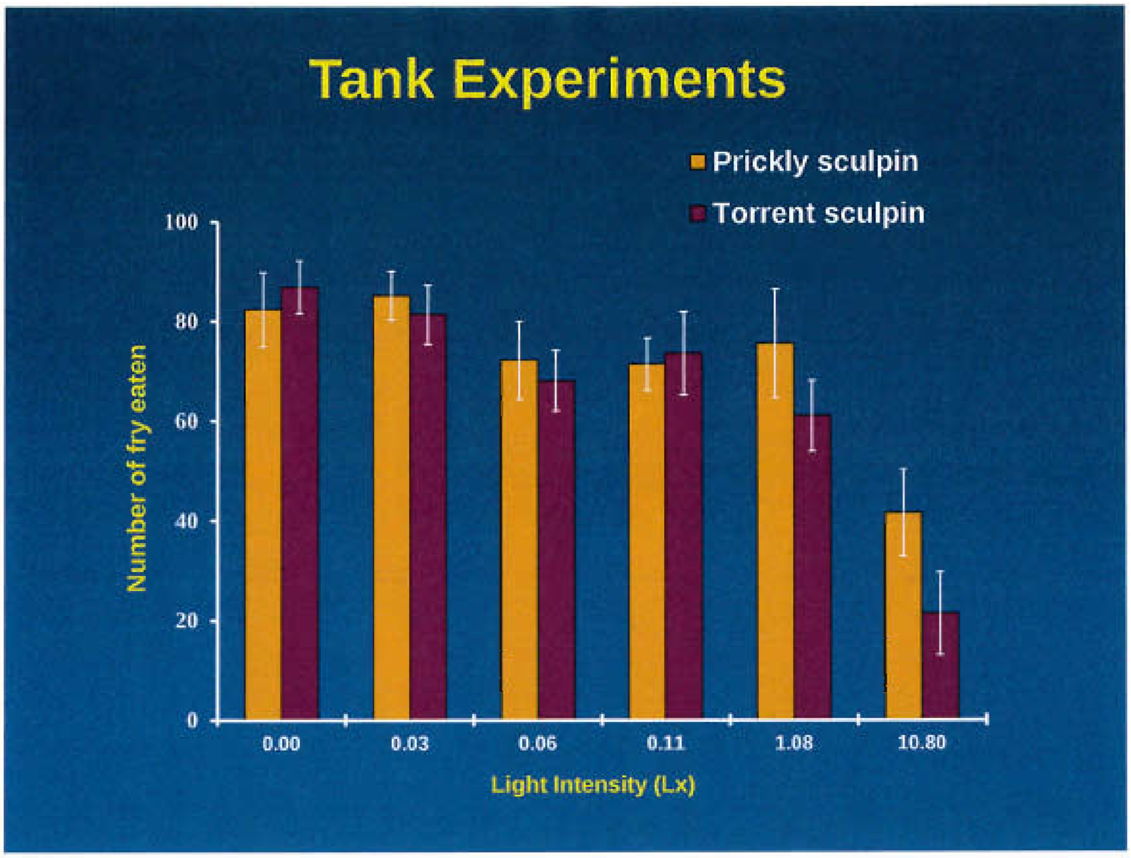
Prey Detection of Piscivorous Salmonids

Mazur and Beauchamp. 2003. Visual prey detection among species of piscivorous salmonids. Environmental Biology of Fishes 67:397-405.

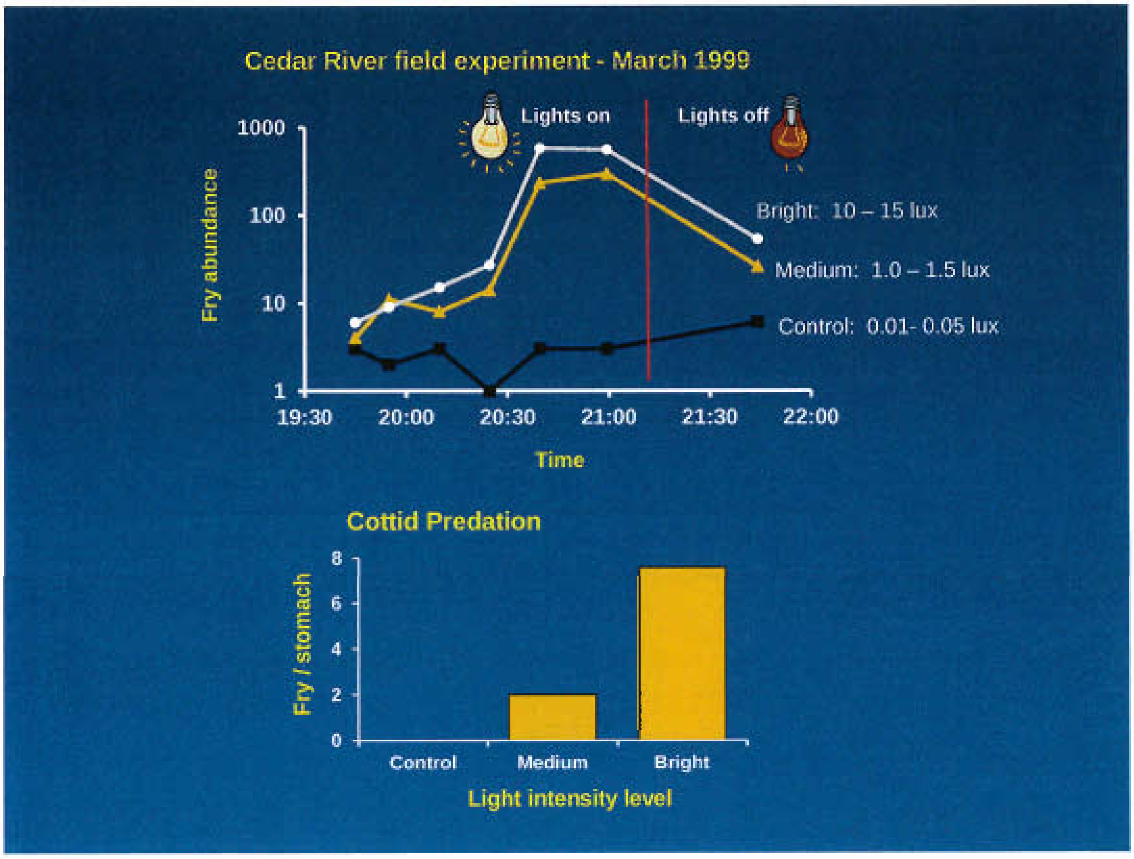
Cedar River

Sockeye salmon fry and Sculpin Study

- Sockeye salmon fry
  - Migrate at night
  - One or two nights to reach the lake
  - Select mid-channel areas with high velocities
- Sculpin
  - Predator of sockeye fry
  - Abundant
  - Easy to work with in lab
  - Sedentary

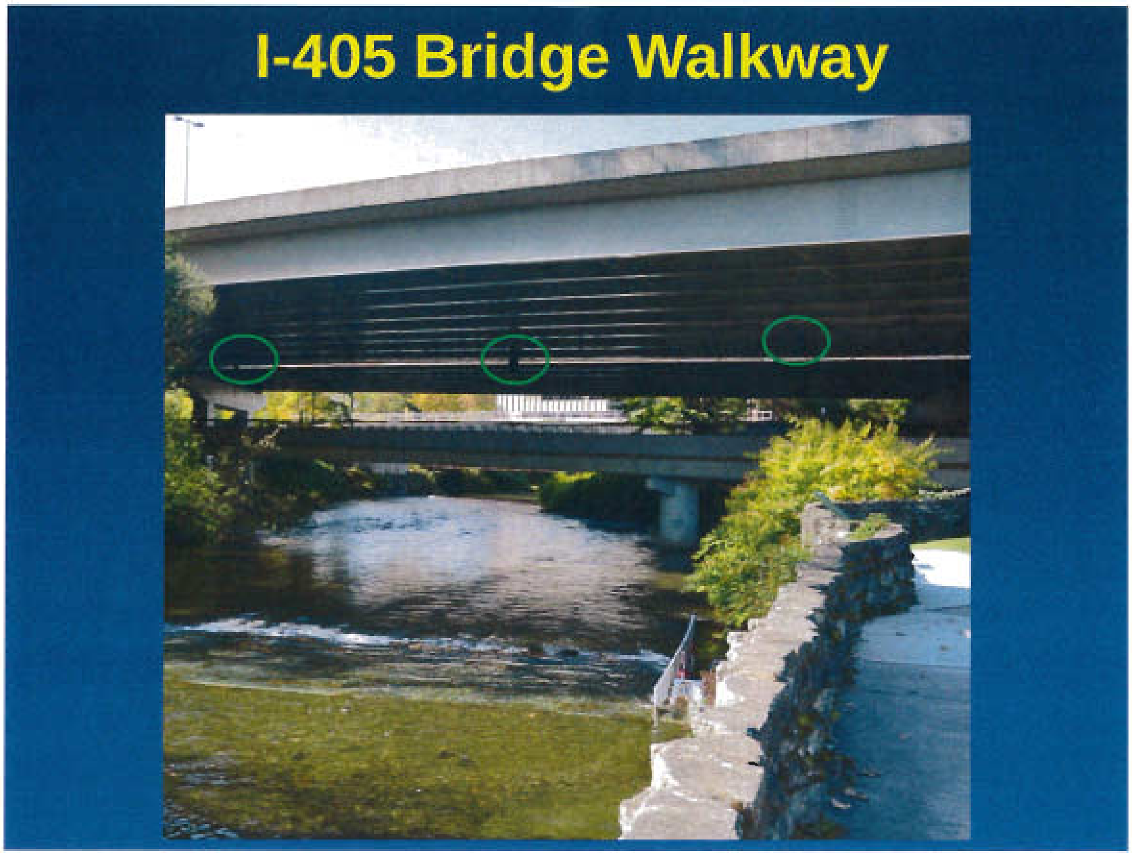


Tank Experiments

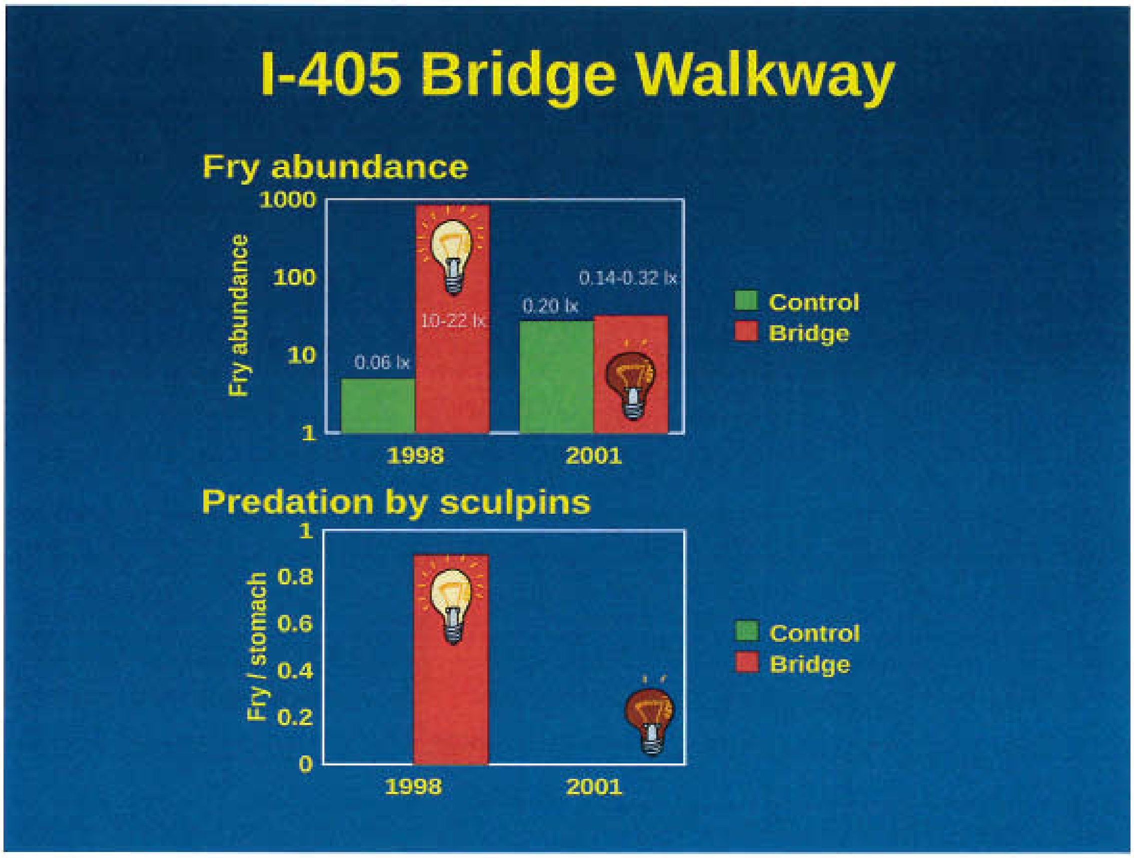


Cedar River field experiment - March 1999

Cottid Predation



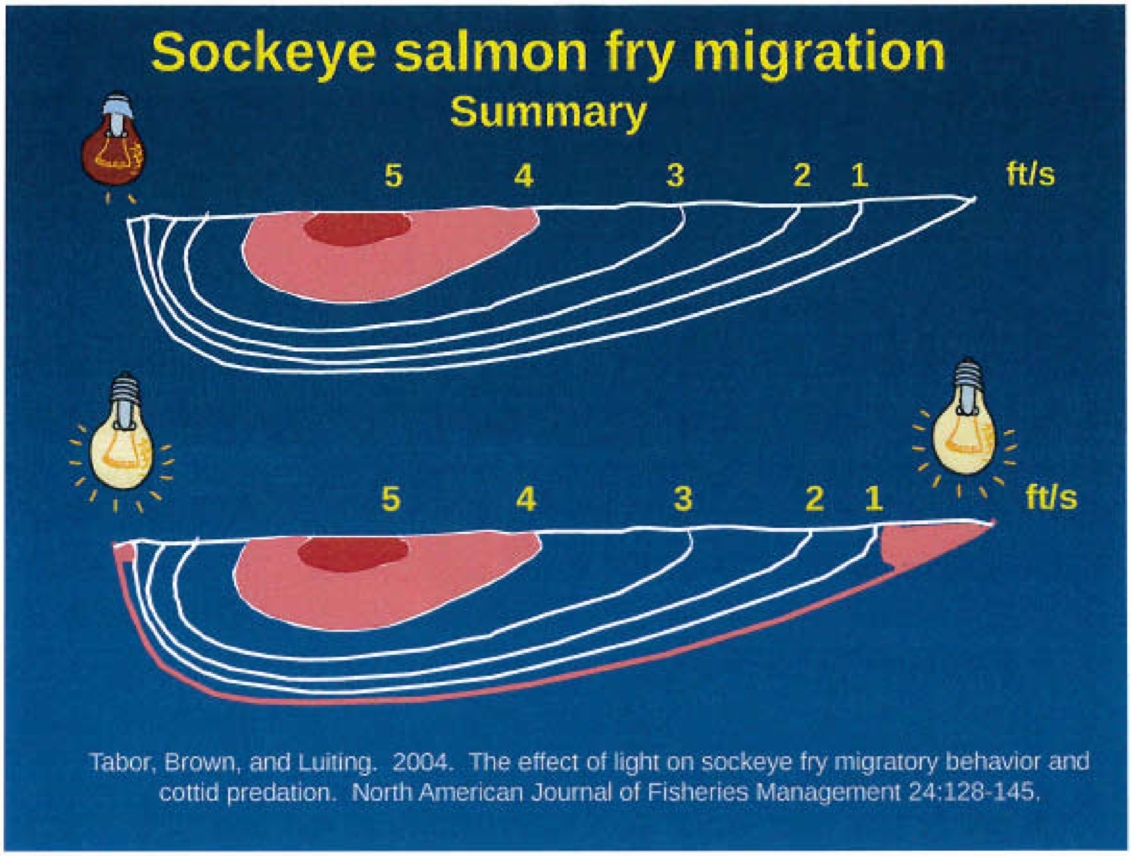
I-405 Bridge Walkway



I-405 Bridge Walkway

Fry abundance

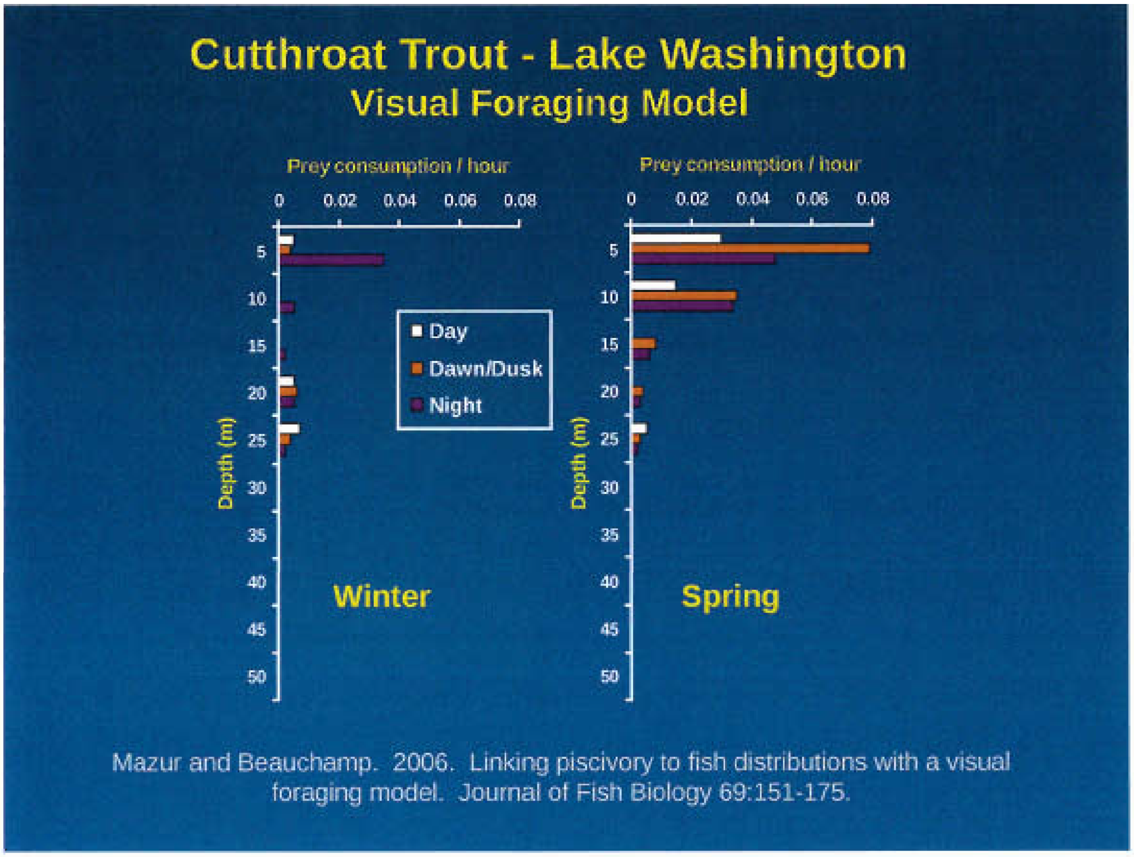
Predation by sculpins



Sockeye salmon fry migration

Summary

Tabor, Brown, and Luiting. 2004. The effect of light on sockeye fry migratory behavior and cottid predation. North American Journal of Fisheries Management 24:128-145.



Cutthroat Trout - Lake Washington

Visual Foraging Model

Mazur and Beauchamp. 2006. Linking piscivory to fish distributions with a visual foraging model. Journal of Fish Biology 69:151-175.

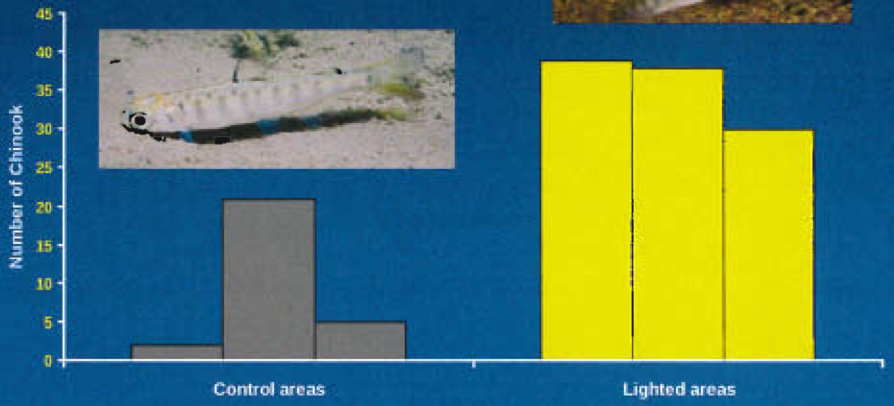
Cedar River/Lake Washington Juvenile Chinook Salmon

- Juveniles rear in Cedar River or Lake Washington
- Inhabit shallow shoreline areas from January to May

Artificial Lighting Experiment

February 23, 2005

Mean length – 49 mm FL



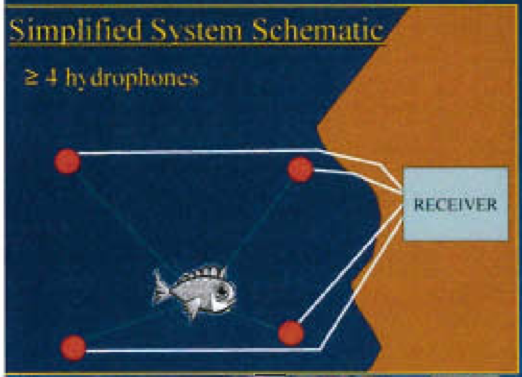
0.2 – 0.3 lux

Mean: 5 – 10 lux
Max: 80 – 100 lux

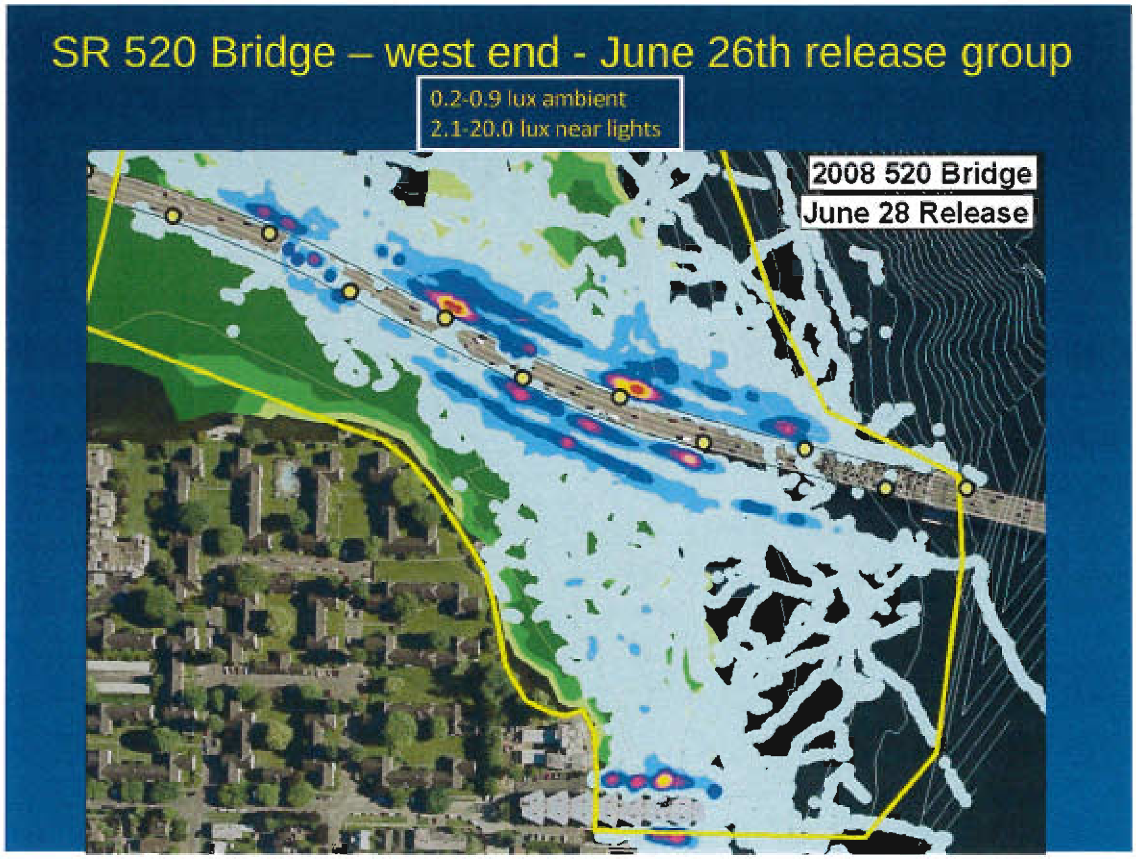
Chinook Salmon Smolts

- Outmigrate from Lake Washington and through Ship Canal in May-July
- Migrate along shoreline

Fine-scale Acoustic Tracking - HTI

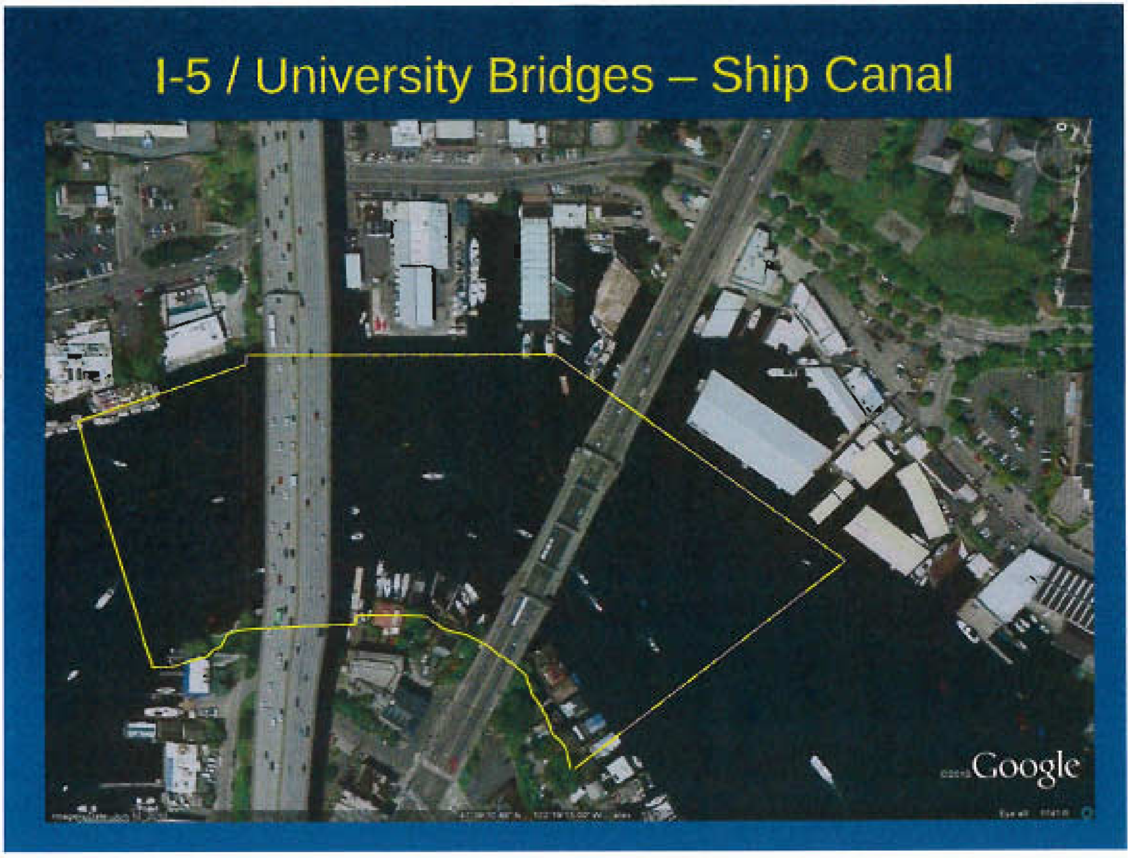


SR 520 Bridge – west end

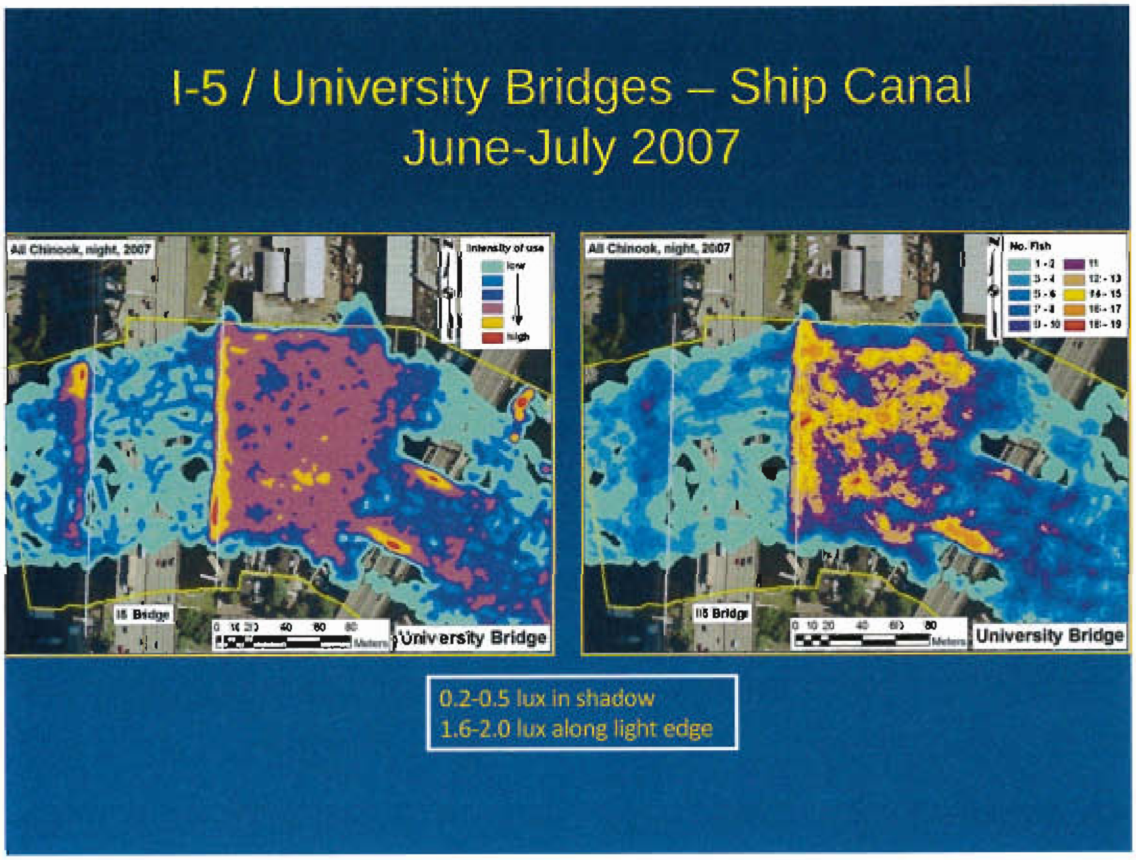


SR 520 Bridge – west end - June 26th release group

0.2-0.9 lux ambient
2.1-20.0 lux near lights

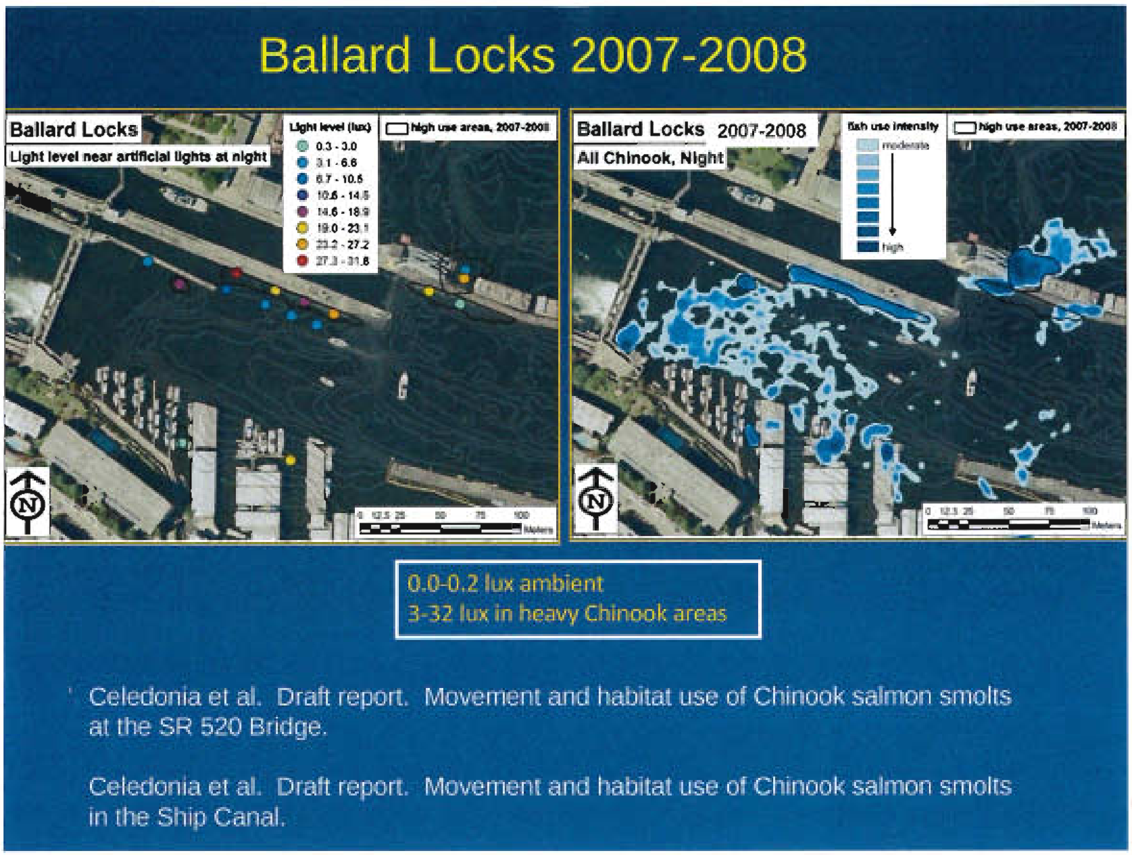


I-5 / University Bridges – Ship Canal



I-5 / University Bridges – Ship Canal
June-July 2007

0.2-0.5 lux in shadow
1.6-2.0 lux along light edge

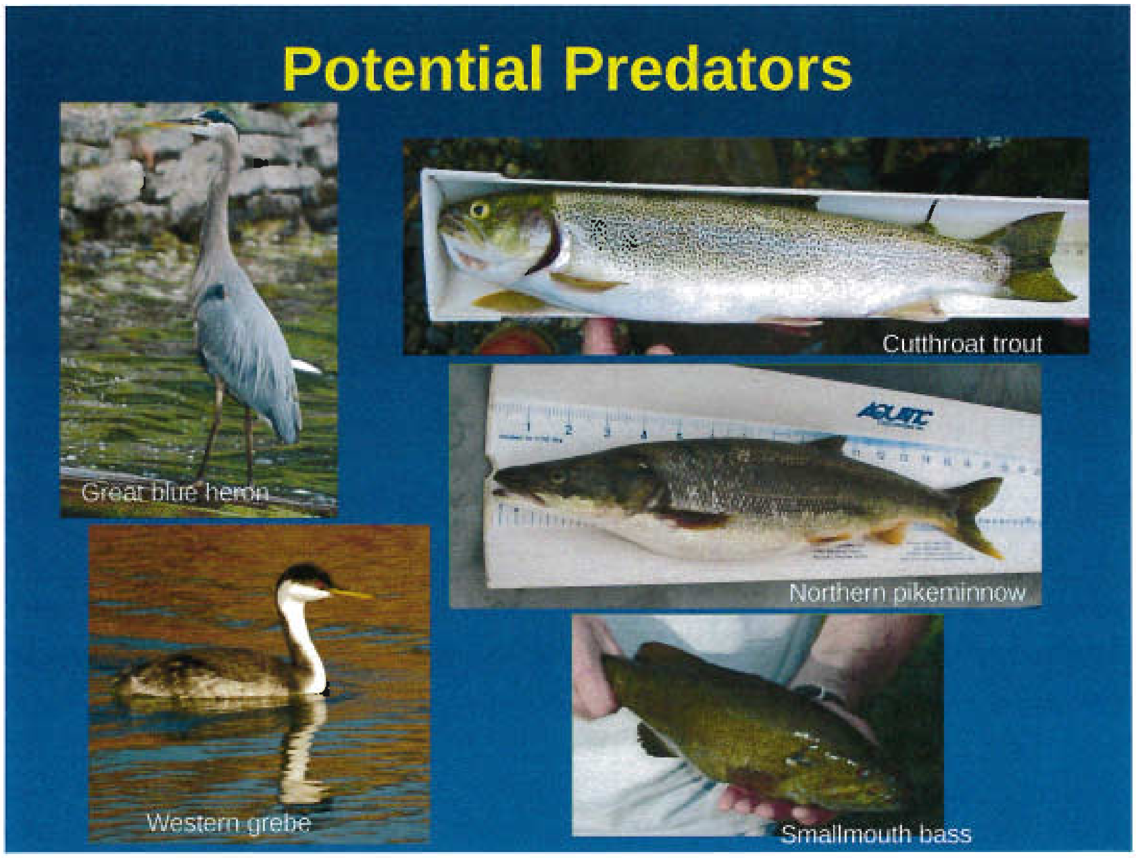


Ballard Locks 2007-2008

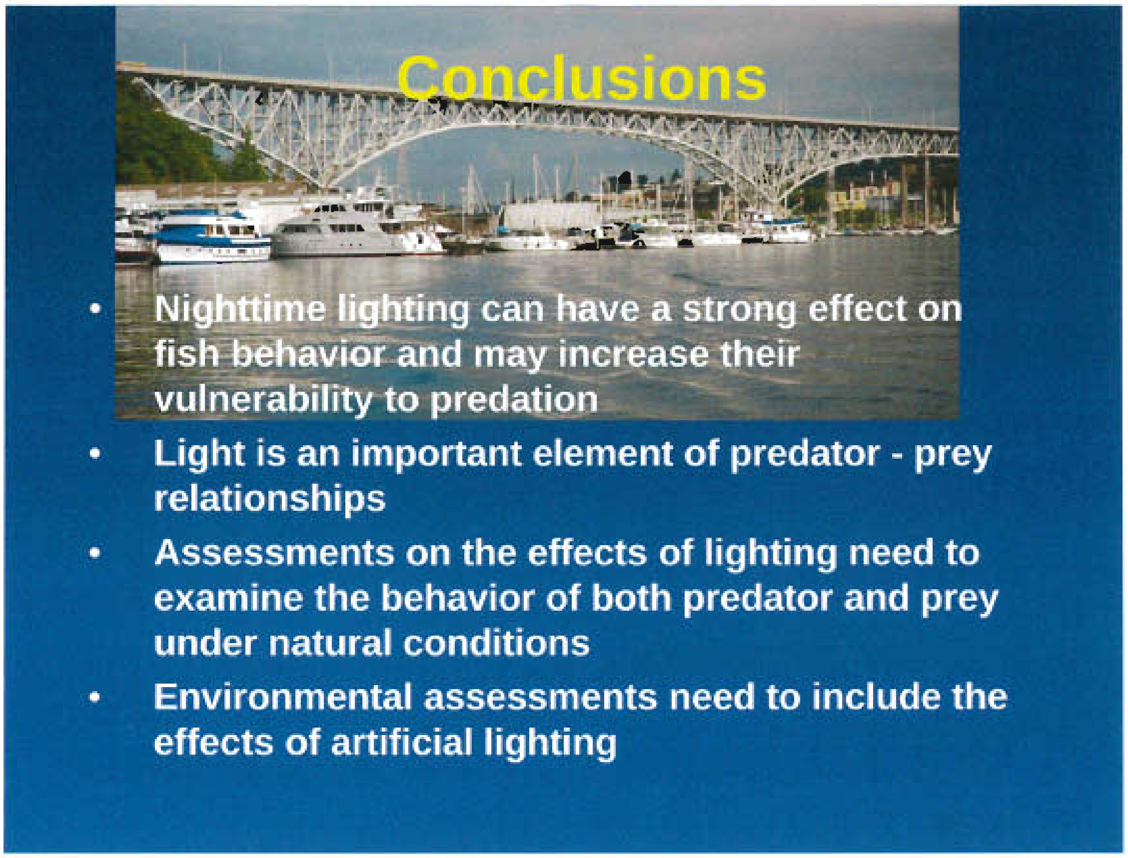
0.0-0.2 lux ambient
3-32 lux in heavy Chinook areas

Celedonia et al. Draft report. Movement and habitat use of Chinook salmon smolts at the SR 520 Bridge.

Celedonia et al. Draft report. Movement and habitat use of Chinook salmon smolts in the Ship Canal.

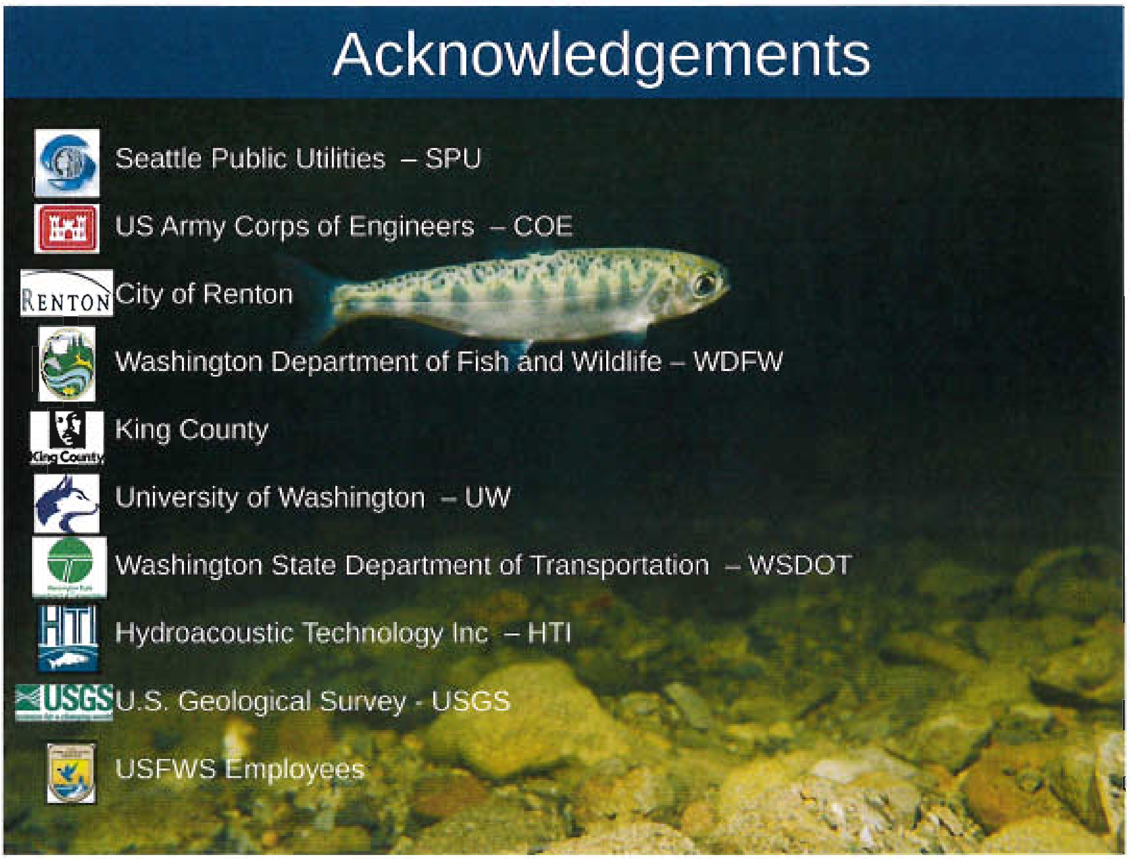


Potential Predators



Conclusions

- Nighttime lighting can have a strong effect on fish behavior and may increase their vulnerability to predation
- Light is an important element of predator - prey relationships
- Assessments on the effects of lighting need to examine the behavior of both predator and prey under natural conditions
- Environmental assessments need to include the effects of artificial lighting



Acknowledgements

Seattle Public Utilities – SPU
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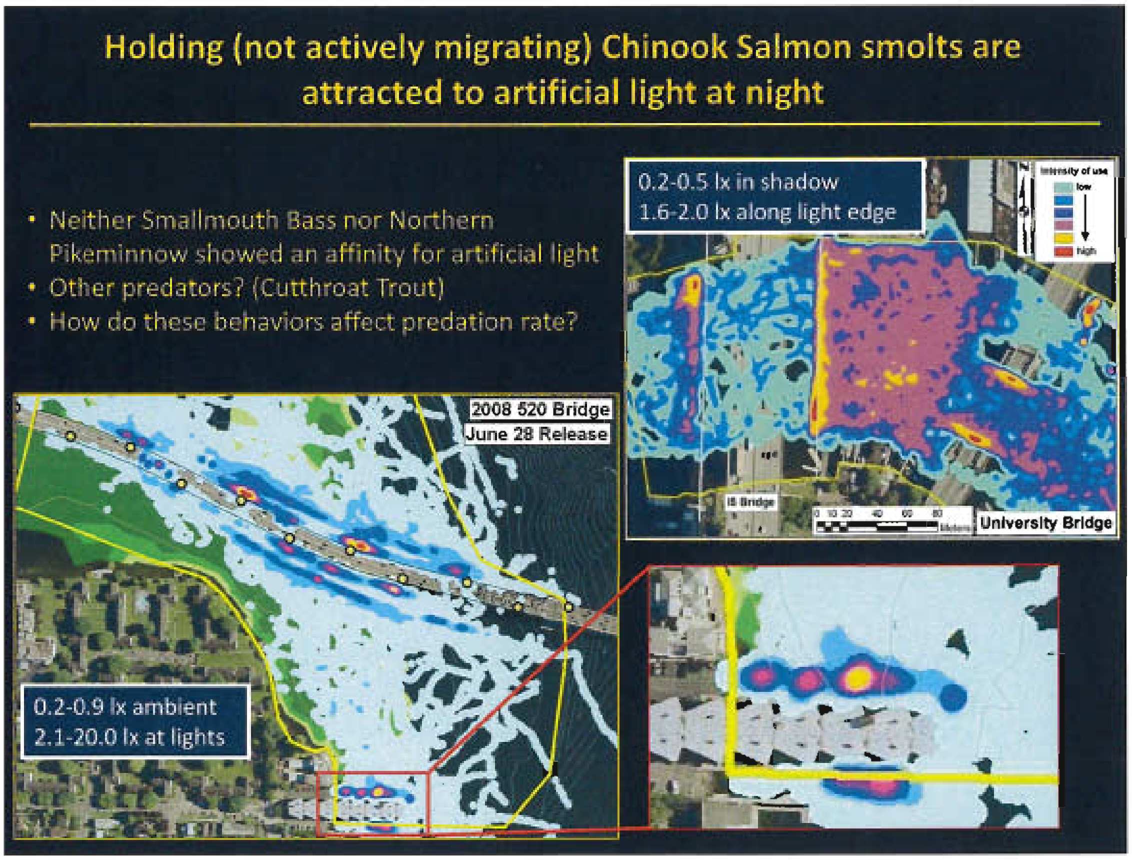
Washington Department of Fish and Wildlife – WDFW
King County
University of Washington – UW
Washington State Department of Transportation – WSDOT
Hydroacoustic Technology Inc – HTI
U.S. Geological Survey - USGS
USFWS Employees

Chinook Salmon Smolt Behavior in Lake Washington and the Ship Canal: 2004-2008 Acoustic Tracking Studies

Mark T. Celedonia & Roger A. Tabor

U.S. Fish & Wildlife Service
Washington Fish & Wildlife Office
510 Desmond DR., SE
Lacey, WA 98503

Slide 1



Holding (not actively migrating) Chinook Salmon smolts are attracted to artificial light at night

- Neither Smallmouth Bass nor Northern Pikeminnow showed an affinity for artificial light
- Other predators? (Cutthroat Trout)
- How do these behaviors affect predation rate?

0.2-0.5 lx in shadow
1.6-2.0 lx along light edge

0.2-0.9 lx ambient
2.1-20.0 lx at lights

Slide 31

U.S. Fish and Wildlife Service

Movement and Habitat Use of Chinook Salmon Smolts, Northern Pikeminnow, and Smallmouth Bass Near the SR 520 Bridge

2008 Acoustic Tracking Study

December 2011

By Mark T. Celedonia, Roger A. Tabor,
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Kenneth Ostrand

U.S. Fish and Wildlife Service
Washington Fish and Wildlife Office
Lacey, Washington

Washington State Department of Transportation

Funded by the Washington State Department of Transportation

MOVEMENT AND HABITAT USE OF CHINOOK SALMON SMOLTS, NORTHERN PIKEMINNOW, AND SMALLMOUTH BASS NEAR THE SR 520 BRIDGE

2008 ACOUSTIC TRACKING STUDY

by

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EXECUTIVE SUMMARY

This study continued and extended research performed in 2007 by the Washington State Department of Transportation (WSDOT) and the U.S. Fish and Wildlife Service (USFWS) to evaluate influence of the SR 520 bridge (the bridge) on behavior and habitat use of Chinook salmon *Oncorhynchus tshawytscha* smolts and piscivorous fish. Results obtained in 2007 suggested that the bridge was having some influence on migration, movement, and habitat use of Chinook salmon, and that at least one potential predator - smallmouth bass *Micropterus dolomieu* - often used the bridge as selected habitat. Further study was needed due to high variability in Chinook salmon behavior, uncertainty with regard to important causal factors, and low sample sizes of predators (namely northern pikeminnow *Ptychocheilus oregonensis*). Results will help guide design and construction of the new bridge to minimize impacts to Chinook salmon.

The primary objectives of the 2008 study were to: 1) increase the sample size of Chinook salmon used for evaluating migrational delay at the bridge; 2) evaluate interannual variability in fish behavior relative to the bridge; 3) collect additional ancillary data to help understand observed fish behavior patterns; 4) increase sample sizes of tagged northern pikeminnow and smallmouth bass; and, 5) explore potential predation consequences of the bridge on Chinook salmon. In order to meet these objectives, the 2008 study largely replicated the 2007 acoustic tracking study design. Components added for 2008 included: 1) Chinook salmon smoltification (gill Na^+, K^+ ATPase) sampling; 2) zooplankton sampling; 3) predator abundance and diet sampling.

Four groups of 27-53 tagged Chinook salmon smolts were released between June 12 and July 10, 2008, and 75-85% of tagged fish were tracked at the study site. Overarching patterns in Chinook salmon smolt behavior were similar to those observed in 2007. Behaviors were generally similar within release groups and varied considerably between release groups. The first three release groups primarily exhibited holding behaviors at and near the study site. The fourth release group represented a unique case: most fish (93%) actively migrated through the site in one of two schools.

As in 2007, fish response to the bridge was at least partially dependent upon whether fish were actively migrating or holding. Behaviors of actively migrating fish were similar in both years, although few independent observations were obtained in 2008 (n=11). Combining both years (n=57), 35% of actively migrating smolts showed minimal or no response to the bridge, 42% paralleled the bridge before passing underneath, and 23% paralleled the bridge and milled near the bridge before passing underneath. Median delay was 63 seconds (range 6 seconds to 19 minutes) for paralleling fish, and 22 minutes (range 3-46 minutes) for paralleling and milling fish.

The bridge appeared to attract some Chinook salmon that exhibited a holding behavior. Holding fish spent 2 hours to 11 days on and near the study site, and median 51% of this time was spent on-site. When on-site, fish most commonly selected for areas near the bridge (within 20 m of the bridge edge) and the condo on the south side of the site. Of secondary importance were areas directly beneath the bridge and areas with moderately dense to dense vegetation not

near the bridge. During the day, fish selected more offshore areas when near the bridge (5-7 m bottom depth) or condo (7-8 m bottom depth) than when they were not near either structure (2-5 m bottom depth). Similar observations were made in 2007. Data suggested that the bridge may provide a source of nearby cover and thus function as a corridor to deeper water where there is a better foraging base and occasionally more favorable water temperatures.

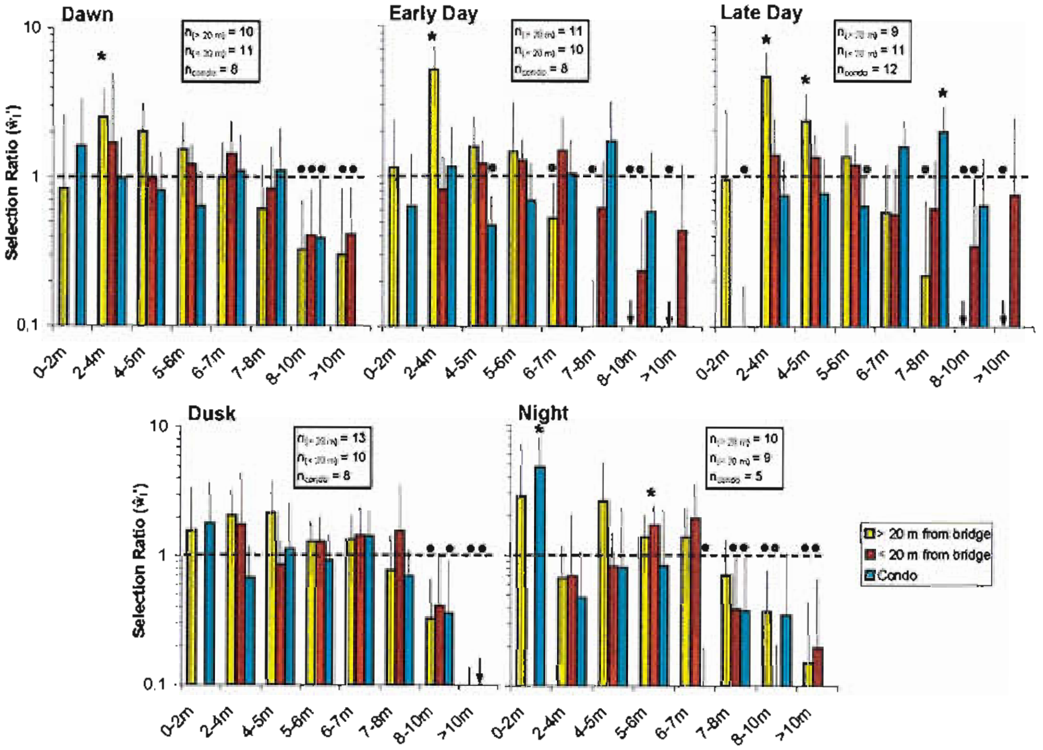
At night, Chinook salmon were attracted to areas where street lamps on the bridge cast light into the water. A reevaluation of 2007 data found that it occurred then also. Bridge lighting thus appears at least partially responsible for the nighttime selection of near bridge areas by Chinook salmon. Neither smallmouth bass nor northern pikeminnow appeared particularly attracted to the lights. Other studies suggest that predation rate may be higher in lighted areas even if predators on the whole do not select for these areas. Any potentially negative consequences to Chinook salmon might be minimized by reducing the intensity of light reaching the water surface.

We tagged 21 northern pikeminnow and 10 smallmouth bass at the study site, and obtained extensive tracking results on 8 northern pikeminnow and 7 smallmouth bass. Results for both species were similar in 2007 and 2008; therefore, data were combined to provide more robust analyses. This yielded sample sizes of 15 northern pikeminnow and 19 smallmouth bass (> 240 mm FL).

Northern pikeminnow were primarily concentrated at 4-6 m depth during all diel periods. Moderately dense vegetation, which occurs at 4-6 m depth, was the most commonly used habitat type. The small pier at the Madison Point Condominiums was used extensively. During each diel period, less than 50% of northern pikeminnow showed positive selection for the bridge or areas near the bridge. Overall, we did not document a strong affinity for the bridge. Instead, the bridge was generally used in proportion to its availability.

Smallmouth bass showed a strong affinity for overwater structures, including the bridge. Smallmouth bass were often closely associated with bridge columns. At dawn, they often moved into sparse vegetation and the offshore edge of vegetation. These movements are probably indicative of foraging activity. Additionally, they occasionally used dense and moderately dense vegetation, primarily at dusk and night. In both years, smallmouth bass were primarily concentrated in water 4-8 m deep during all diel periods.

We set a series of gill nets at five locations (the bridge, two sites north of the bridge, and two sites south of the bridge) on a weekly basis during the study period to determine the relative abundance and diet of northern pikeminnow and smallmouth bass. We collected a total of 135 northern pikeminnow and found no evidence that northern pikeminnow were congregated at the SR 520 bridge in comparison to four nearby sites. Additionally, there was no evidence to suggest that juvenile salmonids were preyed upon at a higher rate by northern pikeminnow near the bridge. Juvenile salmonids (Chinook salmon and unidentified salmonids) made up 35% of the overall diet of all sites combined. One important observation was the prevalence of river lamprey *Lampetra ayresi* in the diet of northern pikeminnow. Previous studies of northern pikeminnow in Lake Washington have rarely found river lamprey in their diet.



[redacted]

FIGURE 25. Diel bottom depth selection ($\hat{w}_i'$, selection ratio; log scale) of Chinook salmon released on June 12, 2008. Selection is for the entire water column and not for the position of the fish within the water column. Depth selection was determined for three distinct areas: 1) directly beneath bridge and within 20 m of the bridge edge; 2) > 20 m from bridge edge; and, 3) within 20 m of the edge of the Lakeshore West Condominiums. Error bars represent Bonferroni-adjusted 90% confidence intervals. Errors bars indicate if selection for (>1) or against (<1) a water column depth occurred. An asterisk (*) denotes selection for a depth and a circle (o) denotes selection against. Each area contained all depth categories, except minimum depth near bridge was 2-4 m and maximum depth near the condo was 8-10 m.

At night, areas where fish spent a greater proportion of time near the bridge coincided with locations of street lights on the bridge (Figure 28). This suggested that fish were attracted to areas with artificial lighting. Street lights appeared to attract fish in two general areas. The strongest area of attraction was directly adjacent to a street light on the same side of the bridge as the light. Most street lights had high concentrations of fish use near them (Figure 28). A weaker yet still apparent association was observed in 2007 (Figure 29). High concentration areas were on the same side of the bridge as the light. Areas on the opposite side of the bridge from the light usually did not show elevated fish usage. A weaker area of fish attraction appeared as a line of elevated fish usage running parallel with the bridge approximately 15-27 m from both the northern and southern edges. This appeared in both the June 12 and June 26 releases (Figure 28). This may be caused by lights on the opposite side of the bridge. The distance from the bridge where these lines occurred may correspond with the bridge shadow created by lights on

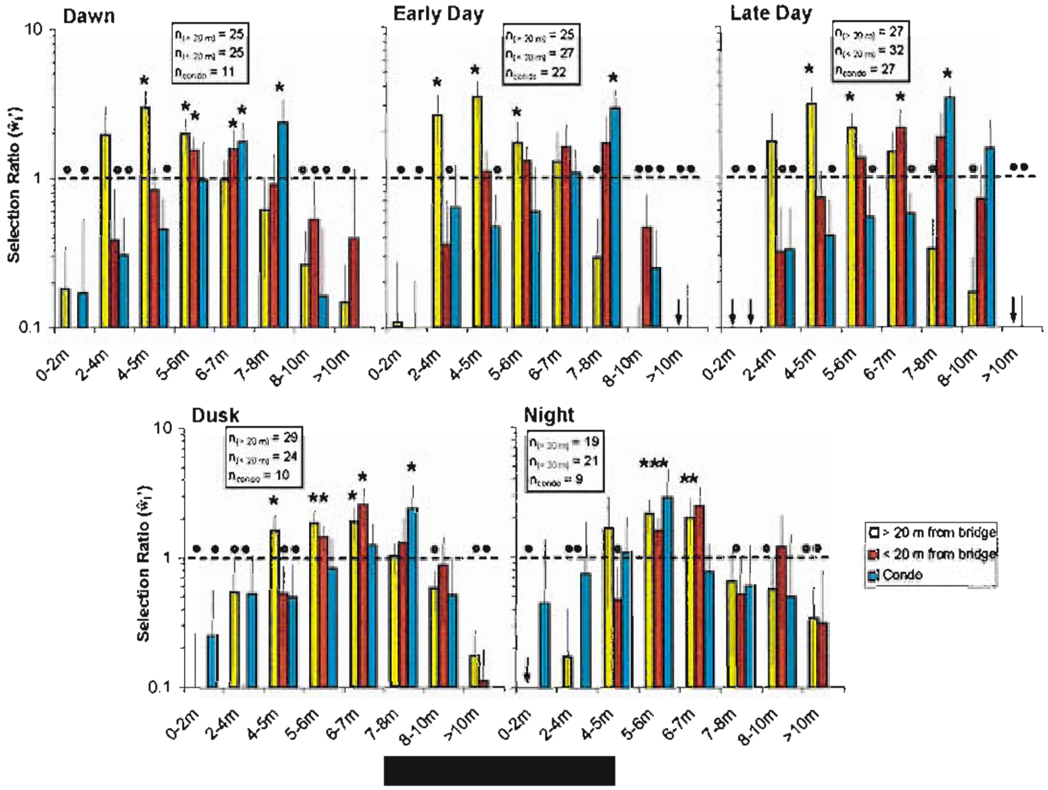


FIGURE 26. Diel bottom depth selection ($\hat{w}_i'$, selection ratio; log scale) of Chinook salmon released on June 26, 2008. Selection is for the entire water column and not for the position of the fish within the water column. Depth selection was determined for three distinct areas: 1) directly beneath bridge and within 20 m of the bridge edge; 2) > 20 m from bridge edge; and, 3) within 20 m of the edge of the Lakeshore West Condominiums. Error bars represent Bonferroni-adjusted 90% confidence intervals. Errors bars indicate if selection for (>1) or against (<1) a water column depth occurred. An asterisk (*) denotes selection for a depth and a circle (o) denotes selection against. Each area contained all depth categories, except minimum depth near bridge was 2-4 m and maximum depth near the condo was 8-10 m.

the opposite site of the bridge. That is, lights on the north side of the bridge were about 14.5 m from the southern edge of the bridge. Therefore, the shadow cast by the bridge would lie not only directly beneath the bridge, but would also be cast some distance from the bridge. We did not measure light levels in any of these areas.

Washington and the LWSC. Water clarity was generally lower in the LWSC than along the western shore of Lake Washington during the study period. Turbidity and light intensity can substantially alter juvenile fish habitat use patterns (Gregory 1993; Miner and Stein 1996; Abrahams and Kattenfeld 1997; Reebs 2002). In general, predation risk declines in turbid conditions allowing prey species to abandon anti-predator behaviors. For example, in clear water small bluegill remain in shallow areas when predators are present, but spend substantial proportions of time (> 80%) in deepwater habitat under turbid conditions (Miner and Stein 1996). Similarly, Gregory (1993) observed that juvenile Chinook salmon concentrated in one part of a test arena under clear conditions, but that fish distributed more evenly throughout the arena under turbid conditions. Higher water clarity in Lake Washington may force Chinook salmon closer to shore, and diminished clarity in the LWSC may allow fish to utilize open water areas during the day and take advantage of presumably better foraging opportunities as well as lower, more favorable water temperatures.

In both years of the SR 520 bridge studies, holding Chinook salmon smolts showed significant selection for and/or considerable use of the SR 520 bridge edge and the condo edge, and selected for deeper water when near these structures than when they were away from the structures. Chinook salmon and other salmonids have also been observed at high densities along outside edges of overwater structures in Puget Sound (Toft et al. 2007). In 2007, we hypothesized that during the day holding Chinook salmon have a positive selection for deep waters near the bridge, which may be related to access to preferred foraging locations and/or cooler, more favorable water temperatures. This hypothesis can also be extended to the condo. Specifically, the bridge, the condo, and other overwater structures extending into deeper littoral and pelagic zones may provide a source of cover or refuge from open water predators, thus allowing juvenile Chinook salmon to access areas that they would otherwise avoid.

The depths selected by smolts near the 520 bridge and the condo corresponded with elevated *Daphnia* abundance. Zooplankton typically avoid nearshore areas and are instead found in greatest abundance farther from shore (Wetzel 1975; Hall et al. 1979; Naud and Magnan 1988; Werner and Hall 1988; Tabor and Wurtsbaugh 1991; Diehl and Eklöv 1995). The width of the nearshore zone of low abundance depends on elevation of the horizon, position of the sun, and differential light levels nearshore compared with offshore (Wetzel 1975). In 2008, our zooplankton sampling at the SR 520 study site showed zooplankton mass substantially higher at areas where the bottom depth was ≥ 7 m than at areas with bottom depths [redacted], suggesting that the zone of low abundance extended from the shoreline to 5-7 m bottom depth. Chinook salmon smolts selected for depths within the zone of low zooplankton abundance when not near the bridge or condo during the day: daytime depth selection of Chinook salmon smolts was highest for 2-5 m and typically quite low for depths > 7 m when not near the bridge or condo. When at the bridge edge, however, daytime depth selections were typically highest for 5-7 m - the transitional area between low and high *Daphnia* abundance - and deeper depths consistently showed higher selection ratios when fish were near the bridge than when they were not (condo excluded). When at the condo edge, daytime depth selections were highest for 7-8 m depth.

birds, and other fishes (Woodhead 1966). Artificial lighting may allow juvenile Chinook salmon to feed actively at night. Commonly, small zooplanktivorous fishes feed heavily at dawn and dusk and do not feed much at night (Hall et al. 1979; Wurtsbaugh and Li 1985). However, they may feed throughout the night during full moon conditions (Gliwicz 1986). Artificial lighting generally reduces the abundance of *Daphnia* in surface waters (Moore et al. 2000); however, other components of the zooplankton community such as larval fishes (Gregory and Powles 1985) may be more abundant and vulnerable to predation by juvenile Chinook salmon.

Lighted areas may allow zooplanktivorous fishes an opportunity to forage throughout the night but their increased abundance may attract their predators (Nightingale et al. 2006). Even if piscivorous fishes are not attracted to lighted areas, the predation rate by piscivorous fishes that inhabit the lighted area may be dramatically higher than that in other areas (Tabor et al. 2004a). Research at petroleum platforms has shown that artificial lighting allows fish to feed on zooplankton that have concentrated in the light field; however, they may be more vulnerable to large piscivorous fishes (Stanley and Wilson 1997; Keenan et al. 2003). In Lake Tanganyika in Africa, fishermen use lights to attract zooplanktivorous fishes, which in turn attract large piscivorous fishes (Coulter 1990). In Lake Washington, we have observed great blue herons and western grebes feeding around lights but no information is available on their nighttime diet. Piscivorous fishes may also be attracted to lighted areas due to an aggregation of small fishes like juvenile Chinook salmon. Cutthroat trout appear to feed heavily at night in Lake Washington because of reflected artificial lighting from surrounding urbanized areas (Mazur and Beauchamp 2006). Obviously artificial lighting on the bridge is important for safety concerns; however, lighting should be designed to minimize the amount of light that reaches the water surface.

Gill ATPase sampling suggested that the physiological smoltification process was dampened or muted in our study fish. This may explain the predominance of holding behaviors observed: lacking sufficient physiological cues, fish may be more prone to holding than actively migrating seaward. However, ATPase activity may not be a good predicator of predisposal to migrate seaward. Seaward movement can occur without elevated ATPase activity (Ewing et al. 1980a; Tiffan et al. 2000), and, conversely, slow moving fish can have high levels of ATPase activity (Tiffan et al. 2000). Nonetheless, the general suppression of ATPase activity in our study fish was curious because ATPase should peak at some point during the outmigration season. ATPase suppression can be associated with adverse or stressful conditions, such as elevated water temperatures (Marine and Cech 2004), low levels of food abundance (Ewing et al. 1980b), high levels of suspended sediment (Shrimpton et al. 2007), and high rearing densities (Strange et al. 1978). Shrimpton et al. (1994) found ATPase activity suppressed in hatchery-reared coho salmon and speculated that stressful hatchery rearing conditions may have been to blame. Release from the hatchery environment can stimulate smoltification (McCormick et al. 2003) assuming release occurs within the environmental smolt window.

Northern pikeminnow

Results of 2008 northern pikeminnow tracking appeared to be similar to 2007 results. Both depth selection and habitat use of northern pikeminnow appeared to be similar between years. In both years they were primarily concentrated in 4-6 m depth interval during all diel periods. At

Although northern pikeminnow did not strongly use the bridge structure, several used the Madison Point Condominium pier. Within our study area, there were four overwater structures from a small pier (Edgewater Apartments) in shallow water to the large bridge structure. The Edgewater Apartment pier was probably in too shallow of water to attract northern pikeminnow. The Madison Point Condominium pier is a narrow pier but extends out into the water depths (4-5 m) preferred by northern pikeminnow. It is unclear why they would prefer this small pier over the two larger structures (Lakeshore West Condominiums and SR 520 bridge). The Madison Point pier may enable pikeminnow to observe approaching prey (i.e., juvenile Chinook salmon) from a variety of directions and still provide overwater cover from their predators such as piscivorous birds. Also, vegetation under the pier may be denser and more preferred by northern pikeminnow. Perhaps this site attracts northern pikeminnow because of some other type of forage. Northern pikeminnow often consume plant material and dead animal remains (Tabor et al. 1993; Petersen et al. 1994; Shively et al. 1996; Tabor et al. 2004b). If condominium residents regularly discard fish or shellfish remains at this pier or another source of plant or animal material is present, northern pikeminnow may congregate here.

Substrate selection by northern pikeminow was markedly different between day and night. Differences may reflect their foraging strategies and prey availability. Northern pikeminnow are opportunistic predators with a wide range of prey types. During the day they may attempt to prey on diurnally-active prey (e.g., juvenile salmonids, threespine stickleback, and other littoral fishes) near macrophyte beds where silt substrates predominate. At night, they may attempt to prey on nocturnally-active prey such as sculpin and crayfish which are often more abundant in areas with larger substrates (Mueller 2002; Tabor et al. 1998).

Northern pikeminnow showed a slight attraction to street lights on the SR 520 bridge. Because juvenile Chinook salmon congregate near the lights, pikeminnow may in turn be attracted to the increased density of potential prey. Northern pikeminnow actually appear to prey more effectively on juvenile salmonids at extremely low light levels than at high light levels (Petersen and Gadomski 1994). However, the increased density of juvenile salmonids could result in higher predation rates by northern pikeminnow. Similarly, sockeye salmon fry are more vulnerable to sculpin predation at street lights because of the increase in density of fry even though sculpin are more effective at preying on fry at extremely low light levels (Tabor et al. 2004a).

Smallmouth bass

In 2008, we were able to track an additional eight large smallmouth bass. In general, results of these fish appeared to be similar to 2007 smallmouth bass tracking results. Combined, they showed a strong affinity for overwater structures. In both years, they were primarily concentrated in 4-8 m depth interval during all diel periods. At dawn, they often moved into sparse vegetation and the offshore edge of vegetation. Additionally, they occasionally used dense and moderately-dense vegetation, primarily at dusk and at night.

Unlike northern pikeminnow, we were able to effectively track most tagged smallmouth bass. Smallmouth bass usually have a defined home range (Kraai et al. 1991; Ridgway and Shuter 1996; Hodgson et al. 1998; Cole and Moring 1997) and may not be as mobile as northern

At dawn and dusk, some smallmouth bass made forays along the shore or into deeper waters. These movements may have been movements to actively search for prey. Piscivores, such as smallmouth bass, are well adapted to feed in dim light and are often more active during crepuscular periods because they have the greatest advantage over prey species. Results of two smallmouth bass implanted with depth tags at the SR 520 bridge site showed crepuscular activity patterns (Celedonia et al. 2008a). In the Columbia River, smallmouth bass show a crepuscular feeding pattern, but it is not pronounced (Vigg et al. 1991). An extended period of morning feeding has also been observed. Emery (1973) also found peak feeding was at dawn and dusk and they fed opportunistically during the daytime. In the Snake River, smallmouth bass were most active in the early morning (Munther 1970). In laboratory experiments, Reynolds and Casterlin (1976) also found smallmouth bass displayed a crepuscular activity pattern.

Most smallmouth bass did not appear to be active at night. Other studies have also found they are inactive at night and rest on the bottom near some type of cover such as large woody debris (Munther 1970; Emery 1973). During our snorkeling in Lake Washington and the LWSC, we often encountered smallmouth bass that were motionless and appeared to be resting on the bottom (R. Tabor, unpublished data). Our tagged smallmouth bass were mostly inactive at night, however there were some exceptions. Nighttime activity may be related to artificial lighting or moonlight. Some of the night-active smallmouth bass in Portage Bay and at a site near the Seattle Tennis Club in Lake Washington were near artificial lighting (Celedonia et al. 2008b). In laboratory experiments, Reynolds and Casterlin (1976) found smallmouth bass were often active at night. Largemouth bass, which have similar crepuscular activity patterns (Reynolds and Casterlin 1976), can feed at night especially under full moon light conditions (McMahon and Holanov 1995).

Restricted movement at night by smallmouth bass is most likely indicative of resting behavior; whereas restricted movement throughout the day may be related to either resting behavior, typical behavior of an ambush predator, or related to spawning activity. During the spring, male smallmouth bass often are guarding a nest and have a small home range during this period (Savitz et al. 1993) and foraging activity is presumably reduced Of the adult smallmouth bass we tagged at the study site, all appeared to move over a relatively large area during the day and did not appear to be nest guarding. Spawning activity occurs in the spring and our tracking may have been conducted after spawning season was over. Also, adult smallmouth bass collected at the study site were collected with gill nets, which selects for more active fish and probably not for nest guarding males.

Relative abundance and diet of piscivorous fishes at the SR 520 bridge site

We found no evidence that northern pikeminnow were congregated at the SR 520 bridge in comparison to four other nearby sites. Northern pikeminnow have been shown to congregate around dams (Beamesderfer and Reiman 1991) and at the outlets of hatchery facilities (Collis et al. 1995); however, this is likely due to prey availability and not the structure itself. The use of overwater structures by northern pikeminnow in lakes has not been well documented. Acoustic tracking of northern pikeminnow at SR 520 bridge indicated they occasionally use overwater structures; however, they most frequently used a small pier near shore instead of the SR 520 bridge. Exactly why they preferred this small structure is unclear.

The diet composition of northern pikeminnow at the SR 520 bridge site consisted of juvenile salmonids, river lamprey, threespine stickleback, longfin smelt, and crayfish. They did not appear to be feeding on juvenile salmonids to a larger degree than at other sites. Northern pikeminnow are considered opportunity predators that will eat a wide variety of food including plant material (Tabor et al. 1993; Shively et al. 1996) and dead fish (Petersen et al. 1994) and will quickly switch to other prey items as it becomes abundant (Collis et al. 1995; Shively et al. 1996). The diet composition of northern pikeminnow at the SR 520 bridge is probably a reflection of prey abundance and availability. There was no evidence to support the hypothesis that juvenile salmonids are more vulnerable to northern pikeminnow predation due the bridge structure. Similarly, Ward et al. (1994) found no difference in the frequency of occurrence of juvenile salmonids in northern pikeminnow diets between developed and undeveloped areas of the lower Willamette River.

Juvenile salmonids made up a substantial portion of the diet of northern pikeminnow at all of our five sites in the central-west part of the lake. All of the identifiable salmonids were Chinook salmon. Previous studies of northern pikeminnow in Lake Washington have found Chinook salmon is a rare prey item in their diet (Olney 1975; Brocksmith 1999; Beauchamp et al. 2007a). The others studies usually had small sample sizes in June and their sampling was spread out over the entire lake and thus they could have missed this predation event. If predation of Chinook salmon is strongly concentrated in the central-west part of the lake and little sampling occurred in this area, the overall predation levels on juvenile salmonids may be underestimated by these other studies.

One important finding of our diet analysis was the prevalence of river lamprey in the diet of northern pikeminnow. In previous sampling of northern pikeminnow in Lake Washington by Olney (1975), Brocksmith (1999), Beauchamp et al. (2004) and Beauchamp et al. (2007a), river lamprey was not mentioned as an important prey item. Olney (1975) only states that a few Pacific lamprey *Entosphenus tridentatus* were consumed and does not mention river lamprey. Brocksmith (1999) found lamprey in 3 of 124 gut samples but does not mention which species was present. Beauchamp et al. (2004) and Beauchamp et al. (2007a) did not mention lamprey; instead they found northern pikeminnow preyed on longfin smelt, threespine stickleback, salmonids, yellow perch, and sculpin. These other studies conducted sampling throughout the year and across the entire lake. In our study, we intensively sampled one area of the lake over a short time period. River lamprey may congregate in this area to prey on juvenile salmonids and are in turn preyed on by northern pikeminnow. Because river lamprey was only observed in northern pikeminnow, river lamprey may be particularly vulnerable to piscivorous fishes at night. Northern pikeminnow appear to be able to forage under lower light conditions than the other species (Petersen and Gadomski 1994).

The ecology and abundance of river lamprey in Lake Washington is poorly understood. Typically, river lamprey are anadromous, spending about 5 years in freshwater as ammocoetes and then migrating to estuarine and marine environments to feed on fish and then return to freshwater as adults to spawn and die (McPhail 2007). In Lake Washington, they appear to be able to complete their life history in freshwater. Other landlocked populations have been documented in British Columbia lakes (McPhail 2007). Currently river lamprey is listed as a support columns; and, 5) decrease the overall number of support columns. Two options (Options A and L) would raise portions of the bridge higher than current elevations. It is unclear how the third design option (Option K) would affect bridge height in the study site area.

Based on our acoustic tracking studies and other studies of migrating Chinook salmon (Kemp 2005; Tabor et al. 2006; Celedonia et al. 2008b; R. Tabor, USFWS, unpublished data), actively migrating Chinook salmon smolts attempt to avoid passing beneath overwater structures. Upon encountering structures such as docks and piers, fish generally move into deeper water and either pass beneath the structure or swim around the perimeter of the structure. Once beyond the structure, fish generally move back into shallower water. Some factors that appear to influence behaviors are structure width, height of structure above the water surface, light conditions beneath the structure, degree of contrast at the light/shadow edge, type and size of adjacent structures, and macrophyte distribution. These are anecdotal observations, however, and more rigorous study is needed to better understand how size, shape, and other parameters of overwater structures influence salmonid behavior. Elevating the bridge above the surface of the water may allow more ambient light beneath the bridge and may thus diminish any influence the bridge shadow has on migrating Chinook salmon. However, a wider bridge may counteract this. It is uncertain how these two factors (bridge width and height of bridge above the surface) would interact to influence behaviors of actively migrating Chinook salmon behaviors.

Given the complexity and uncertainty of factors influencing holding Chinook salmon's use of the bridge, we cannot infer with much certainty the influence of the new bridge design on holding Chinook salmon. Specific features that may influence attraction of Chinook salmon smolts to the current bridge during the day may include one or more of the following: 1) shading under and near the bridge; 2) structural complexity provided by the bridge (i.e., the bridge columns); and, 3) the presence of macrophytes near and/or under the bridge. Elevating the new bridge may diminish the bridge shadow's darkness and the degree of contrast at the light-dark edge, and may thus diminish the attractiveness of shadow as cover as well as allow more dense growth of macrophytes beneath the bridge. The greater width of the new bridge may, however, offset these effects as a wider bridge would allow less ambient light underneath thereby darkening the shadow. Tagged Chinook salmon smolts usually selected for the bridge edge. Thus, a wider bridge would have no influence on these fish. However, we did observe occasional selection for a small area directly beneath the bridge where the bridge was elevated above the surface of the water. A wider bridge that is elevated throughout the study area may thus increase under-bridge area used by Chinook salmon. Fewer and more widely spaced bridge columns may diminish any role the columns serve in providing cover to holding Chinook salmon smolts. The new bridge alignment moves the new bridge slightly north of the current location which will change the proportion of water column depths spanned. For example, the current bridge spans a large proportion of 4-6 m deep water relative to other depths. The proposed bridge alignment will diminish this proportion and will increase the proportion spanning 6-8 m depth. When Chinook salmon were near the bridge, depths of 6-8 m had the highest selection ratios in 2007 and in the later 2008 releases. The proposed bridge would increase the availability of near bridge habitat at these depths. Although it is difficult at best to predict how these changes in bridge design and alignment will interact to influence holding Chinook salmon during the day, we believe that patterns in holding Chinook salmon habitat use near and under the bridge will most likely either be similar to those observed at the current bridge or that selection

U.S. Fish and Wildlife Service

Movement and Habitat Use of Chinook Salmon Smolts in the Lake Washington Ship Canal

2007-2008 Acoustic Tracking Studies

May 2011 *By Mark T. Celedonia, Zhuozhuo Li, Scott T. Sanders, Roger A. Tabor, Steve Damm, Daniel W. Lantz and Benjamin E. Price*

U.S. Fish & Wildlife Service
Washington Fish & Wildlife Office
Lacey, Washington

Funded by Seattle Public Utilities (City of Seattle), U.S. Army Corps of Engineers, and King Conservation District

More than fifty percent of the tagged fish also used south Lake Union, often for more than 24 hours.

In general, tagged Chinook salmon in the LWSC distributed broadly throughout areas with bottom depths ≥ 4 m, although shallower areas were used on occasion. Seasonal and inter-annual shifts in spatial distribution appeared to be related to diel period, water temperature, and water clarity. Overwater structures may have also influenced spatial distribution in some cases. We found little evidence of strong shoreline orientation in the LWSC, although extensive shoreline development throughout the LWSC may have obscured the natural tendencies of the fish. This contrasts with findings in Lake Washington where fish remain relatively close to shore in areas with bottom depths of 1-6 m during the day. Lower abundance of some Chinook salmon predator species in the LWSC may contribute to the shift in horizontal spatial distribution of Chinook salmon here.

Tagged Chinook salmon smolts often used the edges of overwater and in-water structures where water depth was greater than 6 m. This was observed primarily at the University Bridge and South Lake Union sites. In general, Chinook salmon milled throughout a zone that started at the structure edge and extended outward 20 m. These findings were similar to those observed in studies at the State Route (SR) 520 bridge and a nearby overwater condo in Lake Washington (Celedonia et al. 2008a; Celedonia et al. 2009). It is possible juvenile Chinook salmon use structure edges to be near cover. This behavior has important management implications in that use of these areas puts Chinook salmon in close contact with known smallmouth bass *Micropterus dolomieui* habitat. However, the extent to which these behaviors result in increased predation requires further study. Nonetheless, resource managers and policy makers should consider this in the design, modification, and permitting of over- and in-water structures in the LWSC where bottom depths are 6 m and deeper.

At the University Bridge site, fish migration behavior was strongly influenced by the University Bridge. Many tagged fish responded by milling along the eastern edge of the bridge and in nearby areas prior to passing beneath the bridge. Similar behaviors were observed at the SR 520 bridge (Celedonia et al. 2008a; Celedonia et al. 2009). Few if any fish responded to the presence of the I-5 bridge, presumably because it is much higher than the University Bridge and has no in-water structure. The milling behaviors at the University Bridge put fish in prolonged contact with edges of in-water structures that were frequented by smallmouth bass (Tabor et al. 2010). This may increase predation on Chinook salmon smolts. In one cases, data showed predation upon a tagged Chinook salmon in this area.

At night, tagged Chinook salmon frequented areas with artificial lighting and spent prolonged periods in these areas. Similar observations were made along the SR 520 bridge (Celedonia et al. 2009). Relatively dim light levels (1.6-2.0 lx) attracted tagged Chinook salmon. Other studies suggest that predation rates by piscivorous fishes may be higher in lighted areas even if predators on the whole do not select for these areas. Any potentially negative consequences to Chinook salmon might be minimized by reducing the intensity of light reaching the water surface.

Influence of artificial lights on nighttime movement and habitat use

We observed influences of artificial lighting on nighttime movement and habitat use of tagged Chinook salmon at three study sites: University Bridge, South Lake Union, and the Ballard Locks. This study was not intended to provide a thorough evaluation of artificial lighting. However, upon observing in our tracking data indicators that artificial lighting may have influenced tagged Chinook salmon habitat use, we conducted follow-up site visits to provide at least a minimal level of verification. We identified sources of artificial lighting and/or measured light levels near the water surface. These light surveys were not intended to be rigorous: we did not attempt to locate and measure every source of artificial light. Light intensity levels were measured at the water surface with an Extech Instruments light meter to the nearest 0.1 lx.

At the Ballard Locks, areas of the site that were intensively used by tagged Chinook salmon at night were often associated with artificial light (Figures 44 and 45). These included areas at the large lock approach/entrance along the north pier wall, the area immediately to the north of this pier wall, at the small lock approach/entrance along the north pier wall, as well as two other localized areas (Figure 44). Light levels in these areas were generally greater than 10 lx, although one point was measured as low as 0.3 lx (Figure 45). Ambient light levels measured at 11 points throughout the site were generally 0.0 lx (7 points), and was as high as 0.2 lx (3 points). Interestingly, some areas with elevated light levels were not associated with greater use by tagged Chinook salmon. For example, light levels along a line running parallel to and 15 m from the small lock pier wall were generally 3-10 lx (Figure 45). However, we did not observe any elevated use by tagged Chinook salmon in this area. This may have been due to the proximity of this area to higher light levels closer to the pier wall.

At the South Lake Union site, we observed several instances of tagged Chinook salmon spending prolonged periods near known artificial lights at night (Figure 46). Light levels were measured at only two known sources, and were 2.3-6.0 lx about 1 m above the surface of the water. Ambient light levels measured along the shoreline were 0.5-0.7 lx. Artificial light sources were on structures in areas where the water was relatively deep (> 6 m). There were numerous other areas near overwater structures in deep water where some tagged Chinook salmon spent prolonged periods at night. It is uncertain if there was artificial lighting in these areas. A more rigorous light survey is needed to verify all artificial lights sources and the light level at these sources.

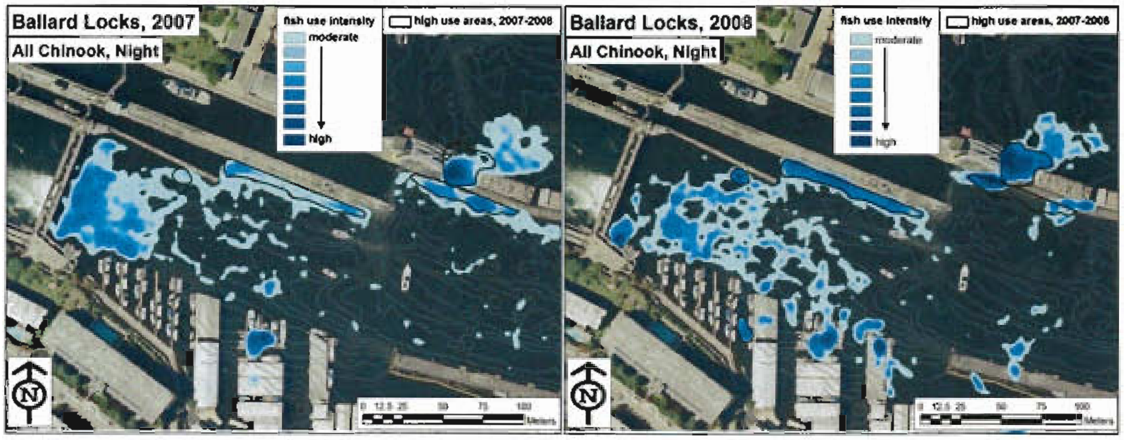


FIGURE 44. Areas of moderate to high intensity use by tagged Chinook salmon at night at the Ballard Locks, June-July, 2007 (left) and 2008 (right). Areas of higher use that were associated with artificial lighting are outlined in black. See Figure 45 for light level measurements in these areas.

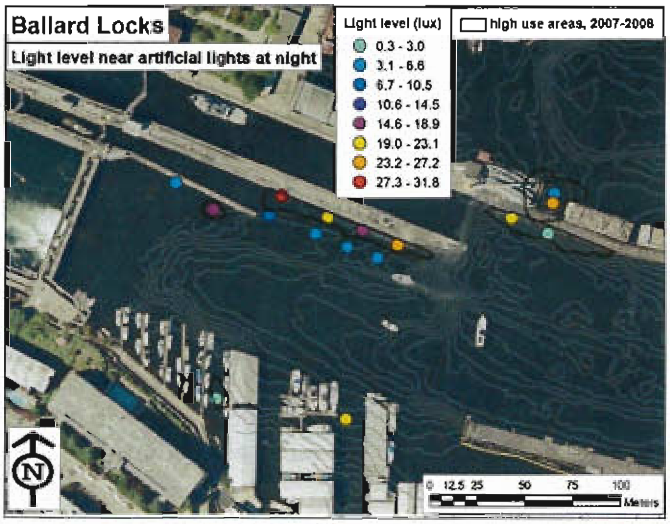


FIGURE 45. Light level readings (lx) in selected areas of the Ballard Locks study site. Selected areas used more intensively by tagged Chinook salmon are outlined in black. See Figure 38 for distribution of tagged Chinook salmon usage intensity. Ambient light level was generally 0.0 lx, although in some areas was as high as 0.2 lx.

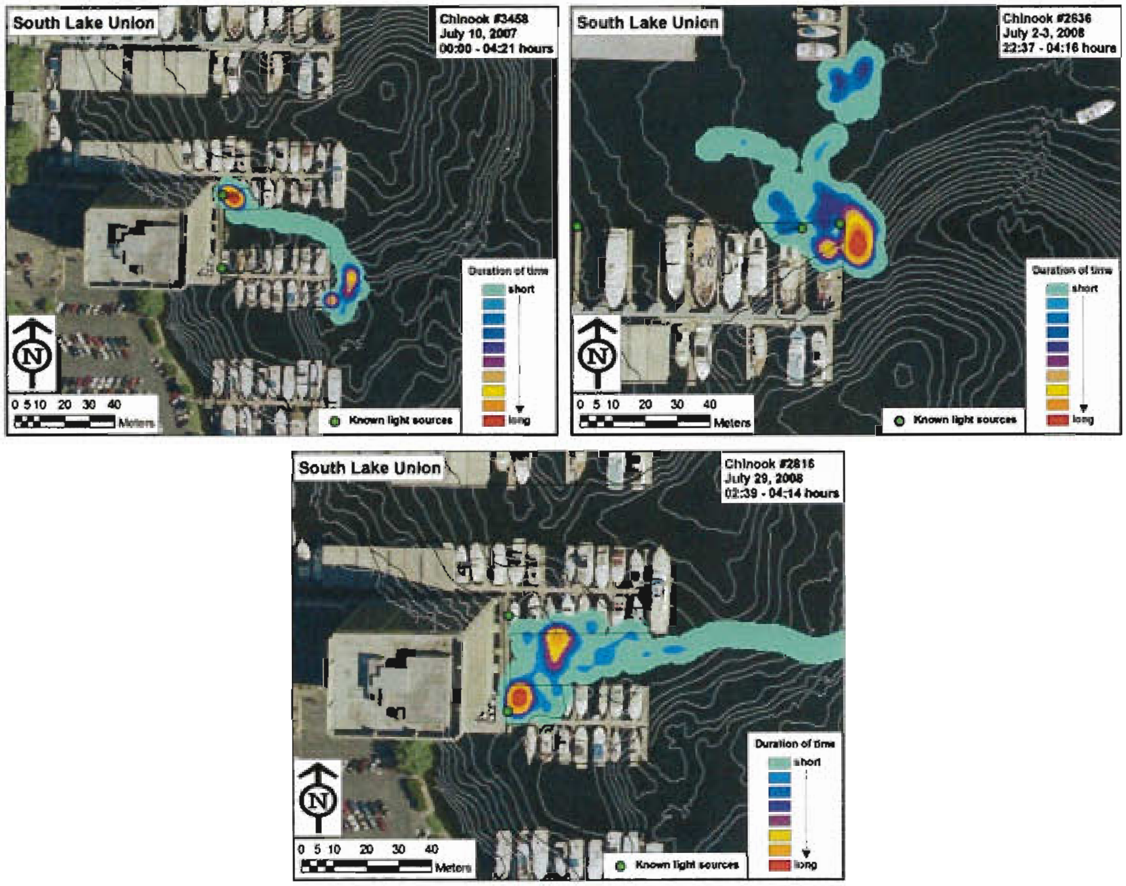


FIGURE 46. Three examples of tagged Chinook salmon use of artificially lit areas at night at the South Lake Union site: Chinook #3458 (upper left), #2636 (upper right), and #2816 (bottom). Sources of known artificial light are shown. Other sources of artificial light may have also been present. Light levels at the two sources in the upper left and bottom images measured about 1 m above the water surface were 6.0 lx (north source) and 2.3 lx (south source). Ambient levels measured along the shoreline were 0.5-0.7 lx. Light levels at the sources in the upper right image were not measured.

At the University Bridge site, there was a notable response of tagged Chinook salmon to artificial lighting on the I-5 bridge deck and the light/shadow edge this lighting created in the water (Figures 47, 48, and 49). Light levels were 1.6-2.0 lx (measured at 3 points) within 1 m of the edge on the light side, and were 0.2-0.5 lx (measured at 6 points) in the shadow area between the lines. Many fish milled along the light/shadow edge on the eastern side of the I-5 bridge and milled between this edge and the University Bridge. These areas were highlighted on both spatial frequency distribution maps (suggesting that many fish spent time milling in this area) and density plots (suggesting that many fish spent prolonged periods here relative to other parts of the site) (Figure 47). Movement pathways of many fish also showed extensive north-south milling along this edge (e.g., Figure 49). Many of these fish also milled in the area between the edge and the University Bridge, often interspersing periods of milling along the light/shadow edge with periods milling between the bridges. There was a marked reduction in activity in the shadow zone beneath and adjacent to the I-5 bridge. This was evident on both density plots and spatial distribution maps (Figure 47). Tracks of tagged fish suggested that many fish either did not enter the shadow area or moved quickly through without spending much time. Movement pathways of some fish suggested that this light/shadow edge influenced their movement. For example, when Chinook salmon #3168 encountered the western light/shadow edge from the east, it twice changed its pathway and moved away from the edge before crossing the edge on its third encounter (Figure 49).

Also at the University Bridge site, we observed areas of high tagged fish use in the mid-channel area adjacent to the University Bridge support structures (Figure 47). These areas were associated with artificial lighting beneath the bridge attached to the support structures (Figures 47 and 50), presumably as a boating navigational aid. We did not measure light levels here.

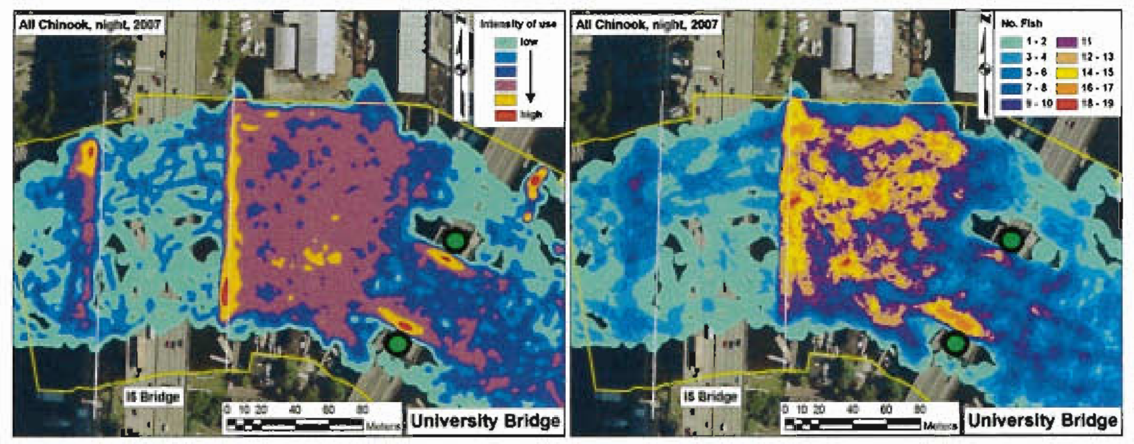


FIGURE 47. Distribution of tagged Chinook salmon at night at the University Bridge study site, June-July, 2007. Density plot (left) shows intensity of fish use for all tracked fish (weighted by time), and spatial frequency distribution (right) shows number of fish tracked by area. The white lines parallel to the I-5 bridge show the location of the light/shadow edge created by artificial lighting on the I-5 bridge deck (see Figure 48). Light levels were 1.6-2.0 lx (measured at 3 points) within 1 m of this line on the light side, and were 0.2-0.5 lx (measured at 6 points) in the shadow area between the lines. Green circles show approximate locations of lights beneath the University Bridge (see Figure 50).

FIGURE 48. Artificial lighting on the I-5 bridge deck spanning the Lake Washington Ship Canal (looking north).

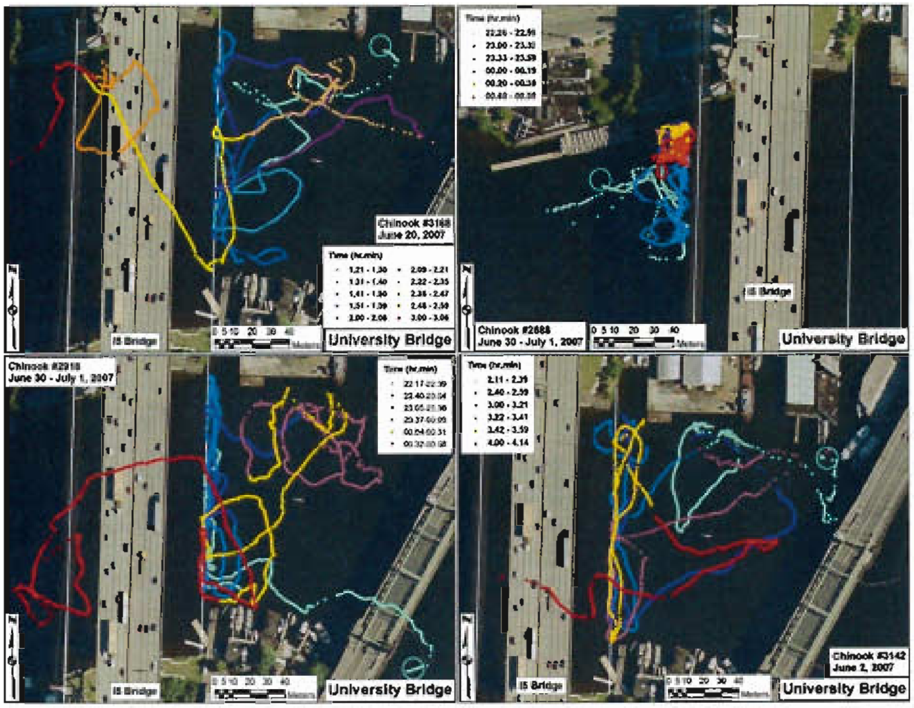


FIGURE 49. Four examples of tagged Chinook salmon behavior near the light/shadow edge created by artificial lighting on the I-5 bridge deck: Chinook #3168 (upper left), #2688 (upper right), #2918 (bottom left), and #3142 (bottom right). The white lines parallel to the I-5 bridge indicate the light/shadow edge created by artificial lighting on the I-5 bridge deck. Light levels were 1.6-2.0 lx (measured at 3 points) within 1 m of this line on the light side, and were 0.2-0.5 lx (measured at 6 points) in the shadow area between the lines. The color scale indicates the time sequence of each track. The blue circle shows the starting point of the fish in each image.

FIGURE 50. Artificial lighting under the University Bridge. Lighting is directed down onto the water surface. Light on the north bridge support structure is pictured. Light on the south support structure is similar. These lights correspond with green circles in Figure 47.

Submission #2
Subject: Sundial Bridge - CDFG - GGSA

✓Ecosystem Restoration Program Conservation Strategy for Restoration of the Sacramento-San Joaquin Delta, Sacramento Valley and San Joaquin Valley Regions, CDFW, USFWS and NMFS, May 2014
https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=87585

✓Potential Effects of Artificial Light fomr the Sundial Bridge on Juvenile Chinook Salmon Migratory Behavior and Predation by Predatory Fishes in the Sacramento River, Redding, Shasta County By Andrew Jensen, August 6, 2012
URL = none at this time

✓State wildlife officials say Sundial Bridge lighting may be hurting salmon, by Damon Arthur, Feb 21, 2013 Record Searchlight redding.com
URL = http://www.redding.com/news/state-wildlife-officials-say-sundial-bridge-may

✓Lights on the river kill salmon, by John McManus, May 5, 2013 The Record Searchlight Redding Ca. redding.com
URL = http://www.redding.com/opinion/john-mcmanus-lights-on-the-river-kill-salmon

✓Golden Gate Salmon Association, Golden Gate Salmon Rebuilding Plan, Project B.6 Eliminate or Reduce Lighting at In-River Structures, Dec 2013
URL = http://www.ggsalmon.org/salmonplan/GGSA_Salmon_Plan.pdf

Ecosystem Restoration Program

Conservation Strategy for Restoration
of the
Sacramento-San Joaquin Delta, Sacramento Valley and San Joaquin Valley Regions

May 2014

Additionally, assessment of the impacts from light sources along the Sacramento River which lead to increased predation on juvenile salmonids is also needed. A notable example is the Sundial Bridge in Redding, which uses numerous floodlights that illuminate the Sacramento River all night, year round. Approximately 80 percent of the winter-run Chinook salmon population in the state spawn upstream of the bridge and the out-migrating juveniles must pass through the lighted portion of the river below the bridge and face predators. Studies in Washington State have found lighted portions of streams have significantly higher predation rates on juvenile fish. Downstream of the Sundial Bridge, there are several other light sources ranging from highway bridges to lighted water intake structures. These should all be evaluated and recommendations should be developed to fix identified problems.

Conservation actions will include coordination of protection, enhancement, and restoration of occupied and historic Central Valley salmon habitats with other federal, state, and regional programs. These efforts will include implementation of measures in the restoration plan for the AFRP, the Central Valley Salmon and Steelhead Recovery Plan and applicable CDFW management measures; appropriate operation of hatcheries such that natural populations are not threatened; management of fish passage to reduce predation on juveniles and increase their survival; improved export flows to improve conditions for upstream migration of adults; and operation of physical barriers consistent with achieving recovery goals.

Steelhead. Steelhead (*O. mykiss*) depend on essentially all habitats of the Sacramento River system: the main channel for migrating between the ocean and upstream spawning and rearing areas and the tributaries for spawning and rearing. The construction of low elevation dams on major tributaries of the Sacramento River has denied steelhead access to most of their historical spawning and rearing habitats in upstream areas. See full write-up in Delta species section.

Conservation actions will include coordination of protection, enhancement, and restoration of occupied and historic Central Valley steelhead habitats with other federal, state, and regional programs; implementation of measures in the restoration plan for the AFRP, the Central Valley Salmon and Steelhead Recovery Plan and applicable CDFW management measures; and the minimization of flow fluctuations to reduce or avoid stranding of juveniles.

Green and White Sturgeon. Sturgeons are native anadromous fish that inhabit both salt water and freshwater and tolerate a wide range of salinity concentrations. Spawning occurs in larger rivers upstream of the Delta. White sturgeon rear in the Sacramento-San Joaquin estuary and spawn in the Sacramento and San Joaquin rivers and their major tributaries. Green sturgeon (*Acipenser medirostris*) are an at-risk species native to the Sacramento River, yet little is known about the habitat needs of this species and its response to restoration. The ERP funded research to conduct telemetric, physiological, reproductive, and genetic studies to provide State and Federal agencies such as the ERP Implementing Agencies with information on the size of the population and its critical habitat within the Sacramento-San Joaquin watershed. This

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Potential Effects of Artificial Light from the Sundial Bridge on Juvenile Chinook Salmon Migratory Behavior and Predation by Predatory Fishes in the Sacramento River, Redding, Shasta County

By:
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August 6, 2012

This white paper is being prepared in response to the concern within the Department regarding the artificial night lighting on the Sundial Bridge (Bridge), and the potential effects the lighting may have on juvenile Chinook salmon (*Oncorhynchus tshawytscha*) migration and rates of predation. The purpose of this white paper is to provide a brief overview of the key aspects of the Bridge, outline some of the potential effects artificial night lighting may have on biological organisms (with an emphasis on salmonids), highlight some of the research that has been performed to assess impacts of artificial light, provide some avoidance and minimization measures, highlight the need for future research, and to provide a starting point for future discussions between the resource agencies and the City of Redding.

The Bridge, designed by renowned Spanish architect Santiago Calatrava, is a cantilever spar cable-stayed bridge for bicycle and pedestrian access that spans the Sacramento River in Redding, Shasta County, California. The Bridge is suspended by steel cables from a single 217-foot tall pylon and spans more than 700 feet across the river without touching the water, which was a design criterion to help protect the salmon spawning areas in the vicinity of the Bridge. The Bridge is 23 feet wide and weighs more than three million pounds (Saflex 2009). The construction on the Bridge began in 1999 was completed in 2004, officially opening on July 4, 2004.

Calatrava's design called for a pedestrian walkway of nonskid glass that at night would be illuminated from underneath by 210 lights, creating an ethereal effect (Via 2004). At night, the laminated glass deck is illuminated from underneath with 1/3 of the lights pointing downstream, 1/3 facing upstream, and the remaining 1/3 facing up towards the Bridge deck (Saflex 2009). The result is that from dusk to dawn the Bridge and the Sacramento River in the vicinity of the Bridge are illuminated (Attachment 1). While the Bridge is undoubtedly an architectural masterpiece, a local icon, a major tourist attraction, and has been designed to be environmentally sensitive in many ways, the night time lighting of the Bridge and Sacramento River may be causing detrimental effects to salmon populations that spawn and rear upstream and in the vicinity of the Bridge.

Natural light plays a fundamental role in the biology of organisms. It is important to consider whether artificial illumination outside of the normal circadian cycle affects organisms (Rondorf et al. 2010). Artificial light has the potential to disrupt the biology of many species (Royal Commission 2009). Rich and Longcore (2006) concluded that artificial night lighting may alter the spatial distribution, diel movements, demography, and overwintering success of some freshwater organisms. Light is one of the most potent agents interacting with our biological systems. Biological responses to light include phototropism and stimulation of hormone production, including the fine tuning of cyclical changes. The intensity, spectral quality, duration and periodicity of exposure to light affect the biochemistry, physiology, and behavior of organisms. Wherever artificial light floods into the natural world there is a potential for some aspect of life and its biological rhythms such as migration, reproduction, and feeding, to be affected (Royal Commission 2009). Artificial lighting that is present on over-water structures may disorient migrating juvenile salmonids, compromise their ability to avoid nocturnal predators, and affect the photosynthesis of aquatic vegetation (Rondorf et al. 2010).

The issue of potential biological impacts from artificial lighting of the Bridge was acknowledged and addressed during the environmental review and approval process (City of Redding 2000). Pursuant to the California Environmental Quality Act (CEQA) and the CEQA Guidelines, mitigation measures were identified and included in the *Mitigation Monitoring Program for the Pedestrian Bridge at Turtle Bay, Redding, California, Addendum to the Mitigated Negative Declaration (Use Permit 43-97, SCH 1995023013).* Specifically, *Biological Resources BR-9 – Fisheries Impacts Due to Lighting of Surface Waters,* states that "Artificial flood lighting along surface waters is known to attract fry and juvenile salmonids, and other predator fish species." Mitigation measure *BR-9m*, states "No direct lighting onto the river shall occur at either approach or from the bridge." The City of Redding Community Services Department is responsible for monitoring and implementing the above mitigation measure.

Due to the complex nature of light in water, fish have evolved well-developed and highly specialized eyes (Rondorf et al. 2010). The *Oncorhynchus spp.* eye contains a large number of rods and cones, showing that it is adapted for vision in both bright and dim light (Brett and Ali 1958). When light levels change abruptly, the eye has to adapt quickly in order to distinguish objects in the background (Dowling 1967). When the introduced light is bright, the eye will not respond to a dim light, which it may have detected under lower light conditions (Simenstad et al. 1999), making it difficult for juvenile salmon to visually detect predators in the areas beyond the brightly lit area.

Scientific research on the effects of artificial lighting on salmonid populations has been limited, thus the overall impacts of such lighting is poorly understood. However, the studies that have been conducted to address this issue, have illustrated results which indicate that increased light intensity appears to slow or stop out-migrating salmon fry, and increase feeding patterns, making them more vulnerable to predation (McDonald 1960; Patten 1971; Ginetz and Larkin 1976; Tabor et al. 2004). Salmonid fry presumably reduce their vulnerability to predators by emigrating at night and selecting areas of the river channel with the fastest current velocities (McDonald 1960). Juvenile salmonids feed primarily on drifting invertebrates during sunrise and dusk, but do not feed during complete darkness (Brett and Groot 1963; Fraser et al. 1997). Therefore the presence of artificial lighting and illumination of the water may facilitate juvenile salmonid feeding, which in turn may increase their vulnerability to predation at night (Rondorf et al. 2010). Ginetz and Larkin (1976) found that predation of sockeye salmon (*Oncorhynchus nerka*) fry by rainbow trout increased as light intensity increased in the artificial streams they used during their research. According to Skykeepers (2008), research shows that artificial light on newly hatched salmon causes vision problems and reduced survival rates. In addition, nighttime lighting of the Bridge presents a possible predator trap for juvenile salmonids migrating downstream from spawning and rearing areas above the Bridge. Celedonia et al. (2011) found that at night, Chinook salmon were attracted to areas where street lamps on a bridge cast light into the water, increasing their risk to predation, and that any negative consequences to Chinook salmon might be minimized by reducing the intensity of light reaching the water surface. Tabor et al. (2004) found that in the Cedar River in Washington, predation of migrating sockeye salmon fry increased as a result of artificial nighttime lighting, and that the lighting may be one of the factors in the overall decline of the Cedar River sockeye salmon population. With no predators present, the sockeye fry migrated through the river at a faster rate under complete darkness (0.001 Lux)) than in the other two light intensities assessed (1.08 and 5.4 Lux).

On June 14, 2012, I performed light measurements at several locations under and around the Bridge, as well as in an adjacent parking lot, using an EXTECH Light Meter (Model LT300). All measurements were taken in Lux, an International System of Units unit of illuminance and luminous emittance. One Lux is equal to one lumen per square meter (Wikipedia 2012). In addition, I took light measurements under the Cypress Road Bridge as a comparison of a bridge spanning the river that has artificial lighting associated with it. The Cypress Road Bridge is located a couple of miles downstream of the Sundial Bridge. Skies were clear and there was no moon visible during the collection of light intensities.

For reference, a moonless clear night sky would result in surface illumination levels of 0.002 lux, a full moon on a clear night would result in 0.27 lux, family living room lights result in 50 lux, and a dark overcast day would be 100 lux (Wikipedia 2012).

Below are the results I obtained:

- Location #1: Located directly under the Sundial Bridge on the south side of the Bridge, taken at the edge of water of the Sacramento River.
  - Time: 10:12 P.M.
  - Result: 25.55 lux

- Location #2: Located approximately 100-feet downstream of the Sundial Bridge on the south side of the Sacramento River, at the water's edge.
  - Time: 10:22 P.M.
  - Result: 1.34 lux

- Location #3: Located approximately 400-feet downstream of the Sundial Bridge on the south side of the Sacramento River. Minimal artificial lighting present, although a minor amount filtering through the trees from the Turtle Bay Museum.
  - Time: 10:31 P.M.
  - Result: 0.01 lux

- Location #4: Located in the Sundial Bridge Parking Lot, in close proximity to a street light, however, not directly beneath it.
  - Time: 10:38 P.M.
  - Result: 6.95 lux

- Location #5: Located in the Turtle Bay Parking Lot directly under a street lamp.
  - Time: 10:45 P.M.
  - Result: 19.56 lux

- Location #6: Located under the Cypress Road Bridge, approximately 2 miles downstream of the Sundial Bridge, taken near the water's edge on the west side of the river. The Cypress Bridge has some artificial lighting shining down into the river; however the lighting appeared much less intense than the Sundial Bridge lighting.
    - Time: 10:55 P.M.
    - Result at downstream side of bridge: 3.47 lux
    - Result at upstream side of bridge: 7.14 lux

In the Sacramento River and tributaries such as Clear Creek, studies have been conducted to assess the seasonal, spatial and diel distribution patterns of juvenile Chinook salmon, M. Brown, U.S. Fish and Wildlife Service (personal communication April 16, 2012; Gaines and Martin 2002). The U.S. Fish and Wildlife Service has been assessing the diurnal timing of juvenile Chinook out-migration in Clear Creek, with 14 trials/studies conducted about every other week from December 2011 through June 2012, and have found that 80% of the fish caught in the rotary-screw trap (RST) entered the RST in a five hour block of time from 1800 to 2300. During this same time period, sunset times ranged from 1645 on December 1, 2011 to 2034 on June 30, 2012 (Calendar-365). The peak of the migration took place from 2000 to 2100. Similar results were observed in two trials that took place in May and June 2011, M. Brown (personal communication April 16, 2012; July 5, 2012). On the Mainstem Sacramento River, Gaines and Martin (2002) found that relative abundance of Chinook salmon fry and pre-smolt/smolts (all runs combined) captured by RST's below Red Bluff Diversion Dam was significantly greater during nocturnal periods. They found that the same results held true for all sizes of rainbow trout (*Oncorhynchus mykiss)* combined, a potential predator species of the juvenile Chinook. Based on these studies, it appears most juvenile Chinook are out-migrating under the cover of darkness, thus artificial lighting could delay or inhibit out-migration and increase predation. McDonald (1960) was able to completely stop the nightly movement of sockeye salmon fry with artificial lighting kept on all night at levels of 30 lux. Tabor et al. (2004) found that if sockeye salmon fry encountered lighted areas, many held their position in low-velocity water, and the migration was delayed. They also found that the fry resumed their migration shortly after the lights were turned off.

Tabor et al. assessed several sources of artificial lighting, including laboratory experiments that included artificial streams, experimental field trials consisting of constructed artificial lighting, and existing sites, such as the Renton Library and the I-405 bridge. Both the library and the bridge span the entire width of the Cedar River, and both structures have several sources of artificial light that illuminate the river, similar to the current conditions of the Sundial Bridge. In addition, sampling was conducted in 1998 and again in 2001 after artificial lights had been shielded and light intensities along the river had been substantially reduced from 9.7-21.5 lux (1998) to 0.14-0.32 lux (2001). Overall, the results from Tabor et al. (2004) suggest that reductions in light intensity can be beneficial for emigrating juvenile salmonids and that the impact of lighting should be considered for any future or existing projects.

Chinook salmon populations in the main-stem Sacramento River have fluctuated greatly in the last decade. Table 1 provides a summary of Chinook salmon run sizes in the main-stem Sacramento River from 2000 through 2011. Currently, three separate Chinook runs migrate to, spawn, and reside as juveniles in the Redding area, both above and below the Bridge. The three runs (known by their timing as they pass San Francisco) are late-fall, winter and fall-run. Winter-Run Chinook salmon are currently only found in the Sacramento River near Redding, and the majority of the population spawns above the Bridge. Winter-Run are currently federally and state listed as Endangered, which makes them the intense focus of fisheries and water agencies, at both a state and federal level, since their juvenile and adult numbers determine harvest regulations for both sport and commercial fishers, as well as guiding agricultural and urban water use transfer limitations, D. Killam (personal communication June 29, 2012). Chinook salmon in this area typically rear for up to a year near the location where they emerged from their redd. They then migrate to the ocean, and return to the same area as adults in 2 to 5 years (typically in 3 years). Understanding this "life history" is important because if the lights from the bridge were impacting juvenile salmon survival, the effects would typically not be apparent until 3 years after juvenile downstream migration occurs, once the juveniles return to the Redding area as adults to spawn. An example of this is if the Bridge lights were first turned on in mid-2004 then the juveniles from 2003 would not have been impacted and would have returned in 2006. The juveniles from 2004 however could have been impacted, but they would have returned in 2007. For purposes of this discussion, populations of adult Chinook salmon from mid-2007 to the present day could have reduced numbers as a result of lighting impacts at the Sundial Bridge.

Table 1. Adult populations of Chinook salmon runs in the main-stem Sacramento River for years 2000 to 2011, (from Princeton to Keswick Dam). Grey area indicates populations whose juveniles could not have been impacted by Sundial Bridge lighting.

	Total Main-stem Sac River Population			% Spawning above Sundial Brg.		
Year	**Late-fall**	**Winter**	**Fall-Run**	**Late-fall**	**Winter**	**Fall-Run**
2000	8702	1,350	96,688	0%	6%	6%
2001	19276	8,224	75,168	26%	35%	7%
2002	36004	7,441	65,690	27%	49%	9%
2003	5532	8,218	89,229	58%	66%	6%
2004	8884	7,869	43,604	84%	16%	10%
2005	10603	15,839	57,012	47%	52%	27%
2006	10175	17,290	55,468	35%	35%	14%
2007	15340	2,541	17,061	57%	52%	20%
2008	3979	2,830	24,743	48%	51%	1%
2009	3424	4,537	5,827	73%	16%	25%
2010	4365	1,596	16,372	72%	48%	16%
2011	3725	824	11,592	73%	6%	34%

As shown in Table 1 above, in 2004, when the Bridge was completed the population was 7,869. In 2005 and 2006 the population topped out at 15,839 and 17,290, respectively. In 2007, three years after the Bridge was completed and night lighting first occurred in this section of river, which is the typical return interval for Chinook salmon (2004 Year Class), the population had declined to 2,541 fish. In 2008 and 2009, the years in which the 2005 and 2006 year class fish would be expected to return, the populations were 2,830 and 4,537, respectively.

The causes of the population declines since 2007 can be many, and no one cause is likely solely responsible for the declines. However, with the correlation of timing between the completion of the Bridge and the corresponding declines in returning adults, and the fact that research has demonstrated artificial light has a detrimental effect on emigrating juvenile salmonids, this issue warrants further discussion to find possible solutions to avoid and minimize future impacts. Such measures may include changing the position of specific lights to face up rather than out and down towards the river, install shields on some of the lights, turn off some of the lights if not needed, change the type of light used, etc. In addition, it may be deemed necessary to conduct some site specific studies in the vicinity of the Bridge, to help determine the level of biological response occurring due to the nighttime illumination from the Bridge.

In summary, Department staff will propose to meet with other resource agencies such as NOAA Fisheries and the U.S. Fish and Wildlife Service to discuss these issues, determine an appropriate course of action, and outline potential minimization measures that could be implemented to reduce potential impacts from the artificial lighting of the Bridge. Additional meetings should then be conducted with the City of Redding to agree on an appropriate approach. As stated above, The City of Redding is responsible for implementation of the *Mitigation Monitoring Program – Pedestrian Bridge at Turtle Bay,* specifically mitigation measure *BR-9 – Fisheries Impacts Due to Lighting of Surface Waters*. Tabor et al. (2004) states that when attempting to reduce artificial light, efforts should be made to keep levels below 0.1 lux as a prudent management goal. The recommendations of The Royal Commission (2009) regarding artificial lighting, state that artificial light should only be used at times when the benefits are needed, and that lighting standards should require the provision of light at an intensity no greater than the minimum necessary to deliver the intended benefits. In addition, the light should be directed at only those areas which are intended to be illuminated. Therefore, taking this type of approach, we should be able to develop some criteria for lighting that would provide the necessary level of safety for pedestrians using the bridge during the nighttime hours, lighting of the Bridge for its incredible architecture, while providing a necessary level of protection for migrating juvenile Chinook salmon, as well as the overall aquatic ecosystem in the vicinity of the Bridge.

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Attachment 1 – Photos of Sundial Bridge

Photo 1. Sundial Bridge under construction.

Photo 2. Sundial Bridge information sign showing hours of operation.

Photo 3. View of the Sundial Bridge from downstream.

Photo 4 – Sundial Bridge lit up at dusk, with lights pointing down towards the Sacramento River, in a downstream direction.

Photo 5. Nighttime lighting of the Sundial Bridge, resulting in illumination of the Sacramento River across its entire width.

Photo 6. Nighttime lighting of the Sundial Bridge with significant illumination of the Sacramento River.

Photo 7. View of the Sundial Bridge under-deck lights, with one facing down towards the river and one facing up towards the bridge deck.

Photo 8. Looking down into the Sacramento River from the Sundial Bridge at 7:12 P.M., into approximately 5-8 feet of water, with a dead adult Chinook salmon visible on the bottom. It was completely dark outside when the photo was taken, thus the illumination of the river bottom is solely from the lights on the bridge.

State wildlife officials say Sundial Bridge lighting may be hurting salmon

BY: Damon Arthur
POSTED: 10:00 PM, Feb 21, 2013
TAG: local (/topic/local) | sacramento river (/topic/sacramento+river) | kurt starman (/topic/kurt+starman)

Redding's Sundial Bridge may be bringing about the demise of endangered winter-run Chinook salmon.

Since the bridge opened to walkers and bicycle riders in 2004, the number of winter-run Chinook salmon returning to spawn in the Sacramento River has plummeted from over 15,000 fish in 2005 to 824 in 2011.

The lights under the pedestrian bridge may be one of the reasons why the number of salmon is declining, according to the state Department of Fish and Wildlife, which is studying the effects of the bridge lights.

"Intense levels of artificial light slow or stop juvenile migration of salmon" on their annual trek to the Pacific Ocean, said Andrew Jensen, a DFW staff environmental scientist.

And when the young fish stop in the water under the lights, larger fish, such as rainbow trout, are there to eat them, Jensen said. Other bridges over the Sacramento River in Redding also may have lighting underneath that is disrupting fish migration, he said.

The DFW and the city of Redding have been working together to test different light levels under the Sundial Bridge, he said. Light levels under the bridge deck this week were less than half of what they were before the testing began.

Redding City Manager Kurt Starman said the city is interested in working with the DFW on finding out whether the lights are hurting fish. But whether the lights were harming young salmon was still a "supposition" and further studies were needed, he said.

"I'm not aware of any conclusions or facts to support that," Starman said of the DFW's concerns.

Years before the bridge was built, environmental impact reports noted that light from the bridge shining on the water would hurt fish.

John Oldham, the city's environmental compliance officer, said because of the lighting concern, lamps under the bridge were pointed up to avoid light shining directly on the water.

Some of the lights may have inadvertently been pushed down or slipped down over the years, Oldham said.

There were 240 lights installed under the bridge and they were aimed into the air, said Bob Morrison Jr., the engineer who supervised construction on the bridge.

"There are no lights that shine down on the water," Morrison said. He said the fish may be seeing the light that is pointing into the air.

In an August 2012 report Jensen wrote on the bridge lighting. From dusk to dawn, one third of the lights were pointed up, another third were pointed upstream and another third were pointed downstream, the report says.

The light is apparently reflecting off the translucent panels on the bridge deck and back toward the water, Jensen said.

That light could be influencing how the young salmon migrate to the ocean. About 60 percent of the winter-run salmon, listed as an endangered species under California and federal law, spawn upstream of the Sundial Bridge.

After the salmon eggs hatch in the river and the young salmon swim to the ocean they are preyed upon by larger fish, Jensen said. He said the juvenile salmon migrate at night. But when they encounter bright light on the water it stops them at the light. The light also attracts bugs the young salmon like to feed on, Jensen said. But again, when the juveniles stop to feed on the bugs, the bigger fish can prey on them, he said.

Jensen said he found other scientific studies that back up the DFW's claim that the lights could be hurting young salmon.

In June, the DFW took nighttime measurements of the lighting under the bridge at the water's edge and found it at 25.55 lux, a measurement of illumination per square meter. One hundred feet downstream, the light was 1.34 lux. Light levels near a lamp in the Sundial Bridge parking lot measured 6.95 lux, according to Jensen's report.

City officials have turned down the light under the bridge and it's currently about 11 lux, he said. To help the fish, the lighting level on the water may need to be reduced a level ranging from 1.5 to 3 lux, he said.

Turning down or turning off some of the lights may not be the only solution, Jensen said. The city could place shields over the lights or use shade cloth, or even a different type of light, he said.

Jensen said the DFW is interested in working with the city to solve the problem because of the Sundial Bridge's popularity and because the lighting is part of the bridge's appeal.

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Lights on the river kill salmon

By John McManus

Staff Reports

Sunday, May 5, 2013

This may not sound intuitive, but many brightly lit bridges, docks and marinas along the Sacramento River are causing the deaths of untold numbers of young salmon. Some of these structures, like bridges, have to be lit so drivers can see the roadway, but there's no need to light up the water below. Reducing the lights' brightness, or redirecting them so they don't light up the water, is all that's needed.

Here's the problem. Baby salmon get eaten by most fish bigger than they are. Survival is tough. The baby salmon have pretty good eyesight, but their eyes work in either day or night mode, not both at the same time. They eat during the day and when they travel, they do it at night to minimize detection. When they swim under lit bridges at night, their eyes shift from night to daytime mode. So does their behavior. They slow down and start thinking about food. This is when they become very vulnerable to bigger fish lurking in the shadows.

Scientists have been able to bring migrating baby salmon to a stop by turning on the lights. Officials knew this would be a problem with Redding's Sundial Bridge. When Redding got a permit to build the bridge, one of the conditions said, "No direct lighting onto the river shall occur at either approach or from the bridge." Somehow this got overlooked when the bridge was built. Some lights underneath the bridge were pointed down and lit the river. Recently the city of Redding has been responsive to the problem and has taken steps to fix it, which salmon advocates very much appreciate. But the problem persists at other bridges, marinas, docks and water-intake structures up and down the river.

Among the baby salmon being gobbled up due to lights on the water are some on the federal endangered species list, including winter-run salmon. This creates a big problem for fishing communities on the coast and elsewhere that are seeing their fishing seasons restricted, at great loss, to avoid contact with winter-run fish. Water diverters in the Delta also face restrictions in an effort to protect the winter run.

Experts have pointed to a possible correlation between a recent steep decline in winter-run salmon and the Sundial Bridge's lights.

Before the effects of the bridge's lights on salmon kicked in, winter-run returns hit a high of over 17,000 in 2006. Once the effect of the lights was felt, winter-run salmon numbers dropped to 2,541 fish. They haven't recovered since. Others have pointed to a steep increase in Delta water diversion as a more likely cause of the winter-run decline, and multiple factors can't be ruled out.

Easy steps can be taken to make bridges and other structures more salmon friendly.

Changing the position of specific lights to face up rather than toward the river, installing shields, turning lights off when they're not needed, and changing the type of light used are a few.

Losing winter run, or any juvenile salmon, due to misdirected lighting is something that should be addressed because the fix is so simple. Those of us downstream who rely on salmon for a living are most appreciative of any steps taken in this direction.

John McManus is the executive director of the Golden Gate Salmon Association.

Project B.6 Eliminate or Reduce Lighting at In-River Structures

Bright lights shining into the water at night from bridges and other structures in the Sacramento River and its tributaries create a significant predation hazard for salmon fry and smolts. These fish tend to move at night when they can avoid predators. When they encounter bright lights they become disoriented and are easy predator prey.

One of the prominent problem bridges was the Sundial foot bridge which crosses the Sacramento River in Redding. Lowering the very bright lights on the bridge was taken up as a project by the regional office of the California Department of Fish and Wildlife. The City of Redding cooperated and the intensity of the lights has been lowered significantly. They have also been redirected away from the water. The next step will be the installation of lower intensity LED lights which will lower the level more plus save electricity. The City and CDFW are also working to reduce lights on other nearby bridges.This project is near complete and will save thousands of smolts.

The two pictures on the left show the bridge before the lights were lowered and the picture on the right shows it after they were lowered.
Photos by Andrew Jensen, California Dept. of Fish and Wildlife

More Detail

GoldenGate
Salmon Association

Welcome to the Golden Gate Salmon Rebuilding Plan

GoldenGate
Salmon Association

Submission #__
Subject: Columbia River Crossing: Biological Assessment
CRC Biological Assessment - June 2010 - Section 6 (1 of 2) Page 6-48 and 6-49
http://www.columbiarivercrossing.org/FileLibrary/Biological_Assessment_Opinion/
CRC_BA_12_Section_6_1of2.pdf

6.1.4.1 General Effects of Artificial Lighting on Fish

Artificial light sources associated with overwater structures or construction activities may attract fish. Because salmon rely on vision for capturing prey, the artificial lights may improve both prey detection and predator avoidance (Tabor et al. 1998, as cited in Carrasquero 2001). During a study of the Columbia River at Bonneville Pool, Collis et al. (1995) observed that juvenile salmon were attracted to work lights directed at the water surface. In Lake Washington, juvenile Chinook have been observed congregating at night near streetlights on the SR 520 bridge (Celedonia et al. 2008). Tabor et al. (2004) observed sockeye fry in the Cedar River, noting that they were significantly more abundant under city street lights than at nearby sites that were not illuminated. Light levels as low as 0.22 lux (0.020 foot candle) appeared to influence fry behavior. In one location, turning off the streetlights resulted in a significant decrease in the number of sockeye fry present.

Artificial lights can create sharp boundaries between dark and light areas under water. This, in turn, may cause juvenile fish to become disoriented or avoid crossing the light-dark interface, as outlined in detail in Section 6.1.3.1. Williams and Thom (2001) noted that artificial lighting on docks may change nighttime movement patterns in juvenile salmon. Numerous other studies (Fields 1966, Prinslow et al. 1979, Weitkamp 1982, Ratte and Salo 1985, Pentec 1997, Taylor and Willey 1997, and Johnson et al. 1998; as cited in Southard et al. 2007) corroborate these findings, noting behavioral changes in juvenile salmon in response to artificial lighting. McDonald (1960, as cited in Tabor et al. 2004) found that sockeye fry will stop swimming downstream upon encountering artificial lighting, and was able to completely stop nightly migration of sockeye salmon fry with artificial lighting kept on all night at 30 lux (2.8 foot candles). A USFWS (1998) literature review noted that sockeye fry moved through experimental streams more quickly in complete darkness than under bright lights (Tabor et al. 1998). Increased light appeared to inhibit migration of sockeye fry, with significant effects to migration when light levels reached 2.0 lumens/ft^2 (2.0 foot candles). A later study (Tabor et al. 2004) corroborated the finding that fewer sockeye moved through illuminated artificial streams than in darkness, and those that did move, moved more slowly. In this study, light intensity levels from 1.08 to 5.40 lux (0.1 to 0.5 foot candle) appeared to inhibit migration. The same study noted that the delay in outmigration in sockeye fry increased their vulnerability to predation.

Another USFWS study (Tabor and Piaskowski 2001) observed juvenile Chinook in nearshore habitat in Lake Washington, noting that individuals became active when light levels reached 0.08 to 0.21 foot candle and were scarce in the study area when light levels were between 2.2 to 6.5 foot candles. A review of the impact of ferry terminals on juvenile migration in Puget Sound (Simenstad and Nightingale 1999) cites Ali (1958, 1960, and 1962) as stating that light is tremendously important for numerous life functions of chum, coho, sockeye, and pink salmon, noting that feeding, minimum prey capture, and schooling are dependent on light levels lower than 10^{-4} foot candles (similar to a clear, moonless night) and that maximum prey capture for chum and pink fry occurs when the light level is 1.0 foot candle (similar to light levels at dawn and dusk).

Artificial light sources may provide an advantage to predators such as smallmouth bass, largemouth bass, northern pikeminnow, and salmonids. Rainbow trout predation on sockeye fry in artificial streams increased with increased lighting at levels of less than 1.1 lux (Ginetz and Larkin 1976, as cited in Tabor et al. 2004). Northern pikeminnow are attracted to areas where juvenile salmonids congregate, such as hatchery release sites and dams (Collis et al. 1995;

Beamesderfer and Rieman 1991). If light sources attract congregations of juvenile salmonids, this could cause an increase in predation by northern pikeminnow. Celedonia et al. (2008) found that smallmouth bass may feed at night in the vicinity of artificial light or under moonlight. Largemouth bass have been shown to forage efficiently at light levels ranging from low-intensity daylight to full moonlight, with less foraging at light levels equivalent to a starlit, moonless night (McMahon and Holanov 1995).

Tabor et al. (2004) observed the effect of light intensity on cottid predation of sockeye fry in artificial streams, noting that cottids consumed 45 percent of the fry under intense illumination (5.4 lux or 0.50 foot candle), 28 percent under dim light (0.22 lux or 0.020 foot candle), and 5 percent in complete darkness (0 lux or 0 foot candle). The study also observed that fewer fry emigrated in illuminated streams and did so at a faster rate when predators were present than in lighted streams where predators were not present, indicating that the presence of predators may inhibit migration in some individuals. In a field study in the Cedar River, Washington, Tabor et al. (2004) further noted that the number of shoreline fry and rates of predation by cottids increased with an increase in light levels. At one site, shielding the lights to levels of 0.1 to 0.32 lux (0.013 to 0.030 foot candle) substantially reduced predation.

The literature is not in complete agreement about light levels that are likely to impede migration or increase predation on juvenile fish. However, data from Tabor et al. (2004) may present a worst-case scenario. That is, light levels as low as 0.22 lux (0.20 foot candle) may delay migration or increase predation on juvenile salmonids.

6.1.4.2 Effects of Lighting on Fish in the CRC Action Area

The project will install both temporary and permanent lighting.

Temporary Lighting

Temporary overwater lighting sources will include the cofferdams, barges, work platforms/bridges, oscillator platforms, and tower cranes. Figure 6-17, Figure 6-18, and Figure 6-19 show the locations and sequencing of temporary structures requiring artificial lighting in the work area. Temporary lighting will not be uniform over all of the in-water construction years. During the Columbia River in-water construction period, temporary lighting will be limited to the first three pier complexes during the first year, expand to all six in the second, and taper off to three or fewer during the last 2 years (Figure 6-17). In North Portland Harbor, temporary lighting will be distributed more or less evenly over the first 2 years of the in-water construction periods with illumination-producing structures concentrated in the last in-water construction year (Figure 6-18). Temporary lighting will be distributed evenly across the Columbia River in-water demolition period (Figure 6-19).

The barges and temporary in-water structures will cast light at the water surface during construction and demolition in the Columbia River and North Portland Harbor. At this stage in the project design, the intensity of light likely to be cast on the water surface is not known. However, to the extent practicable, the project will implement conservation measures that minimize the effects of lighting on fish. Measures may include using directional lighting with shielded luminaries to control glare and to direct light onto work areas instead of surface waters.

Hi Ciara

The email below was forwarded to me. I don't know if this email will reach the intended targets but any discussion of rebuilding any bridge over the Sacramento River should take into account the damage that night lighting of the river below can have on ESA-listed salmon as well as other fish. Here's a link to a piece I wrote on the issue http://www.redding.com/opinion/john-mcmanus-lights-on-the-river-kill-salmon

Attached is a document with a more detailed discussion of the problems associated with lights illuminating the Sacramento River at night. I would hope these concerns will be proactively addressed as the planning for the replacement structure proceeds. Thanks.

John McManus
Executive Director
Golden Gate Salmon Association
650-218-8650

DRAFT

D.6. Project: Eliminate or reduce lighting at in-river structures.

Relevant Stressor Reduction Target: To reduce predation on juvenile salmon.

Action: This project proposes to reduce night-time predation in the vicinity of man-made structures in the rivers and Delta (e.g., fish screens, bridges, docks, marinas) by eliminating or altering lighting methods and equipment.

Expected Outcome: Reduced predation, increased fish survival, increased fish production.

Background: Artificial night-time lighting at structures near water is believed to have adverse impacts on juvenile salmon by altering fish behavior and making the fish more prone to predation. For example, in 1984, the U.S. Fish and Wildlife Service and the California Department of Fish and Game (DFG) requested that the U.S. Bureau of Reclamation turn off large sodium vapor lights on top of the Red Bluff Diversion Dam on the Sacramento River to reduce the opportunities for Sacramento pikeminnow predation on juvenile salmon passing the dam (Vogel and Smith 1984), a measure that was ultimately believed to be beneficial for salmon (Vogel *et al*. 1988). More recently DFG identified a potentially severe problem with lighting on the Sundial pedestrian bridge (Figures D.6.1 and D.6.2) over the Sacramento River in Redding:

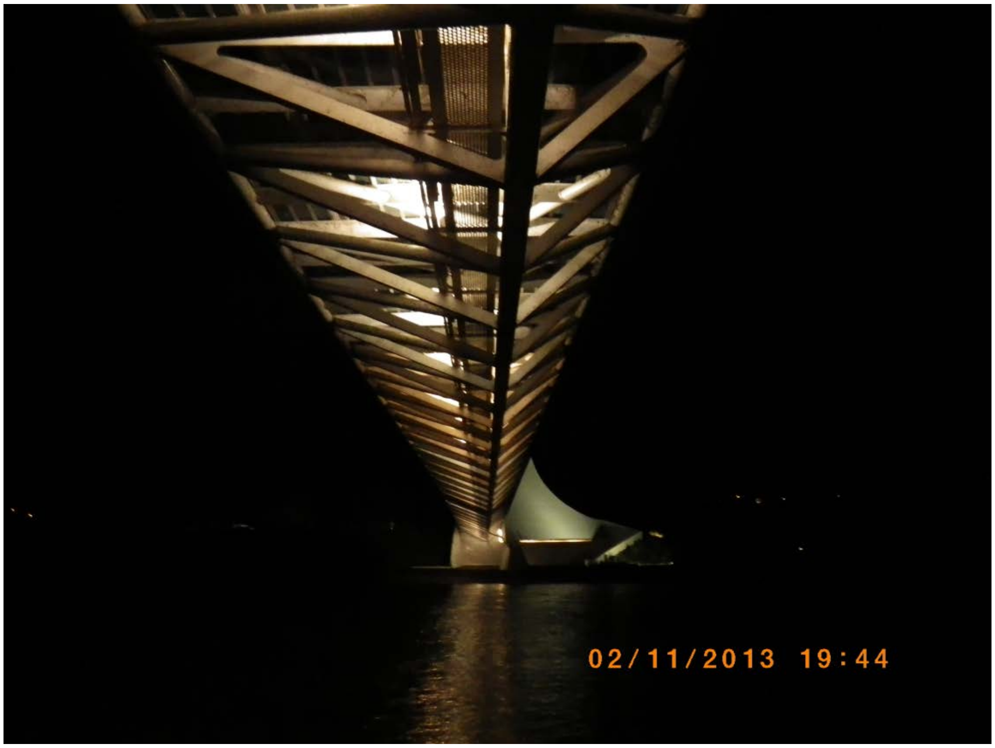
> *Assessment of the impacts from light sources along the Sacramento River which lead to increased predation on juvenile salmonids is also needed. The most upstream issue is the Sundial Bridge in Redding which uses numerous flood lights which illuminate the Sacramento River all night long every night of the year. Approximately 80% of the winter-run Chinook salmon population in the state spawn upstream of the bridge and the out-migrating juveniles must pass through the lighted portion of the river below the bridge and face predators. Studies in Washington State have found lighted portions of streams have significantly higher predation rates on juvenile fish. Downstream of the Sundial Bridge from Redding to the bay, there are several other light sources ranging from highway bridges to lighted water intake structures. These should all be evaluated and recommendation should be developed to fix identified problems* (DFG 2011).

The primary purpose of the Sundial Bridge is aesthetics. The massive array of lights shining directly down on the river all night posed significant risks to fry and juvenile salmon. At night, the structure was likely causing mortality of young fish, including threatened and endangered species. Fortunately, in mid 2013 the city of Redding, working with the California Department of Fish and Wildlife, greatly reduced the lights to the point where they are believed to no longer pose a significant threat to salmon.

The Sacramento River between Redding and the Delta has dozens of structures over or immediately adjacent to the river illuminated at night which may disrupt the downstream migration of juvenile salmon and make the fish more susceptible to predation. The cumulative impact on rearing or migrating salmon from the upper rivers to the Delta could be enormous.

Predators are known to take advantage of lighting on bridges in the Pacific Northwest to prey on migrating salmonids (Nightingale and Simenstad 2002). The USFWS found that lighting on a bridge over the Cedar River in Washington state was having a severe adverse impact to migrating sockeye fry which was largely eliminated by adding shielding over the lights directing light away from the river (Washington DOT 2001). This problem may be particularly severe in the Sacramento River and its tributaries because of relatively clear-water conditions. Those structures having a federal nexus and creating adverse impacts on salmon caused by nighttime lighting may constitute “take” of federally listed species under the Endangered Species Act.

Figure D.6.1. Before photos of the Sundial pedestrian bridge over the Sacramento River in Redding at night. Photo credit: Eric Cassano.



After shot of the Sundial bridge showing reduced lighting

Longcore and Rich (2010) identified several options for addressing light pollution and its impacts on the environment:

1) Determination if the need for lighting is actually needed,
2) Direct the light toward where it is needed and eliminate light escaping in other directions,
3) Reduce excess intensity of lighting to more-appropriate levels,
4) Reduce the duration of night-time lighting and,
5) Eliminate full spectrum light and use other wavelengths less disruptive to the ecosystem.

Opportunities and Challenges: This project proposes to eliminate or reduce night-time lighting at structures over or adjacent to the Sacramento River and its tributaries to reduce predation on juvenile salmon. Many structures possess night-time lighting that could likely be simply turned off due to a lack of real need. Some structures possessing night-time lighting for security purposes could be altered to provide motion sensor activation. Many structures could probably be altered by directing the lighting away from shining directly down into the river, shielding the fixtures, using less-disruptive wavelengths or lower-intensity lighting.

This project will require an initial study identifying structures lit at night and the relative risks to salmonids. The outcome of that study would lead to implementation of a program to eliminate or reduce impacts of night-time lighting on salmon.

Cost or Difficulty: The estimated cost for an initial study to identify structures posing risks to salmon from night-time lighting is $150,000. Owners of facilities lit up at night near water are initially unlikely to be willing to turn off their lights at night, physically alter the lighting, or change the methods of lighting; associated costs and security will be of concern. Opposition from owners of night-time lit structures will require education on the need for change in lighting methods or equipment. In some instances, lighting changes may result in cost savings due to lower power consumption. The cost for implementation of remedial actions to eliminate or reduce night-time illumination is unknown until after the initial survey is completed.

Certainty: High probability of reducing night-time predation near man-made structures in the rivers and Delta.

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As noted below -

IDA recommends a correlated color temperature (CCT) of 3000 Kelvin or less for white LED lighting systems. ... see statement attached.

This would be a good standard to include in lighting portions of the zoning code or even better the Outdoor Lighting section of our zoning code (like Citrus Heights).

See IDAs - Blue Rich White Light Paper ---- http://www.darksky.org/assets/documents/Reports/IDA-Blue-Rich-Light-White-Paper.pdf

Seeing Blue ---- http://www.darksky.org/assets/documents/SeeingBlue.pdf

Blue Light Threatens Animals and Humans ---- http://www.darksky.org/assets/documents/PR/2009/PR_Blue_White_Light.pdf

A compromise that would be the upper limit could be a correlated color temperature (CCT) of 3000 Kelvin.

An incandescent lamp is normally rated at a CCT of 2700 Kelvin and nearly all LED lamps in Home Depot/Lowe's etc. are 2700K.

As noted below "energy-efficient nature of LEDs encourages the use of excessive amounts of light", this is an issue that must be addressed.

Close to home dimming and other lighting controls have been pioneered by the California Lighting Technology Center at UC Davis.
http://cltc.ucdavis.edu

Directors Michael Siminovitch and Konstantinos (Kosta) Papamichael have been at the forefront of dimming and concern about blue light.

Please have a look around the CLTC web site and see some of the projects they have been doing at Davis and other campuses.

Regards

Jack Sales

2014 Nobel Prize for Physics Draws Attention To Promise And Challenges of Blue Light

Tucson, Ariz. - The Nobel Committee announced today that it has awarded the 2014 Nobel Prize for physics to three Japanese physicists for their invention of a revolutionary lighting technology. Isamu Akasaki and Hiroshi Amano of Japan and Shuji Nakamura were cited for "the invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources."

Their groundbreaking work on light-emitting diodes (LEDs) more than 20 years ago was crucial in production of the first "white" LEDs. These energy efficient LEDs are increasingly replacing conventional lighting technologies.

The National Lighting Bureau of the U.S. Department of Energy recently estimated that white LED lighting systems will account for 74 percent of lighting sales in the United States by 2030, reducing electricity demand for lighting by nearly 50 percent in the next two decades. In its media statement today announcing the Prize, the Nobel Committee noted that while "incandescent light bulbs lit the 20th Century, the 21st Century will be lit by LED lamps."

There's no question that LEDs are here to stay. The question is, will we have the wisdom to apply this new technology without being excessive and wasteful.

The International Dark-Sky Association (IDA) applauds today's Nobel announcement, but urges the responsible use of LEDs, particularly at night. The energy-efficient nature of LEDs encourages the use of excessive amounts of light. Research has shown that historically, when there is an improvement in the efficiency of lighting technology, a greater amount of outdoor lighting is used.

"There's no question that LEDs are here to stay," said IDA Acting Executive Director Scott Kardel "The question is, will we have the wisdom to apply this new technology without being excessive and wasteful. If we light properly we can use LEDs to save energy, improve visibility, and lower light pollution levels."

Another issue to consider when using LEDs at night is the level of blue-rich, white light they emit. Exposure to blue light at night has known negative effects on ecology and is thought to cause certain kinds of chronic disease in humans. It can also increase glare compromising human vision, especially in the aging eye.

Lastly, the blue component of outdoor white LED lighting increases the brightness of the night sky more than older lighting technologies. IDA warned of these hazards in its 2010 white paper, "Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting."

IDA recommends a correlated color temperature (CCT) of 3000 Kelvin or less for white LED lighting systems. These lights emit less blue light, while providing good rendition of colors. In ecologically sensitive areas, the CCT should be as low as possible to limit harm to wildlife. Information on color temperature is now found on the packaging of most lighting products.

Risks can be further minimized by dimming or turning off lights at night and restricting lighting to the exact space and in the proper amount required for particular tasks.

Cities around the globe are rapidly converting their existing streetlights to LED in an effort to conserve energy and save money. These savings can be maximized by ensuring that our streets are not overly lit and that the new technologies especially suited to LEDs, such as dimming and other lighting controls, are also put into place.

The promise of LED technology to light the world in a new way has drawn a major scientific accolade, but with new capabilities come new concerns about their application. Learn more about outdoor lighting, blue light at night, and dark skies on the IDA website at www.darksky.org.

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