Multiple Stressor Effects on Juvenile Salmon in South Lake Washington

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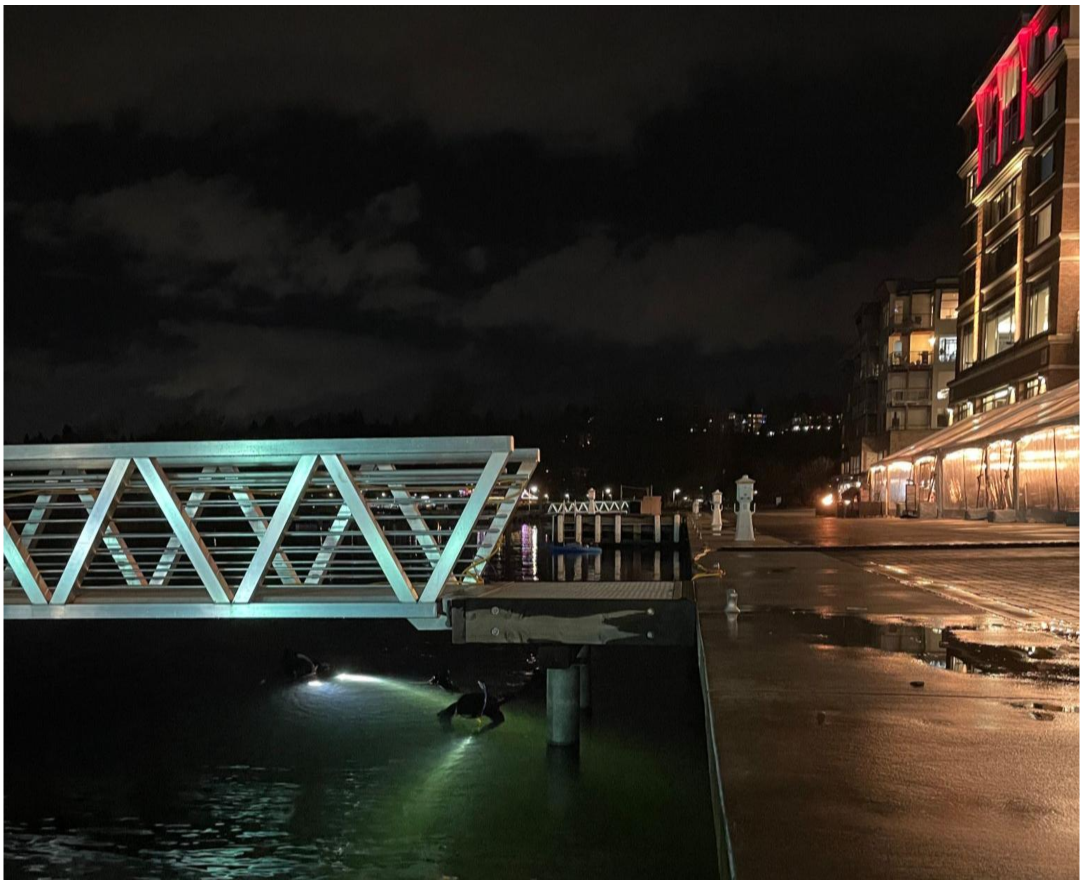
Prepared for WRIA 8 by the University of Washington Wetland Ecosystem Team



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Executive Summary

We conducted a study to assess the relative impact of anthropogenic shoreline influences considered to be stressors on juvenile salmon, including artificial light at night (ALAN) and residential overwater structures (docks). While it is known that ALAN influences Lake Washington juvenile salmon distributions and behaviors (Sergeant and Beauchamp 2006, Celedonia et al. 2011, Tabor et al. 2011, Tabor et al. 2017, 2021, Beauchamp et al. 2020), and juvenile salmon are attracted to a variety of light intensity and spectra (Tabor et al. 2021), the interactive effects of multiple stressors, as well as the fine scale distributions and behaviors of the nearshore fish assemblage, are less well known.

We examined how artificial light intensity along urbanized waterfronts influences juvenile salmon and predators, and how ALAN interacts with other potential stressors (e.g., armoring, overwater structures, water depth) to influence fish distribution and behavior. We conducted day and night snorkel surveys twice per month from February to April 2024 at eight sites in south Lake Washington to assess spatiotemporal changes in fish abundances, including diel and seasonal patterns. Finally, we characterized the nearshore fish assemblage in south Lake Washington including salmon and other fish densities and distributions, which is important given the increase in non-native fish species in Lake Washington in the past decade.

We did not find evidence for an interactive effect of docks and ALAN, or an effect of docks on the nearshore fish assemblage. While there were occurrences of predators using dock structures to hide, residential docks were narrow enough that fish seemed to be less influenced by their presence and reduced light than has been observed among larger commercial overwater structures.

ALAN and water depth interacted to influence salmon and other fish distributions. The brightest ALAN locations, at commercial locations, had the lowest densities of salmon and the deepest shoreline water depths due to extensive bulkhead shoreline armoring. Juvenile salmon preference for shallow water habitat likely superseded the attraction to ALAN. Highest salmon densities were at the shallowest sites 0.5-0.8 m depth and within these sites salmon often congregated in the shallowest water (< 0.3 m) along shorelines and at pocket beach microhabitats. Predator densities were also highest along shallower shorelines, and predators and salmon were frequently observed resting near each other at night. Although ALAN was variable among sites, and consistently higher at commercial sites than at residential sites, converted light values measured less than 1 lux. It is unknown what light levels of skyglow, scattered commercial lighting, or residential light levels enable predators to successfully forage at night. Interactions between ALAN and shallow pocket beach microhabitats should be further investigated to determine whether these habitats can act as refuge for juvenile salmon in the

presence of ALAN, or if they become predation hotspots (i.e., if the crepuscular predation window is extended and predators can feed throughout the night).

In summary, we 1) censused day/night south Lake Washington littoral habitats, updating the fish assemblage data, including quantifying high densities of non-native yellow perch in shallow habitats, we 2) identified a daily migration to the shallow littoral zone to rest at night, wherein juvenile salmon, smaller predators, and other fish move onshore to cohabit shoreline habitats, and 3) quantified a juvenile salmon preference for shallow water habitats that supersedes attraction to ALAN.

For future studies, we recommend identifying fine scale interactions of fish in ALAN and nearshore habitats, including identifying realized rather than hypothesized predation in the presence and absence of commercial and residential ALAN.

Introduction

ALAN and habitat modifications influence Lake Washington juvenile salmon distributions and behaviors (Celedonia et al. 2011, Tabor et al. 2017, 2021, Beauchamp et al. 2020, Tabor et al. 2011, Sergeant and Beauchamp 2006). However, anthropogenic stressors are frequently studied in isolation (e.g., Tabor et al. 2017) or omitted to best understand a single stressor (Tabor et al. 2011; omitted fish attracted to ALAN) yet living organisms in urban environments must reside in habitats subject to multiple anthropogenic-induced stressors. Multiple stressors likely influence organisms in complex and differing ways based on species, season, or ontogeny, and their interactions are often more complex than the sum of their parts (Bruder et al. 2019). Understanding the combined effects of multiple stressors not only enables an understanding of the magnitude of the combined effects but can help managers prioritize stressor combinations that are most important to the organisms of interest. A synthesis of ALAN research with future priorities by Bassi et al. (2021) recognized the importance of conducting ALAN studies in situ to identify potential benefits and costs, study the additive effects of ALAN coinciding with other stressors, and understand impacts at different life stages.

We investigated the impacts of multiple stressors (ALAN and overwater structures) on juvenile Chinook salmon (*Oncorhynchus tshawytscha*) distribution and behavior in southern Lake Washington along shorelines within 1 km of the mouth of the Cedar River. To examine each stressor separately and potential interactive effects, we selected sites representing combinations of each stressor: only ALAN, only overwater structures, and ALAN + overwater structures. We conducted day and night fish surveys via snorkel to capture the diel distribution of juvenile Chinook and potential predators along the shoreline of southern Lake Washington. While our study design was aimed at the impacts of overwater structures and ALAN, we also gained insight into the influence of other habitat characteristics (e.g., water depth, pocket beach microhabitats), seasonal changes (e.g., predator abundances related to reproduction), and diel horizontal migration of juvenile salmon and their predators. We also characterized the nearshore fish assemblage in southern Lake Washington on a fine scale, which had not been undertaken in over a decade (Tabor et al. 2011).

Methods

Sites

Our 2024 study sites were in south Lake Washington, Washington, within 1 km on either side of the outlet of the Cedar River. We sampled at eight sites (four types each with two site replicates) with combinations of two study stressors: with or without overwater structures (small residential overwater structures, henceforth “docks”) and with or without direct nighttime lighting (ALAN) (Figure 1; Table 1). Two sites had docks and were characterized as having high levels of ALAN (due to direct nighttime lighting), two sites had docks and were characterized as having low levels of ALAN (due to skyglow, which is sky brightness due to area light pollution), two sites had no docks and were characterized as having high levels of ALAN, and two sites had no docks and were characterized as having low levels of ALAN.

1. **High Light, Docks, hereafter “$ALAN^{+}$ $Docks^{+}$”:** Residential shoreline sites west of the mouth of the Cedar River with residential and dock nighttime lighting (ALAN) that had a maximum of three docks in a 30 m transect (Sites 4 and 5, Figure 1).
2. **High Light, No Docks, hereafter “$ALAN^{+}$ $Docks^{-}$”:** Commercial shoreline sites east of the mouth of the Cedar River with commercial/industrial nighttime lighting (ALAN) and no docks (Sites 2 and 3, Figure 1).
3. **Low Light, Docks, hereafter “$ALAN^{-}$ $Docks^{+}$”:** Residential shoreline sites west of the mouth of the Cedar River with residential and minimal dock nighttime lighting (ALAN) that had a maximum of three docks in a 30 m transect (Sites 6 and 7, Figure 1).
4. **Low Light, No Docks, hereafter “$ALAN^{-}$ $Docks^{-}$”:** Vegetated shoreline sites east of the mouth of the Cedar River with low shoreline development, low direct sources of ALAN, and no docks; selected as reference sites (Sites 1 and 8, Figure 1).

Sampling

We sampled day and night, twice per month, from February to April to characterize the nearshore fish assemblage during peak juvenile salmon out-migration from the Cedar River into south Lake Washington. To reduce the influence of lunar light, nighttime surveys were conducted near the start of astronomical twilight and within a week of a new moon.

Snorkel Surveys

Paired snorkelers swam 30 meter transects, 3 meters (“shallow”) and 7 meters (“deep”) from the shoreline, recording fish identifications, abundance, size, location along the transect, and behavior patterns (Toft et al. 2007), and recorded digital video for later validation. We sampled mid-afternoon for daylight surveys then waited until the end of nautical twilight before returning for night surveys. At night, we used underwater flashlights to illuminate fish for identification but turned off or lowered flashlight intensity when possible (recording observations or moving between sites) to reduce confounding effects of the flashlights on fish behavior.

Artificial and Ambient Light

To evaluate artificial and natural light, we used three types of sensors with overlapping applications so that we could evaluate the intensity and spectra of light that fishes are exposed to along the southern Lake Washington shoreline. During daylight surveys, we measured light intensity ($\mu mol\ s^{-1}\ m^{-2}$) of Photosynthetically Active Radiation (PAR) (wavelengths of light within the visible light band 400 nm - 700 nm) using a LI-COR LI-193 spherical underwater quantum sensor data logger (hereafter, LI-COR). Daytime light intensity was measured in the air directly above the water, underwater directly below the water surface, and at 0.5 m, 1 m, and 2 m depth. The LI-COR cannot collect data continuously, so we measured light intensity at the beginning, middle, and endpoint of each transect. The LI-COR sensor is not accurate at low light levels underwater at night. Therefore, we intended to use daytime light intensity values to calculate an attenuation coefficient to apply to nighttime in air light measurements to estimate underwater light intensity. However, most salmon were found in the shallowest habitats, where the attenuation coefficient would be near zero; therefore, we ultimately compared surface light values among habitats.

During nighttime surveys, we measured relative blue light intensity using a Wildlife Computers TDR-Mk9 archival tag (hereafter Mk9) that detects light within an overlapping but narrower spectral band (350 nm - 550 nm) than the LI-COR sensor. The Mk9 detects relative blue light intensity and provides unitless data but is sensitive even at low light levels and can continuously collect data throughout a survey transect. We used the Mk9 to supplement the LI-COR at nighttime low light levels and to provide a continuous measurement of artificial lighting along the shoreline. We converted our Mk9 unitless values to Watts cm^{-2}. Finally, we used a Sekonic C-7000 Spectrometer (hereafter Sekonic) (380 nm - 780 nm) to evaluate the wavelengths of light and relative intensities observed at our sites and determine what wavelengths were present but not detected by the limited range Mk9. The Sekonic used for our study is intended for use in photography and high light conditions, which limited its utility in our study.

Acoustic Sampling

We piloted acoustic sampling methods later in the season, as time permitted. Active acoustic sampling is a remote sensing, non-invasive method where large volumes of water can be sampled relative to netting or other visual methods (Martignac et al. 2015). Acoustic cameras have been used to census small fish (Adams et al. 2015, Smith et al. 2021, Accola et al. 2022).

We acoustically sampled using a dual-frequency identification sonar (DIDSON; Sound Metrics, Bellevue, WA, USA; www.soundmetrics.com). The DIDSON is a multibeam sonar that transmits sound pulses, with returning echoes digitized and converted into near-video-quality images. We mounted the DIDSON beneath a 2 m kayak and propelled the kayak by swimming behind it or set it in shallow water. The DIDSON was angled 12° relative to the water surface to ensure that the middle and upper portion of the water column was ensonified and sampled with a horizontal acoustic beam swath of 2.5 m on either side of the kayak. The operating frequency was set at 1.8 MHz and transmitted at ~12 Hz, starting 1 m in front of the kayak for a range of 5 m. The DIDSON was connected to a laptop running data acquisition software (DIDSON V5-26) and a timestamped file was created for each transect.

Data Analysis

We used generalized linear models (GLM), which account for non-linear data distributions, to characterize nighttime fish distributions among fish groups (salmon, predators, and other), along south Lake Washington habitat types (ALAN$^+$ with and without Docks, and ALAN$^-$ with and without Docks, and by categorical depth (shallow, 3m from shore; and deep, 7m from shore). The response variable was the summed counts of each transect for each night. Covariates were selected based on the questions being addressed and by using corrected Akaike Information Criterion (Hurvich and Tsai 1989) to examine best model fit.

Final models incorporated the interactive effects of stressors (e.g., ALAN$^+$ Docks$^+$), functional community group (salmon, predator, other), and categorical transect depth (shallow, deep). We performed post-hoc pairwise comparisons of estimated marginal means from the GLMs and quantified the effect size of the difference. Statistical analyses were performed using R Statistical Software (v4.4.2; R Core Team 2024) and R Studio (Posit Team; 2024.12.0). Data manipulation was performed using “dplyr” (v1.1.4; Wickham et al. 2023). We built GLMs using R package “glmmTMB” (v1.1.5; Brooks et al. 2017), did pairwise comparisons using the package “emmeans” (v1.10.5; Lenth 2024) and used “ggplot2” (v3.5.1; Wickham 2016) for plotting.

Results

Fish Counts

Overall, we observed 504 fish during the day and 4081 at night (Table 2). Although fish observations were less common during the day than at night, the most frequently seen daytime fish were schooling juvenile salmonids, including Chinook (*n* = 208), unidentified juvenile salmon (*n* = 174), and sockeye (*n* = 94) (Table 2, Figure 2). The non-salmonids observed in daytime snorkel surveys, in descending order of abundance, were predominantly yellow perch *Perca flavescens* (*n* = 14), followed by bluegill *Lepomis macrochirus*, carp *Cyprinus carpio carpio*, Bullhead catfish *Ameiurus nebulosus*, unidentified trout *Oncorhynchus* spp., largemouth bass

Micropterus salmoides, and speckled dace *Rhinichthys osculus*. At night, the most abundant fish were yellow perch (*n* = 1338), followed by juvenile Chinook (*n* = 1232), three-spined stickleback *Gasterosteus aculeatus* (*n* = 510), unidentified juvenile salmon (*n* = 395), juvenile sockeye *O. nerka* (*n* = 336), unidentified sculpin *Cottus* spp. (*n* = 291), unidentified sunfish *Centrarchidae* (*n* = 150), smallmouth bass *Micropterus dolomieu* (*n* = 108), unidentified trout (*n* = 40), prickly sculpin *C. asper* (*n* = 30), an unidentified mix of Chinook/sockeye (*n* = 29), largemouth bass (*n* = 28), unidentified bass (*n* = 19), and a few occurrences of Pacific lamprey *Entosphenus tridentatus*, river otter *Lontra canadensis*, green sunfish *Lepomis cyanellus*, juvenile coho salmon *O. kisutch*, and one riffle sculpin *Cottus gulosus*. Densities of all fish combined were highest at the ALAN$^+$ Docks$^+$ locations (followed closely by ALAN$^-$ Docks$^-$/ALAN$^-$ Docks$^+$) and lowest at the ALAN$^+$ Docks$^-$ locations (i.e., Boeing plant and Hyatt hotel).

Acoustically, we quantified large fish ('predators') and small, fast-moving fish (likely salmon) in our sample transects. We were also able to identify fish with darting behaviors, in shallow water. These fish were likely sculpin. In our acoustic sampling we conducted transects at dusk that extended 50m from shore. Although these were test transects, we generally did not observe fish in the top 5m of the water column, indicating juvenile salmon may be inhabiting pelagic habitats until sometime during nautical twilight, when they begin their migration into shallow littoral habitats.

Juvenile Salmon

During the day, we counted 476 juvenile salmon, and most were observed at the ALAN$^-$ Docks$^+$ locations, followed by ALAN$^-$ Docks$^-$, then ALAN$^+$ Docks$^+$ sites (Figure 3, Table 2). One Chinook was observed at the ALAN$^+$ Docks$^-$ sites. Nearly all juvenile salmon were schooling and swam away from the snorkelers. During the day, we observed juvenile salmon 20 times, and school size average was 24 fish, while at night, we observed salmon 498 times with a group size average of 3 fish. Most salmon were in shallow depths, day and night. Chinook fork lengths ranged from 25 mm to 125 mm, with larger fish present later in the season.

At night, we counted 1519 salmon, and most juvenile salmon were observed at ALAN$^+$ Docks$^+$ locations, followed by ALAN$^-$ Docks$^-$ locations. See Table 2 for breakdowns, by salmon species, among stressor locations. Proportionally, 60% of juvenile Chinook were observed at ALAN$^+$ Docks$^+$ residential sites at night, while 43% of sockeye and 36% of unidentified juvenile salmon were observed at ALAN$^+$ Docks$^+$ residential sites.

At night, Chinook were mostly inhabiting the bottom of the water column, followed by the middle and top of the water column. Behaviorally, most Chinook were resting or unaffected by our presence at night, some swam away from us, and fewer were attracted to our flashlights (Figure 4).

Predators

Potential juvenile salmon predators were categorized based on literature values, and when possible, literature specific to Lake Washington. We classified yellow perch as predators when they were 130+ mm (Keast 1977, Pothoven et al. 2000, Bosworth and Short 2024), trout when they were 200 mm or longer (Tabor et al. 2004), largemouth bass when they were 100+ mm (Keast 1985), smallmouth bass when they were 70+ mm and temperatures were 11 degrees C or higher (Tabor et al. 2024; based on King County water temperature (King County Major Lakes Monitoring)), and prickly sculpin when they were 70 mm or longer (Tabor et al. 2004) (Figure 3; inset). Many sculpin were not identified to species and therefore there were likely more prickly sculpin as potential predators. Additional predators included an otter and a Pacific lamprey *Entosphenus tridentatus*. Ten predators were observed during the day, and 1008 at night.

The most abundant predator was yellow perch, followed by smallmouth bass, unidentified trout, prickly sculpin, largemouth bass, and unidentified bass. Most predators were co-located at the same habitats as juvenile salmon at night (Table 2), albeit usually in deeper water than juvenile salmon. Both juvenile salmon and predators had lowest densities at the highest ALAN sites ($ALAN^{+}$ $Docks^{-}$). Most predators were resting at night, and the remaining predators were either unaffected by our presence or swam away from us (Figure 4).

Other Fish

Other non-salmonids were categorized as ‘other’, which included predator species that were too small to prey on juvenile salmon (or water temperature was too low) or fish that are never juvenile salmon predators. The most frequent non-predator species was three-spined stickleback (*n* = 509), followed by smaller yellow perch (*n* = 498), many of whom were borderline length for predators, and unidentified sculpin (*n* = 291). More non-predators were in deep transects (*n* = 827) than shallow transects (*n* = 742) (Figure 3), although three-spined stickleback comprised most of the ‘other’ fish at $ALAN^{+}$ $Docks^{-}$ locations.

Statistical Results

All Fish

Final generalized linear models for all fish abundance comparisons incorporated the interactive effects of anthropogenic stressors (ALAN, docks), functional community group (salmon, predator, other), and categorical depth (shallow, deep), and predicted the densities of fish based on the three categories. Model results showed statistical differences for interactions of fish groups, stressor combinations, and depths.

Overall fish densities were lowest at the highest artificial light at night locations ($ALAN^+$ $Docks^-$). Salmon densities were statistically highest at $ALAN^+$ $Docks^+$. Salmon densities were higher than predators at $ALAN^+$ $Docks^+$, and lower than predators and other fish at $ALAN^-$ $Docks^+$ locations. Contrasts were starker when differentiating by depth, as salmon were found primarily at shallow depths, where they had 1.5 - 2 times higher estimated densities than other fish groups, and 1.5 - 2.5 times lower estimated densities than other groups in deep transects. Compared to the highest density $ALAN^+$ $Docks^+$ locations, salmon densities were statistically lower at $ALAN^-$ $Docks^+$ locations and similar to $ALAN^-$ $Docks^-$ sites (e.g., Gene Coulon Park) (Table 3). Combined juvenile salmon had the highest estimated densities (estimated marginal means; EMM) for all fish, and those were at the residential $ALAN^+$ $Docks^+$ sites (EMM=51 for both depths, 112 for the shallow depth) (Figure 5). Their next highest EMMs were at $ALAN^-$ $Docks^-$ sites (both depths; EMM's = 25; shallow = 57, deep = 11).

The lowest predator EMM's were at the highest salmon density locations, although predators were more evenly distributed among stressor habitats than salmon. Except for low densities at $ALAN^+$ habitats (e.g., Boeing and Hyatt) (both depths; EMM = 15.6), fish in the 'other' category were evenly distributed among the remaining habitats (both depth EMMs; 30.5-36.5). An exception to this is that half of the three-spined sticklebacks we counted were at the residential $ALAN^-$ $Docks^+$ habitats, primarily among the riprap shorelines (Figure 5), conflating the 'other' category at those locations. Highest non-stickleback 'other' densities were at $ALAN^-$ $Docks^-$ habitats, followed by $ALAN^-$ $Docks^+$ habitats. Many of the 'other' fish were future or borderline predators, yet too small or water temperatures were too low.

Salmon

We isolated salmon-only data and used GLMs to compare densities among stressor locations and by salmon groups (Chinook, mixed Chinook/sockeye schools, unidentified juvenile salmon, and sockeye). We did not incorporate categorical depth into our models as salmon were found primarily in shallow transects, and we removed the three Coho salmon that we observed. Highest overall estimated marginal mean densities of salmon were for Chinook at $ALAN^+$ $Docks^+$ (EMM=52) followed by $ALAN^-$ $Docks^+$ (EMM=19) and $ALAN^-$ $Docks^-$ (EMM=17) (Figure 6). Highest unidentified juvenile salmon densities were at $ALAN^+$ $Docks^+$ and $ALAN^-$ $Docks^-$ (both EMMs=10). Highest sockeye salmon densities were at $ALAN^-$ $Docks^-$ (EMM=14) followed by $ALAN^+$ $Docks^+$ (EMM=13), and all remaining EMMs were single digit values. Although overall salmon densities were lower at $ALAN^-$ $Docks^+$ locations than at $ALAN^+$ $Docks^+$ and $ALAN^-$ $Docks^-$ sites, pairwise comparisons show Chinook densities were 2.6 times higher than unidentified juvenile salmon and sockeye at $ALAN^-$ $Docks^+$ sites. Our analyses of fish locations along the transect found that 30% of these Chinook were located at shallow, gently sloping pocket beach microhabitats (<0.3m) that comprised a small portion of these habitats, most of which was riprap shoreline.

Docks

In our study, we did not see a significant effect of overwater structures on salmon and other fish distributions (Figure 7), but we likely do not have sufficient data to fully test for an effect of docks (see Discussion). The most common species under docks in our study was three-spined stickleback, commonly among riprap, followed by sculpin.

Artificial Light at Night

Our commercial/industrial ALAN$^+$ Docks$^-$ (Boeing, Hyatt) and reference ALAN$^-$ Docks$^-$ (Gene Coulon) locations had the most consistent blue light intensity (Figure 8), with ALAN$^+$ Docks$^-$ exhibiting the most consistently high blue light intensity values (measured via Mk9) and Gene Coulon transects had lower, yet consistent light intensity values. Residential light was more variable for blue and non-blue light intensities. Salmon had highest densities at the residential sites that we had categorized as “high ALAN” sites, that is, sites that had consistent yard and dock lighting. However, our “low ALAN” residential sites experienced variable ALAN, including a bright chicken coop light that was frequently on at the end of site 7. Ultimately, all residential sites had variable light intensity measurements.

Discussion

Fish Distributions

Our study censused the diel fish assemblage in south Lake Washington littoral habitats and highlighted diel fish distribution and behavior patterns for salmon, predators, and other fish. Juvenile salmon, predators, and other fish were largely absent from daytime snorkel surveys along shallow shoreline habitats but were observed in high densities at the same habitats several hours after sunset. The few fish observed nearshore during the day were primarily schooling juvenile salmonids. At night, juvenile salmonids, predators, and other fish were observed in high abundances, with fish largely displaying resting/unaffected behaviors on the substrate. This highlights a pattern of diel fish migration into the shallow littoral zone to rest at night (Becker et al. 2011). Our data shows that juvenile salmon and their predators likely undergo daily migration to these nearshore habitats, and this spatial overlap could present predation risks to juvenile salmon.

Abundances of yellow perch have substantially increased in recent decades (Tabor et al. 2024), and while they were not the most abundant non-native predator in a 2024 deeper water gill net study (Bosworth and Short 2024), they were the most abundant fish in our study of shallow nearshore environments. Late spring is yellow perch mating season, a time of heavy feeding, which overlaps with juvenile salmon migration along south Lake Washington shorelines. The spatial overlap of juvenile salmon and yellow perch we observed in the shallow littoral zone at night suggests juvenile salmon may be at risk of predation during their daily migration to their preferred nighttime resting habitat. Since yellow perch feed primarily during dusk (Tabor et al. 2024), the "perpetual twilight" conditions created by ALAN may extend the foraging window of yellow perch, leading to increased predation on juvenile salmon. Salmon may experience increased predation under ALAN conditions from all piscivorous fish due to enhanced nocturnal visual acuity for predators (Bolton et al. 2017, Beauchamp et al. 2020). Further studies on the realized impacts of ALAN on the extent of predation are needed in these critical juvenile salmon rearing habitats in southern Lake Washington.

Juvenile salmon are attracted to artificial light, which is thought to increase predation risk (Tabor et al. 2004, 2021), but our pilot project demonstrates that shallow water habitat preference supersedes attraction to ALAN. Sites with the highest measured ALAN (ALAN$^+$ Docks$^-$) did not contain the highest juvenile salmon densities, but rather the sites with the shallowest shoreline habitat had the highest juvenile salmon densities, regardless of ALAN levels. The ALAN$^+$ Docks$^-$ locations had the lowest overall fish densities, likely due to extensive shoreline armoring and a lack of shallow water habitat for salmon and other smaller fish. Water depths averaged 1.4 – 3 m. At one ALAN$^+$ Docks$^-$ site (Hyatt), our snorkel transects averaged 3 m depth, which made it difficult to see the benthos. It is possible we missed some fish resting on the bottom due to limited visibility, and SCUBA surveys could be useful for these deeper sites. Our additional ALAN$^+$ Docks$^-$ site, the Boeing plant, had deeper water than other sites (average depth=1.4 m), but we were able to clearly see the substrate and observe fish.

We did not find evidence of day or night dock-related distributions for any fish group. Docks can impact fish by altering the light environment through shading (Munsch et al. 2017) and adding artificial habitat structures such as pilings and support beams. We observed several instances of predatory fish including smallmouth bass resting on dock structures at night, but no significant effect of docks on overall fish distribution day or night. At sites where docks were present, most of the area surveyed was between docks rather than under docks, given the relatively small width of residential docks and amount of spacing between docks on adjacent properties. There is evidence that small docks are less impactful than large piers (Accola et al. 2022), yet small, additive effects of small docks and the shoreline armoring typically accompanying the docks along residential shorelines may still negatively influence juvenile salmon. A study by Tabor et al. (2011) found that juvenile Chinook salmon were rarely observed under docks day or night in Lake Washington but were found more often within 5m of docks than in open water areas with no docks. A more rigorous study focused on dock effects may be able to identify and quantify the influence of small docks in littoral habitats in Lake Washington.

ALAN^{+} Docks^{+}, which had the highest salmon densities, had average water depths of 0.65 m (combined shallow and deep transects), which was similar to depths at ALAN^{-} Docks^{-} (0.65 m), which had the next highest salmon densities. Average water depth was deeper at ALAN^{-} Docks^{+} sites (1.3 m) and 30% of Chinook at these sites were found in shallow-water microhabitats (<0.3 m) that we've termed pocket beaches. While shallow transects at the two sites averaged 0.8 m and 1.3 m, most salmon were located at the shallower site. Salmon prioritized inhabiting the shallowest habitats along the shoreline and within transects, demonstrating that when shallow-water habitat is available, juvenile Chinook will use it. Pocket beaches represented less than 30% of shoreline habitat available, which shows that juvenile salmon will disproportionately use these shallow-water microhabitats, similar to another south Lake Washington study that found the highest abundances of juvenile salmon in March/April in 0.5 m water depth or shallower and on mixed sand/gravel substrate (Tabor et al. 2011). Salmon may be attracted to these shallow pocket beaches because they provide cover from predation under dark conditions. However, ALAN has been shown to increase predation efficiency at shallow sloping habitats where juvenile salmon congregate in the lower Cedar River (Tabor et al. 2004).

The extent to which ALAN levels alter predator-prey dynamics at pocket beaches along south Lake Washington residential shorelines is not well understood and is an area that we would like to investigate further using acoustic camera monitoring. Based on our initial acoustic camera surveys and previous studies demonstrating its use (Becker et al. 2011, Accola et al. 2022) we are confident that acoustic methods will be useful for studying fish behaviors in situ.

Although we observed some fish behaviors of attraction to ALAN, feeding, and schooling at night, most fish were resting, unaffected by our presence, or swam away after we approached them. Predators were observed resting or unaffected by our presence more than the remaining fish groups. Salmon and other small fish, while frequently resting or unaffected by our presence, had more behaviors associated with being disturbed by our presence. Nearly all the fish we observed feeding were three-spined stickleback, in riprap habitats.

We did not find juvenile sockeye distribution differences east versus west of the mouth of the Cedar River but found the highest densities of juvenile Chinook west of the Cedar River. Given the habitat and sampling variability, we cannot explicitly state there were differences in Chinook distributions east or west of the mouth of the Cedar River.

Study Design

Juvenile salmon densities were highest at, and not significantly different from each other, at ALAN^{+} Docks^{+} (both light and dock stressors) and ALAN^{-} Docks^{-} (neither stressor) sites, so our study did not find evidence for a substantial influence of either stressor on juvenile salmon distribution. To fully examine the interactive effects of docks and ALAN, it would be necessary to manipulate each stressor while keeping others constant, which is difficult to accomplish in situ studies, given the variability in shoreline lighting, docks, armoring, vegetation, and substrate. However, Bassi et al.'s 2021 synthesis on fish ALAN research stresses the importance of in situ studies.

Across all sites, juvenile salmon had significantly higher densities at shallow transects, and frequently were counted in the shallowest microhabitats, suggesting water depth is more important for juvenile salmon distribution than ALAN or docks. The shoreline habitat at ALAN^{+} Docks^{+} sites was similar to ALAN^{-} Docks^{-}, with gently sloping beaches and longer stretches of shallow water habitat. In contrast, ALAN^{+} Docks^{-} locations were armored with concrete bulkheads and had no shallow water habitat.

The measured light intensity was similar between all sites except the industrial/commercial ALAN^{+} Docks^{-} sites, where it was higher due to the intensity of lighting used for commercial and industrial purposes compared to residential shoreline lights (e.g., string lights for aesthetics). Quantitative ALAN mapping work in the area measured light levels in front of Boeing (ALAN^{+} Docks^{-}) to be over 6 times brighter than measurements taken in a residential section of the western shoreline near one of the ALAN^{-} Docks^{+} sites (Tessa Code, personal communication).

Next Steps

Studies that control for habitat differences which may influence fish distributions can quantify the in situ effects of predator-prey dynamics in littoral ALAN habitats. A study focusing on the influence of ALAN on juvenile salmon predation in shallow water habitats, in which the site is held constant to control for as many environmental variables as possible, and ALAN levels are manipulated, can measure the realized impacts of ALAN on juvenile salmon predation. That is, piscivorous fish diets can be examined and acoustic camera surveys can be used to evaluate the behavior of predators and prey.

We recommend investigating more into the effect of residential lighting on the behavior of yellow perch as it pertains to their predation on juvenile Chinook and sockeye. Our light measurements clearly delineate that residential lighting is very variable, which can make it a challenge to fully understand the influence of residential ALAN levels on fish behavior. Alternatively, there is a possibility that residential lighting does not influence fish behavior, but instead is influenced by overall skyglow, the cumulative influence of landscape-scale lighting including bright industrial lighting from surrounding businesses. Focusing on residential light can also help inform management practices and create a guide for residents to change their behavior for the benefit of salmon habitat.

We recommend fully exploring the issue directly to determine whether ALAN influences crepuscular migration to the shallow littoral zone, the extent to which residential ALAN levels can impact predation on juvenile salmon, and the role of refuge habitats like shallow pocket beaches.

Summary

In summary, we 1) censused day/night south Lake Washington littoral habitats, updating the fish assemblage data, including quantifying high densities of non-native yellow perch in shallow habitats, we 2) identified a daily migration to the shallow littoral zone to rest at night, wherein juvenile salmon, smaller predators, and other fish move onshore to cohabit shoreline habitats, and 3) quantified a juvenile salmon preference for shallow water habitats that supersedes attraction to ALAN.

While much research has warned of hypothesized predation due to ALAN, we recommend in situ studies that identify realized nighttime predation. This can best inform applied management approaches and engage shoreline homeowners in developing stewardship strategies to benefit salmon recovery – whether constructing shallow pocket microhabitats or reducing ALAN levels.

Acknowledgements

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Tables

Table 1: Summary of categorizations of each southern Lake Washington fish survey location. The average water depth (meters) over all surveys (*n*=6) is shown for both Shallow and Deep transects at each site. Sites were visually categorized prior to sampling season as having higher Artificial Light at Night (ALAN) levels from direct light sources, lower ALAN from ambient light, and for presence or absence of small overwater structures (docks). Relative blue light intensity was measured using a TDR-Mk9 archival tag, averaged across each transect for all sampling events, and converted to W cm^{-2}.

Site	Avg. Depth (m)	ALAN categorization	Dock	Stressor sombination	Avg blue light intensity (W cm^{-2})
1	0.5m	Low-Reference	No Docks	$ALAN^{-}$ $Docks^{-}$	3.6E-08
2	3m	High-Commercial	No Docks	$ALAN^{+}$ $Docks^{-}$	1.6E-07
3	1.4m	High-Commercial	No Docks	$ALAN^{+}$ $Docks^{-}$	1.2E-07
4	0.7m	High-Residential	Docks	$ALAN^{+}$ $Docks^{+}$	1.9E-08
5	0.6m	High-Residential	Docks	$ALAN^{+}$ $Docks^{+}$	4.1E-08
6	1m	Low-Residential	Docks	$ALAN^{-}$ $Docks^{+}$	1.3E-08
7	1.6m	Low-Residential	Docks	$ALAN^{-}$ $Docks^{+}$	4.6E-08
8	0.8	Low-Reference	No Docks	$ALAN^{-}$ $Docks^{-}$	3.2E-08

Table 2: Overall day/night salmon counts, and day/night fish counts for top taxa among stressor categories.

<table>
<tr><th></th><th>Chinook</th><th>Sockeye</th><th>Juv. Salmon</th><th>Chin/Sockeye</th><th>Coho</th></tr>
<tr><td>Day</td><td>208</td><td>94</td><td>174</td><td>0</td><td>0</td></tr>
<tr><td>Night</td><td>1024</td><td>242</td><td>221</td><td>29</td><td>3</td></tr>
<tr><th></th><th>ALAN$^+$ Docks$^+$</th><th>ALAN$^+$ Docks$^-$</th><th>ALAN$^-$ Docks$^+$</th><th colspan="2">ALAN$^-$ Docks$^-$</th></tr>
<tr><td>DAY</td><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Chinook</td><td>80</td><td>1</td><td>77</td><td colspan="2">50</td></tr>
<tr><td>sockeye</td><td>0</td><td>0</td><td>9</td><td colspan="2">85</td></tr>
<tr><td>Juv. Salmon</td><td>0</td><td>0</td><td>174</td><td colspan="2">0</td></tr>
<tr><td>NIGHT</td><td></td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Chinook</td><td>611</td><td>17</td><td>206</td><td colspan="2">190</td></tr>
<tr><td>sockeye</td><td>103</td><td>20</td><td>7</td><td colspan="2">112</td></tr>
<tr><td>Juv. Salmon</td><td>80</td><td>42</td><td>5</td><td colspan="2">94</td></tr>
<tr><td>Yellow perch</td><td>270</td><td>154</td><td>528</td><td colspan="2">372</td></tr>
<tr><td>Smallmouth bass</td><td>7</td><td>47</td><td>12</td><td colspan="2">42</td></tr>
<tr><td>Unid. Trout</td><td>7</td><td>2</td><td>21</td><td colspan="2">9</td></tr>
<tr><td>Largemouth bass</td><td>2</td><td>14</td><td>5</td><td colspan="2">5</td></tr>
<tr><td>Prickly sculpin</td><td>8</td><td>0</td><td>8</td><td colspan="2">14</td></tr>
</table>

Table 3: Post-hoc tests estimating the marginal means (EMM) of nighttime salmon densities from generalized linear models for stressor categories. Output includes chi-square EMM values, standard errors (SE), lower and upper confidence intervals (CI), and salmon-only post hoc pairwise comparisons of EMMs. Shown are significant differences. A negative value indicates the latter EMM is lower than the former.

	Salmon				**Predators**				**Other**			
	EMM	*SE*	*Lower CI*	*Upper CI*	*EMM*	*SE*	*Lower CI*	*Upper CI*	*EMM*	*SE*	*Lower CI*	*Upper CI*
ALAN⁺ Docks⁺	51.34	14.00	30.13	87.5	13.16	4.28	6.96	24.9	30.54	8.75	17.42	53.5
ALAN⁺ Docks⁻	8.67	2.8	4.53	16.6	20.93	7.07	10.80	40.6	15.59	4.85	8.47	28.7
ALAN⁻ Docks⁺	10.72	3.12	6.05	19.0	33.27	9.07	19.49	56.8	33.95	9.29	19.86	58.0
ALAN⁻ Docks⁻	25.04	6.92	14.57	43.0	18.33	5.75	9.91	33.9	36.49	9.97	21.36	62.3
Salmon only	**EMM**	**SE**	**p-value**									
ALAN⁺ Docks⁺- ALAN⁺ Docks⁻	1.35	0.4	0.001									
ALAN⁺ Docks⁺- ALAN⁻ Docks⁺	1.78	0.4	0.0001									

ALAN^{+} Docks^{-}- ALAN^{-} Docks^{-}	-1.00	0.34	0.03									
ALAN^{-} Docks^{+}- ALAN^{-} Docks^{-}	-1.4	0.38	0.001									

Figures

Figure 1. Map of 8 sites (red diamonds) in south Lake Washington surveyed for 2024 snorkel surveys. **Inset**: Project study area within the WRIA 8 watershed. Map source: Google Earth 2022.

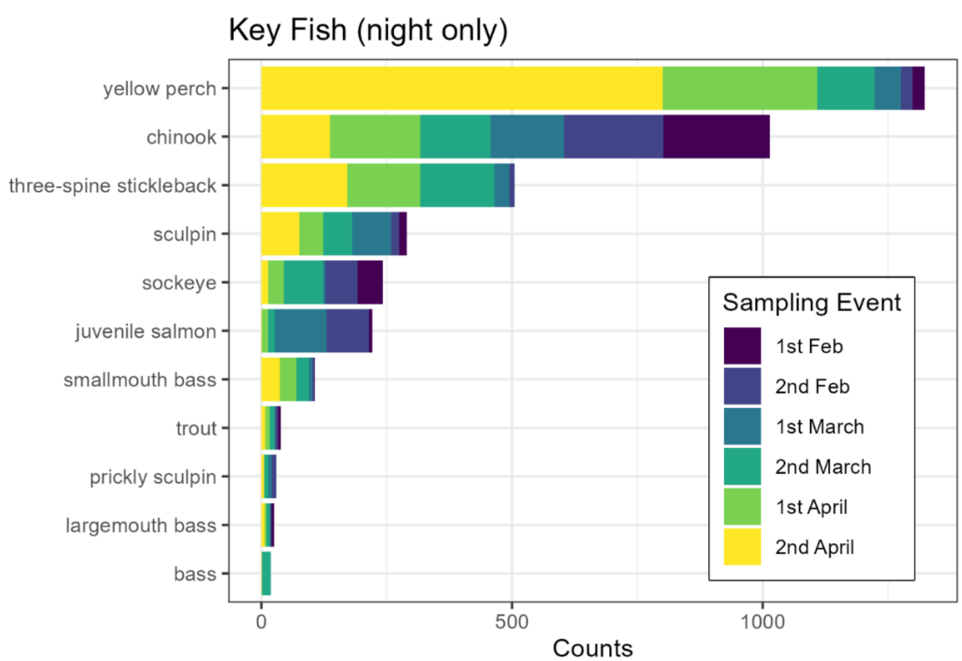


Figure 2. Stacked bar plots of top fishes observed at night. Plots are sorted by overall counts, in descending order, and color sorted by sampling event. 1st and 2nd sampling events of each month occurred two weeks apart.

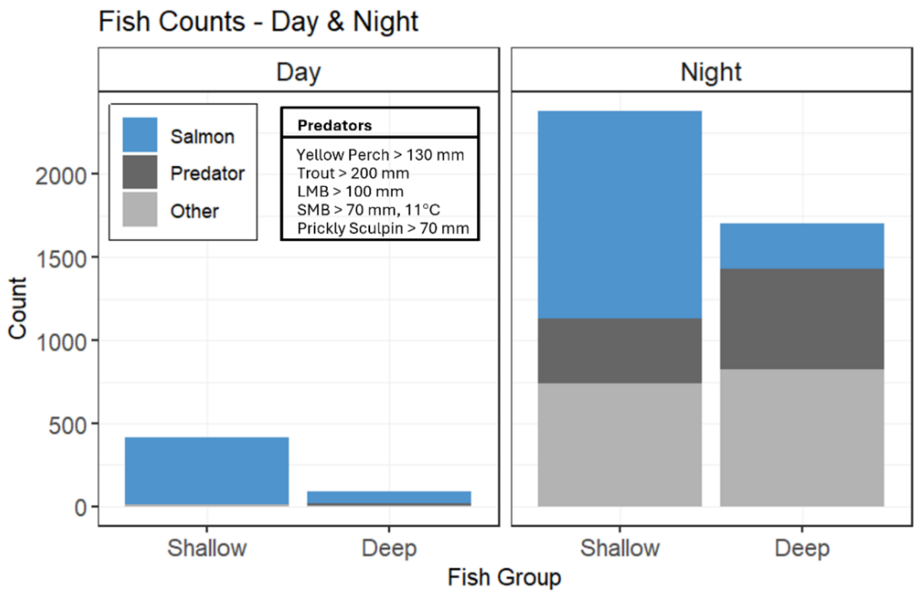


Figure 3. Bar plots of total fish counts, sorted by day/night and categorical transect depth (shallow, deep). Plots are color sorted by functional fish group (salmon, predator, other). Non-salmon fish groups are defined by fish species, size, and water temperature.

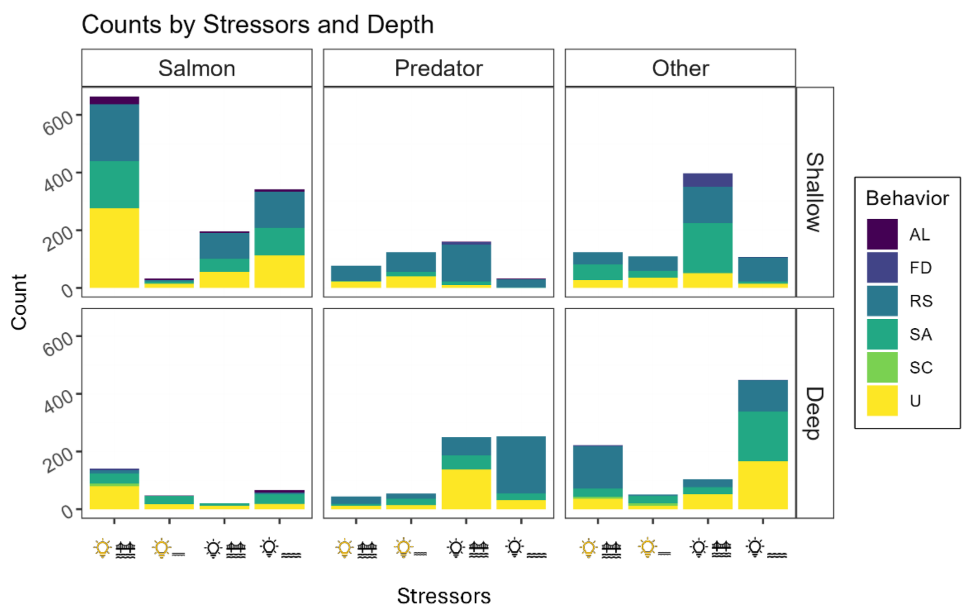


Figure 4. Bar plots of total nighttime fish counts, sorted by stressor (combinations of ALAN and overwater structures), depth (shallow; 3m from shore, deep; 7m from shore), and functional fish group (salmon, predator, and other fish). Stacked bar plots are color sorted by fish behaviors. AL=attracted to our lights, FD=feeding, RS=resting, SA=swam away, SC=schooling, U=unaffected. Yellow light bulb = high ALAN, black structure over water = overwater structures, black light bulb = lower ALAN, and water-only=no overwater structures.

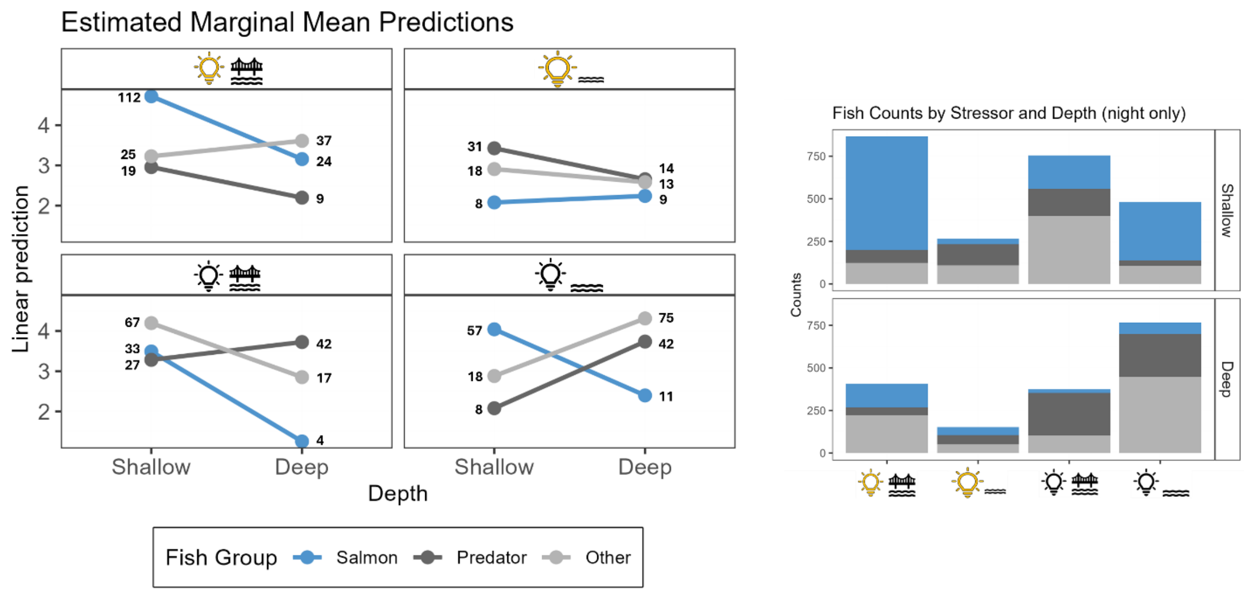


Figure 5. **Left**: interactive estimated marginal mean (EMM) plots, showing EMM densities of each fish group for each stressor category (ALAN, Docks), as estimated by our generalized linear models, and sorted by transect depth. **Right**: Bar plots of total fish counts, sorted by stressor combination and transect depth (shallow, deep). Plots are color sorted by functional fish group (salmon, predator, other).

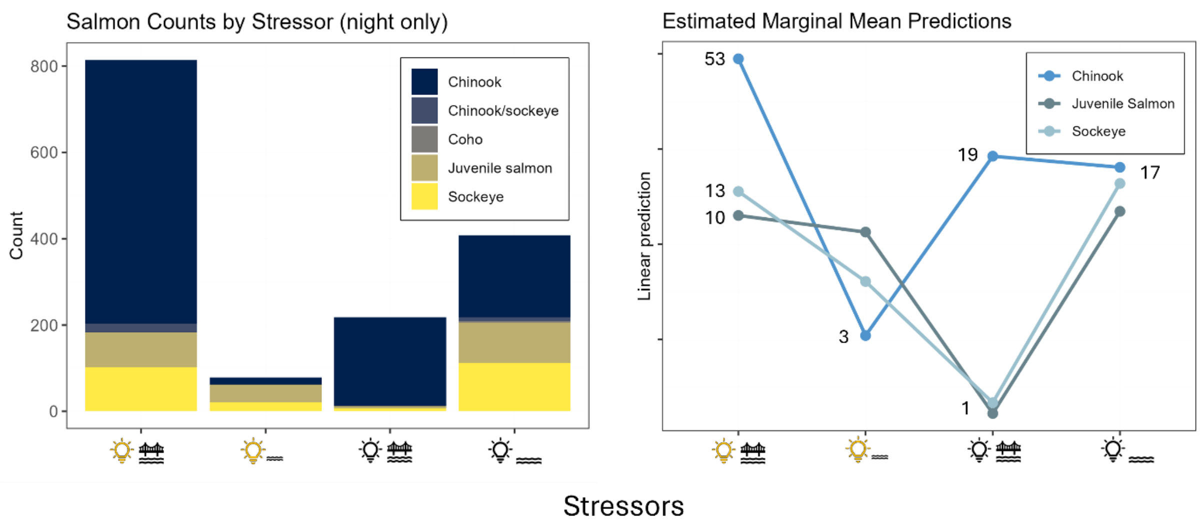


Figure 6. **Left**: stacked bar plots of salmon densities among stressor categories, color sorted by salmon species. **Right**: estimated marginal mean (EMM) plots showing EMM density predictions for each salmon group in all stressor categories (ALAN, Docks), as estimated by our generalized linear models.

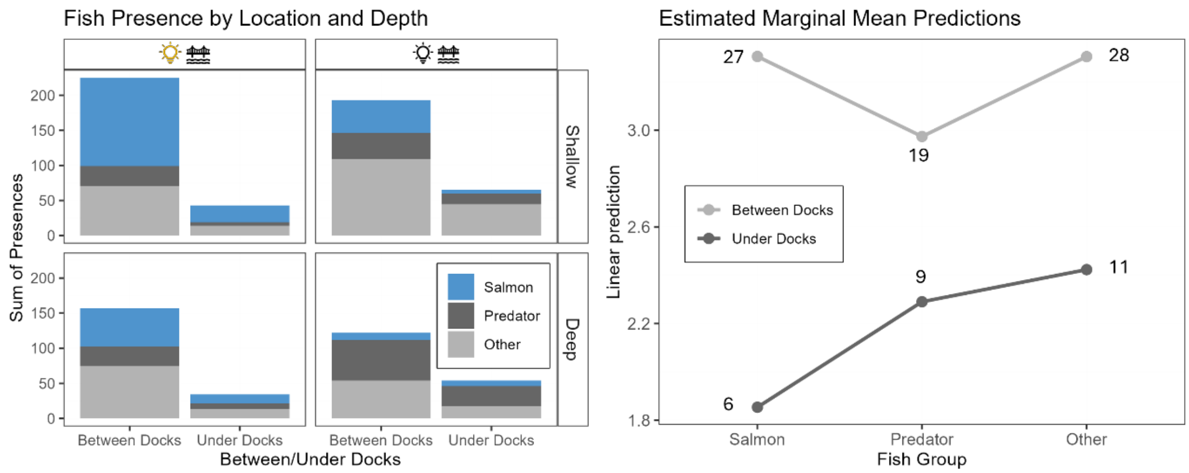
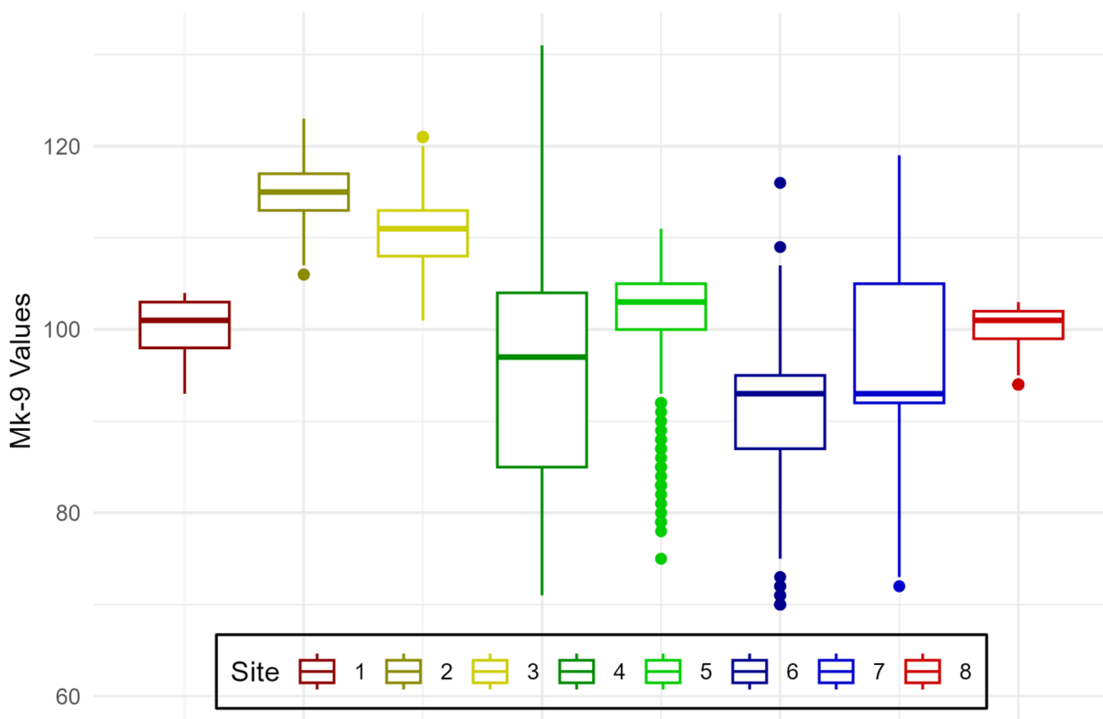


Figure 7. Stacked bar plots of fish *presence* (**left**) and estimated marginal mean (EMM) plots for fish *densities* (**right**) under and between docks along our high docks (3 docks) transects. Bar plots are color sorted by fish group. Although EMMs are higher between docks than under docks, most of each transect was between dock habitat. While our pilot study did not find an effect of docks on fish distribution, we cannot state there is no effect.



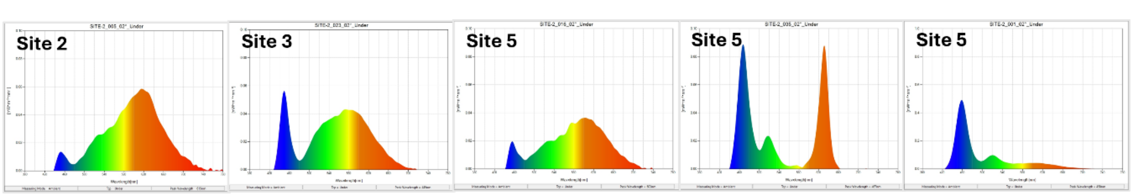


Figure 8. **Top**: boxplots of Wildlife Computers Inc. TDR-Mk9 archival tag (Mk9) relative light intensities (350-550 nanometers) measured along transects. Sampling times were standardized and binned for each transect. Mk9 Values are shown in log-scale on the y-axis. **Bottom**: Sekonic C-7000 Spectrometer images of light wavelengths measurements (380 nm - 780 nm range) among select sites. Sites 2 and 3 were commercial locations with little variability, and site 5 was a residential location with more artificial light variability. The final site 5 plot has a y-axis scaled 10x that of the others. Sites 1, 8 = Low ALAN/no docks, sites 2, 3 = High ALAN/no docks, Sites 4, 5 = High ALAN, high docks, Sites 6, 7 = Low ALAN, high docks. High ALAN = visual categorization of nearby ALAN directed at the water; high docks = 3 docks in transect. Residential sites (4-7) had more variable light than non-residential sites (1-3, 8).