Small overwater structures: a review of effects on Puget Sound habitat and salmon

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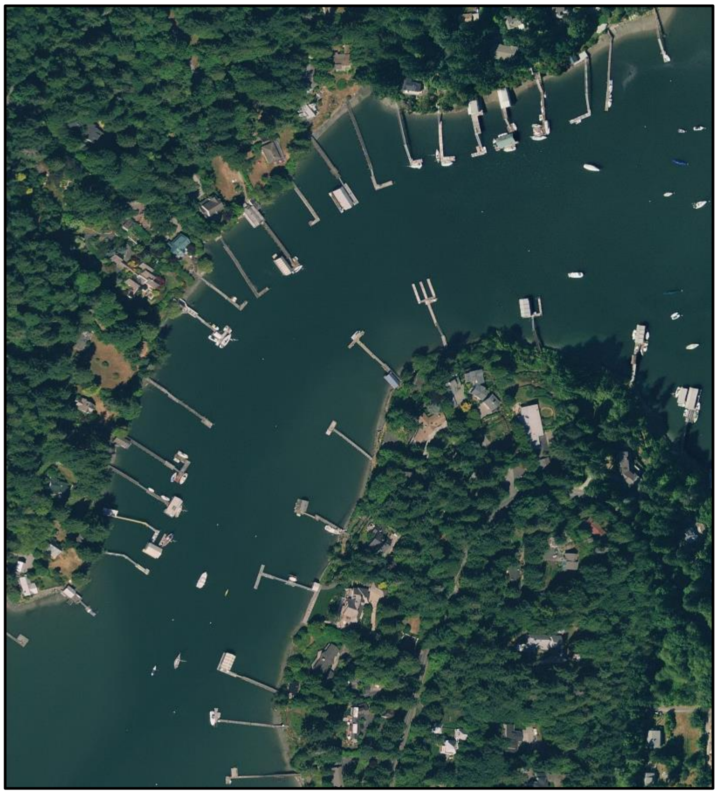

Small overwater structures in Puget Sound, WA. Image from National Agricultural Imagery Program (NAIP 2017).

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1. EXECUTIVE SUMMARY

Small overwater structures (SOWS) like private docks are a common feature of Puget Sound shorelines. Large overwater structures like ferry terminals and commercial piers can cast substantial shadows into the benthos that reduce light penetration, impair submerged aquatic vegetation, and alter salmon behavior and migration. Because of these impacts from large overwater structures, there is concern that SOWS may also impact Puget Sound's nearshore environments and salmon. Here, we review the available literature on the impacts of marine SOWS. We find that there has been considerably less research dedicated to the impacts of SOWS than there has been for large overwater structures. Even so, there is consistent evidence that SOWS impair eelgrass (*Zostera marina*) survival and growth. Beyond eelgrass, there is inconsistent evidence that SOWS impact sugar kelp (*Saccharina latissima*) and we found little research pertaining to other macroalgal species. Studies on associations between fish and SOWS are sparse, although one case study suggests that salmonids avoided moving beneath a single SOWS. To date, there is insufficient research on SOWS in the Puget Sound region to draw robust conclusions about these structures' impacts or what design elements or restoration approaches might mediate any possible impacts from SOWS. However, we emphasize that an absence of evidence is not evidence for an absence of impacts by SOWS. We conclude by outlining critical research questions and the relevant study approaches that would address data gaps surrounding SOWS impacts and management.

2. INTRODUCTION

In Puget Sound – and the Salish Sea more broadly – shoreline development has led to important marine nearshore habitat loss and degradation (Schlenger et al. 2011). Continued population growth and decreasing household sizes are expected to add substantially to the demand for housing around Puget Sound, with the highest relative impact near Puget Sound shorelines (Schlenger et al. 2011, PSRC 2018). This development will likely further degrade Puget Sound habitats, particularly nearshore environments.

The nearshore environment is the area that extends from the top of shoreline bluffs to the deepest extent of the photic zone where sunlight is too diminished for net photosynthesis. Under Washington Administrative Code (WAC) 220-660-320, three edge habitats are considered in nearshore environments that occur along an environmental gradient between upland and aquatic environments, shallow productive zones and deep water, and fresh and marine waters (Clancy et al. 2009). Other nearshore habitat classifications include habitats that are seldom revealed by low tide (shallow subtidal), regularly inundated and revealed by tides (eulittoral), and seldom wet except for sea spray, precipitation, and occasional high tides (supralittoral backshore) (Nightingale and Simenstad 2001). Puget Sound's nearshore environments are vital to a diversity of culturally significant and ecologically important animals, vascular plants, and algae that include salmon, forage fishes, orcas, eelgrass, and kelp (Schlenger et al. 2011). Development in and around marine shoreline and nearshore ecosystem modification can affect the composition, structure, and function of areas that provide habitat for these species like imperiled fishes, notably Pacific salmon species listed under the Endangered Species Act (ESA) (Toft et al. 2007, Moore et al. 2013).

One common component of shoreline development in Puget Sound are overwater structures (OWS) that are often viewed as contributing to a loss of nearshore habitat (Nightingale and Simenstad 2001, Schlenger et al. 2011). Typically located in nearshore inter- and subtidal areas, marine OWS generally encompass a variety of structures – including marinas, ferry terminals, and docks – that can (1) vary in shape, size, material, and height and (2) facilitate access to water for transportation, recreation, and natural resource use. The most comprehensive inventory to date indicates that there are 12,408 OWS of various shapes and sizes in Puget Sound that shade – to various degrees – an estimated 9 km^2 of intertidal habitat (Schlenger et al. 2011, NOAA Fisheries 2018). Puget Sound's ongoing demographic and development trends may have implications for the number of and shading from marine OWS. Large OWS like commercial docks, ferry terminals, and large piers have been relatively well-studied and are known to impact marine environments in many ways, especially by casting shadows that impair vegetation growth, decrease the abundance and species richness of consumers, and alter fish behavior (Nightingale and Simenstad 2001, Munsch et al. 2017). OWS in marine environments are often hypothesized to directly or indirectly impact juvenile salmon by (1) creating a behavioral barrier to migration along the shoreline and (2) decreasing salmon fitness by producing excess stress, reducing salmon prey, and increasing the rate of juvenile salmon predation by concentrating predators (Ono et al. 2010, Able et al. 2013). We note that most of these hypotheses about the impacts of OWS on salmon have been considered with respect to large OWS but have seldom been explicitly studied for smaller OWS.

The effects of large marine OWS, especially commercial docks and ferry terminals, on marine vegetation and juvenile Pacific salmon (*Oncorhynchus spp.*) have been the focus of research for several decades. However, data on the effects of non-commercial small OWS (**SOWS**; i.e., small docks, piers, floats, ramps, and mooring buoys; **Table 1**) are largely lacking despite the call for research in the mid-1990s (Fresh et al. 1995). The emphasis of research on large OWS is perhaps surprising, given that SOWS are the most common type of OWS in representing two thirds of all OWS in Puget Sound (**Figure 1**; 67%, n = 8,316 total; n = 6,064 small docks and n = 2,252 mooring buoys / floats). The remaining OWS in Puget Sound consist primarily of large docks and piers, bridges, buildings, and marinas (NOAA Fisheries 2018). We note that it is unclear how houseboats and boat houses are counted in NOAA's analysis but that these structures may have similar implications to SOWS. Typically, SOWS have a surface area well below 560m^2 and dimensions are dependent on the type of SOWS (NOAA Fisheries 2018, WAC 220-660-380). Contemporary standards require residential piers to be no wider than 1.8m (6ft), require recreational piers to be no wider than needed for a specific use, discuss floats that are up to 2.4m (8ft) wide, and discourage constructing SOWS that are longer than 18m (60ft) when feasible (WAC 220-660-380). Although exact dimensions can vary, large OWS can have lengths over 700m, widths over 200m, and surfaces areas that are at least above 560m^2 but are often tens of thousands of m^2, making them substantially larger than SOWS (Mulvihill et al. 1980, Haas et al. 202, Kelty and Bliven 2003, Toft et al. 2007, Able et al. 2013, Ono and Simenstad 2014). Two decades ago, Nightingale and Simenstad (2001) conducted a thorough review of the effects of OWS on fish and shellfish habitats in marine environments. However, this review focused on large OWS and findings on SOWS were limited. Similar reviews have been commissioned in the Puget Sound region (e.g., Kahler 2000, JSA 2006) but all largely recapitulate the findings of Nightingale and Simenstad (2001), with little added discussion dedicated to empirical studies on SOWS, principally because new studies are limited.

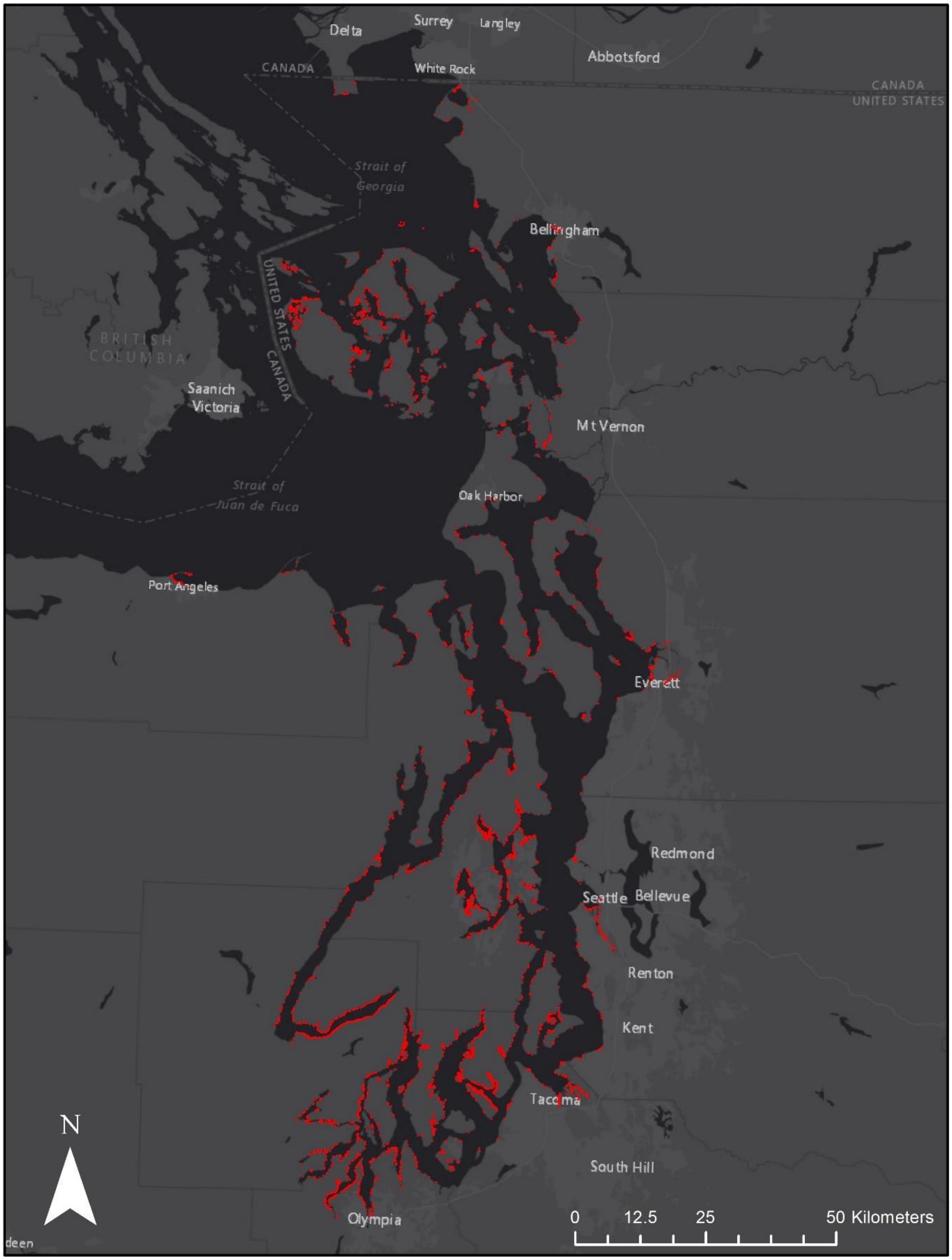

Figure 1. *Small overwater structures (SOWS; small docks, floats, and buoys) in Puget Sound. SOWS are shown as red. SOWS data from NOAA. Basemap courtesy of ESRI.*

Puget Sound, and the Salish Sea more broadly, function as important habitat for multiple salmon species, including those listed under the Endangered Species Act (Quinn 2005). As such, a synthetic understanding of research on marine SOWS specific to the region is essential for proper policy development and permitting. Such a review is particularly pertinent to the Washington Department of Fish and Wildlife (WDFW) which is tasked with issuing Hydraulic Project Approval (HPA) permits for the construction of SOWS (WAC 220-660-380). It is also relevant to the U.S. Army Corps of Engineers which permits overwater structures in consultation with the National Oceanic and Atmospheric Administration [33 CFR 325.2(e)(2), Regional General Permit 6 for Structures in Inland Marine Waters of Washington State]. Many local governments also permit these types of structures consistent with their Shoreline Master Programs and their guidance and permitting would similarly benefit from a critical review of SOWS impacts. The lack of a synthetic understanding of how SOWS influence fishes and nearshore habitat in Puget Sound hinders (1) both general and site-specific technical guidance from agencies and local entities to shoreline landowners, (2) identification of restoration priorities related to negative effects of SOWS, (3) development of better policies governing the construction of new and replacement SOWS, and (4) identification of research gaps needed to better assess and manage the impacts of SOWS.

Here, we review empirical research on the impact of SOWS in Puget Sound. Our review centers on the effects of marine SOWS on light availability, plant and macroalgal cover, and fish behavior (e.g., migration and feeding) and fitness (e.g., predation and food limitation), particularly for Pacific salmon. We limit our review to impacts directly related to the structure of SOWS, rather than effects associated with SOWS construction or use. Additionally, our review centers on small docks, piers, ramps, and floats but does not emphasize mooring buoys. Despite mooring buoys comprising ~ ¼ of SOWS and being similarly permitted to other SOWS under WAC 220-660-380, their impacts are largely unstudied and may be dissimilar from other SOWS given their design. We end by highlighting knowledge gaps and prioritized management-relevant research questions.

3. METHODS

To identify pertinent literature, we first searched Google Scholar with keywords and phrases, including “marine overwater structures” and “residential marine docks”, reviewed Literature Cited sections from relevant publications (e.g., Nightingale and Simenstad 2001, Munsch et al. 2017), and supplemented with additional literature of which we were aware but was not returned in targeted searches. We also obtained input and references from subject matter experts. We included relevant findings from peer-reviewed journal articles, books, theses/dissertations, technical reports, and symposia proceedings. Additionally, we searched a database of literature on the effects of overwater structures compiled by NOAA’s National Centers for Coastal Ocean Science (Kelty and Bliven 2003).

We found that most research on OWS has focused on larger, commercial marine OWS or OWS (mostly SOWS) in freshwater systems. Where possible, we emphasize literature on residential SOWS from Puget Sound and the Salish Sea (including southwestern British Columbia) more broadly. Because of the limited research conducted in our geographic area and on marine SOWS more specifically, we necessarily supplement our review by drawing on literature from a broader geographic area and from larger, commercial OWS and freshwater

SOWS to inform potential impact mechanisms. We define SOWS as those meeting the definition of docks, piers, floats, ramps, and mooring buoys as defined by WAC 220-660-380 (

Table 1). Additionally, we use the term "deck" or "decking" to describe the surface materials of docks, piers, floats, and ramps Although the construction of SOWS likely impacts habitat and fish life, we focus on the long-term impacts directly related to the presence of SOWS.

Table 1. Definitions of small overwater structures (from WAC 220-660-380).

Structure Type	Definition
Docks	Structures that are fixed to the shoreline but floating on the water.
Piers	Fixed piling supported structures.
Floats (Rafts)	Floating structures that are moored, anchored, or otherwise secured in the water, but not directly connected to the shoreline.
Ramps	Gangways that connect a pier or shoreline to a float and provides access between the two. Pilings associated with these structures are timber, steel, or reinforced concrete, or composite posts that are driven or jacked into the bed.
Mooring Buoys	Floating structure on the surface of the water that is used for private and commercial vessel moorage.

We focused our search on the saltwater habitats of special concern identified in WAC 220-660-320. Such saltwater habitats require a higher level of protection because they provide essential functions in the developmental life history of fish by supporting migration, spawning, rearing, and feeding. Relevant to our review, saltwater habitats of special concern include (1) migration corridors and rearing and feeding areas for juvenile salmon, (2) areas of native aquatic vegetation that support fish life, (3) beds of seagrass like eelgrass (*Zostera marina*) and kelp (order Laminariales), and (4) spawning beds, including various macroalgae, for Pacific herring (*Clupea pallasi*) and other forage fishes. Forage fish like herring are an important food for Pacific salmon and are known to spawn on seagrass, kelp, and other macroalgae.

Overwater structures may influence nearshore composition, structure, and functions through a diversity of direct and indirect effects, including alteration of light availability, wave energy, shoreline erosion, sediment transport, water quality, and the exchange of aquatic organisms (Nightingale and Simenstad 2001, Williams and Thom 2001, Schlenger et al. 2011). Our review largely addresses the hypothesis that, because marine SOWS directly attenuate sunlight to the nearshore environment, they impair aquatic vegetation growth and alter vascular plant and algal community composition. Under this hypothesis, fish presence, survival, and behavior are also negatively impacted by reduced light availability and habitat quality due to changes in the vegetation and associated invertebrate community as well as changes in the fish predator community. We focus on this hypothesis, rather than on other possible impacts, because impacts related to light and shading have received the most attention. Furthermore, our review turned up few other studies that explored other potential OWS impacts, even for large OWS. Even so, we do not assume light-mediated impacts are necessarily the only or the most serious consequences of SOWS. We will highlight differences in impacts between large and small structures where possible and identify gaps in knowledge.

The Revised Code of Washington (RCW) 34.05.271 requires WDFW to categorize sources of information used to inform technical documents that directly support implementation of a state rule or statute. Because our review may be referenced in regulations, such as for Hydraulic Project Approval (e.g., WAC 220-660-380) and Shoreline Management Act [e.g., WAC 173-26-221(5) (b)], we classify all references in the literature cited section into the following RCW 34.05.271 categories:

(i) Independent peer review: Review is overseen by an independent third party;
(ii) Internal peer review: Review by staff internal to the department of fish and wildlife;
(iii) External peer review: Review by persons that are external to and selected by the department of fish and wildlife;
(iv) Open review: Documented open public review process that is not limited to invited organizations or individuals;
(v) Legal and policy document: Documents related to the legal framework for the significant agency action including but not limited to: (A) Federal and state statutes; (B) Court and hearings board decisions; (C) Federal and state administrative rules and regulations; and D) Policy and regulatory documents adopted by local governments;
(vi) Data from primary research, monitoring activities, or other sources, but that has not been incorporated as part of documents reviewed under the processes described in (i), (ii), (iii), and (iv) of this subsection;
(vii) Records of the best professional judgment of department of fish and wildlife employees or other individuals; or
(viii) Other: Sources of information that do not fit into categories i - vii.

We tended to assign graduate theses and conference proceedings as category viii because it is often unclear whether such documents have undergone peer review or of what quality. Similarly, reports from various agencies were often classified as category viii because the form of peer review was unclear.

We also supplemented our literature review with expert opinion and unpublished data from subject matter experts when available. Subject matter experts consulted here include Amy Leitman and Maureen Goff (Marine Surveys & Assessments), Thomas Mumford Jr. (Marine Agronomics), Nam Siu (WDFW), and Chris Betcher, Leo Bodensteiner, Eric Eisenhardt, Beth Tate (Jen-Jay Inc.).

4. LIGHT

Light drives photosynthesis which fuels vegetative growth and survival. Light also plays an important role in salmon behavior. Light availability to the water surface depends on multiple site-specific conditions and processes, including solar angle (i.e., time of day and season), atmospheric transparency (i.e., particles, haze, smoke), and cloud cover. The nearshore benthos is inherently light-reduced due to the reflection of light at the water's surface, and attenuation of light related to depth, water clarity, and light absorption by vegetation in the water column (e.g., phytoplankton and epiphytic algae). The depth at which vegetative life survives is related to both the depth of light penetration into the water column and the specific light requirements for individual species (Strickland 1958; Sheldon and Boylen 1977; Duarte 1991; Dennison *et al.* 1993). In Puget Sound, the depth to which sufficient light penetrates to support plant growth (i.e., photic zone) is often under 10m (33ft) below mean lower low water (MLLW) for most vascular plant and algal species but varies depending on the species from ~ 4-30m (up to 98.4ft; Mumford 2007). Beyond effects on vegetation, juvenile salmon may be particularly sensitive to light conditions as shaded environments may alter their migratory behavior. Even so, impacts to fish behavior are not expected to be as pronounced as impacts to vegetation that is more light-sensitive (Blanton et al. 2002, Ono and Simenstad 2014). Natural light regimes are therefore an important component of nearshore ecosystem function.

One of the best understood and intuitive impacts of OWS is the reduction in light availability (Munsch et al. 2017). Overwater structures cast shadows, thereby attenuating incoming solar radiation and reducing the available light beneath and adjacent to docks. Deck height, width, orientation, and construction material are generally understood to influence the magnitude and duration of shading (Burdick and Short 1999, Gayaldo and Nelson 2006). In Washington, current OWS design policy requires at least 30-50% "functional grating" of decks, depending on orientation and structure type (WAC 220-660-380(4)(c, d, f)). Functional grating refers to the percentage of open area in light-permeable grating that is not covered or blocked by any object, including structural components like framing wood, floatation tubs, or objects placed on the surface of the grating (WAC 220-660-030(64)). Functional grating contrasts with classic plank decking, which often permits little light penetration.

Although *ex situ* (not under field conditions) experiments performed by the Washington Department of Natural Resources (DNR) have shown that an increase in the amount of functional grating increases light penetration, these experiments did not find a linear relationship between the amounts of functional grating and shade cast beneath and beside decking (Donoghue 2014). This is because the size, shape, and orientation of functional grating, the thickness of the decking material, and the deck height influence the amount of light that passes through (Donoghue 2014). These experiments found that values of PAR (photosynthetic active radiation; light frequencies used by plants and algae for photosynthesis) measured at the water's surface beneath grated decking was 16-32% of the PAR measured at unobstructed, control light conditions. When grated decking was elevated to 45cm (18in) above the water surface, PAR increased to 26-40% of the PAR measured under control conditions. The amount of PAR recorded under the decking materials at both elevations was below the threshold necessary for long-term eelgrass (*Zostera marina*) survival (3 mol quanta/m^2/day) in the Puget Sound (Thom et al. 2008), however no direct effects on eelgrass were evaluated. These results align with surveys of 212 private docks in Massachusetts which found that decking height and orientation, compared to decking type (grating versus plank), were better associated with light penetration below SOWS (Logan et al. 2017a).

All OWS are expected to cast shadows that limit light penetration into the benthos. However, the reduced size and dimensions of SOWS could potentially produce less pronounced effects on light and associated light-mediated ecological impacts than larger structures. Only a small number of studies have evaluated the ambient light conditions under residential SOWS (compared to other OWS) in Puget Sound. Szypulski (2018) evaluated available PAR below and adjacent to SOWS compared to paired controls (no structures) at three locations in Puget Sound. Available PAR in the benthos was significantly higher at control sites (means = 3,517 – 13,2923 $\mu mol/m^2/s$) than at nearby paired docks (means = 1,247 – 10,834$\mu mol/m^2/s$). However, we note that the dock measurements reported here are 2.5m north of the dock and not directly beneath the dock. This is because Szypulski (2018) reported measurements beneath the docks only at depths of 1m below the water's surface but reported control measurements at 0.5m above bottom. Because PAR diminishes with water depth, control and beneath-dock measurements cannot be meaningfully compared due to the different depths of these measurements. Beneath-deck PAR measurements at 1m below the surface are reported by Szypulski (2018), but PAR measurements at a comparable depth at the control sites were absent due to technical problems with some PAR sensors (Szypulski, personal communication). Even so, the measurements taken 2.5m north of the docks' edges are largely comparable to the control measurements because they are at similar depths (Szypulski, personal communication). Although measurements taken 2.5m from dock edges are more conservative than those measurements taken directly beneath the dock, these measurements indicate that SOWS shadows can impede light availability several meters beyond SOWS footprints. In the case of these docks, only 10.7% of incoming PAR on average was available 2.5m away from dock edges near the bottom compared to 17.3% of incoming PAR at control sites.

A study at a private dock in San Juan County measured PAR beneath a SOWS and at a nearby, uncovered reference site (Fairbanks 2010). Only 4.0% (68.25$\mu mol/m^2/s$) of available PAR reached 1.2 m below the water's surface under the SOWS, whereas 68.1% (1,161.50 $\mu mol/m^2/s$) of available PAR reached the same depth at the reference site (Fairbanks 2010). Additionally, 9.6% (163.50$\mu mol/m^2/s$) of available PAR reached 2.4m below the water's surface beneath the SOWS, whereas 42.4% (722.00$\mu mol/m^2/s$) of available PAR reached the same depth at the reference site. In this study, less than a quarter of PAR that naturally penetrates unobstructed waters was available to eelgrass beneath the SOWS (Fairbanks 2010), although the reduced amount of PAR under SOWS is sufficient to sustain eelgrass growth (Thom et al. 1998).

Studies of large OWS provide additional information on shading and light availability. In a comparative field study, Gabriel and Donoghue (2016) measured light conditions under docks at the Pleasant Harbor Marina in Brinnon, WA (along Hood Canal). The mean percent of PAR available below OWS, and at a water depth ranging from 25 to 46cm (9.8 to 18.1in), ranged from 3.4 to 19.7% of available light at nearby, uncovered (control) sites. Likewise, in the main body of Puget Sound, work on salmon at the Mukilteo ferry terminal found that large OWS reduced PAR by up to 97% compared to uncovered, adjacent areas (Williams et al. 2003). Similarly, Munsch et al. (2014) found that PAR values under a single large pier in Elliott Bay were 1-3 orders of magnitude reduced relative to ambient PAR, depending on the depth and distance from the pier edge at which PAR was measured.

Data from a variety of OWS provide unsurprising and unambiguous evidence that overwater structures reduce light penetration beneath and adjacent to the OWS, although design considerations like OWS height, width, and decking material can influence the degree of light penetration (Gayaldo and Nelson 2006, Logan et al. 2017a, Munsch et al. 2017). The fact that OWS – including SOWS – cast a shadow that limits light to the benthos is a generalizable phenomenon. However, inconsistencies in the depths at which measurements are taken (e.g., bottom in Szypulski 2018, 1.2 m below water surface in Fairbanks 2010) and a lack of systematic surveys across different SOWS traits like deck height obscures robust conclusions about how these different variables influence PAR penetration. For instance, Fairbanks (2010) studied a SOWS composed of a single linear segment that was north-south in orientation, and 1.9 m x 15m in dimensions. In contrast, Szypulski (2018) studied three different SOWS, each of which were either in a north-south or northwest-southeast orientation, but which differed in shape (i.e., one, two, or three dock segments) and size (3.5m x 10m, 2m x 34m, and 2m x 36m). Conclusions from studies on large OWS may also not be transferable to SOWS or generalizable given the same methodological inconsistencies (e.g., PAR measurements at 0.1m deep by Williams et al. 2003 versus 0.5m intervals down to 2m deep by Munsch et al. 2014). Although SOWS certainly limit light penetration to the benthos, targeted studies that explicitly evaluate a diversity of design conditions and which measure PAR at consistent depths are needed to better understand the extent of shading and how shading impacts vegetation and fishes.

5. MARINE VEGETATION

Native, common eelgrass and marine macroalgae (seaweeds) like kelp are important components of Puget Sound’s nearshore ecosystems that help support food webs and provide structural habitat for various invertebrate and vertebrate species, including ESA-listed salmonids (Mumford 2007). Although light (and other) requirements can differ substantially between eelgrass and various macroalgae species, eelgrass and some macroalgae are closely associated with shallower nearshore environments given their high light requirements (Mumford 2007). Light is a critical factor regulating these photosynthetic organisms. Shade under and around the footprint of each OWS has the potential to reduce photosynthetic rates, growth, reproduction, and survival. Prior work and a thorough review of the impacts of OWS two decades ago documented a consistent, negative impact of large OWS on marine vegetation, suggesting light reduction as the primary driver of vegetation loss (Thom and Shreffler 1996, Blanton et al 2001, Nightingale and Simenstad 2001). Although light is reduced beneath SOWS, the effects of SOWS on marine vegetation – light-mediated or otherwise – are less well-studied. Below, we review the small number of available studies on the associations between SOWS and eelgrass and macroalgae.

<u>Eelgrass</u>

The effects of SOWS shading on common eelgrass is relatively well understood compared to macroalgal species. In 1989, WDFW began studying the effects of SOWS on eelgrass. Research conducted from 1989-1990 found that eelgrass was often greatly reduced or entirely absent under SOWS compared to control sites in Puget Sound (Fresh et al. 1995). Results from this research motivated work in 1991 to explore whether implementing functional grating could mitigate light-mediated impacts to eelgrass (Fresh et al. 1995). Functional grating refers to the percent open area of OWS surface material that is not obstructed by structural materials, framing, flotation tubs, or other objects (see above). The purpose of functional grating is to increase light penetration compared to classic plank decking styles that were implemented without consideration of light. By capitalizing on HPA project locations, Fresh et al. (1995) implemented before-and-after monitoring, finding that eelgrass declined dramatically beneath and near recently constructed SOWS with functional grating within a year of installation. This study provided unambiguous evidence that constructing SOWS – even with functional grating – causes rapid declines in eelgrass from shading.

Unfortunately, this study only performed before-and-after monitoring on SOWS that were constructed with functional grating but did not monitor any control SOWS with classic plank decking material. By design, functional grating permits more light penetration than classic plank decking styles. However, factors like deck height and orientation can influence how much light penetrates below SOWS (Logan et al. 2017a, Donoghue 2014), and it remains uncertain whether functional grating permits sufficient light penetration to sustain eelgrass better than classic plank decking. Even if functional grating is insufficient to sustain eelgrass, grating may permit enough light to ameliorate other light-mediated impacts of SOWS, notably salmon behavior given that fish behavior is less likely to be impacted by low light conditions (Blanton et al. 2002).

Because of the lack of a classic plank decking control, Fresh et al.'s (1995) study can only conclude that SOWS, in general, reduce eelgrass cover, but cannot determine whether functional grating reduces the light-mediated impact of SOWS on eelgrass relative to classic plank decking. Although eelgrass was still present (to some extent) under four of the five SOWS that were studied, the lack of comparison between treatment and control SOWS obscures inferences about any effect of functional grating on eelgrass. In other words, it remains unclear whether the presence of residual eelgrass under SOWS reported by Fresh et al. (1995) is a result of the functional grating, whether other extraneous factors (e.g., height or orientation) permitted enough light to sustain eelgrass, or whether eelgrass densities continued to decline over the lifetime of the SOWS, as has been shown with *Spartina* (cordgrass) species in New England marshes impacted by private docks (Logan et al. 2017b). Additionally, data from this study were never statistically analyzed and the raw data are unavailable for analysis. Because of this, it is uncertain whether these effects are statistically significant and what the effect sizes are.

Furthermore, a subsequent Puget Sound study that involved before-and-after SOWS construction monitoring of residential floats with functional grating showed a decline in eelgrass at six of 10 installations, including a total loss of common eelgrass at one SOWS (Fresh et al. 2001, 2006). Although functional grating may enhance light penetration over classic plank decking, this study demonstrated that functional grating cannot fully ameliorate light-mediated impacts to eelgrass. As such, SOWS with functional grating still result in a "net loss" of eelgrass habitat when installed over eelgrass beds (Fresh et al. 2001, 2006). However, as with the prior study by Fresh et al. (1995), no control SOWS with classic plank decking were studied before and after construction. Without proper experimental controls, it is unclear whether functional grating reduced light-mediated eelgrass declines compared to classic plank decking.

Additionally, this study used a multiple regression analysis to explore how the amount of deck grating – relative to water depth, float dimensions, and orientation – influenced the degree of eelgrass lost. Although the percent of open area associated with each SOWS' functional grating tended to be inversely related to eelgrass loss post-SOWS construction in the model, the amount of grating open area explained only a small percent (9.1%) of eelgrass loss. Moreover, the full statistical model was not statistically significant, so it cannot be concluded with certainty that functional grating benefits eelgrass. This finding suggests that other attributes of the SOWS design were likely related to eelgrass declines. Despite limitations of some of these studies, the impact of SOWS on eelgrass was sufficiently consistent that it contributed to regulatory changes in the siting and permitting process since at least 1994 (Randi Thurston and Andy Carlson, WDFW, personal communication). Uncertainty related to the shadow-ameliorating benefits of functional grating to eelgrass may, in some regards, be largely moot, as current policies require SOWS to be constructed at least 7.6m (25ft) from eelgrass beds unless additional mitigation is included for loss of eelgrass beds (WAC 220-660-380).

Data provided by Jen-Jay, Inc.[1] at a single small, private dock with a centerline strip of grating provide further evidence for impact from SOWS to eelgrass and the complexity of identifying impacts. The study included eelgrass shoot counts for a single baseline year collected in 1993 and an additional three years of post-construction monitoring along a centerline transect under the small dock, transects 3m (10ft) to either side (east and west) of the dock, and a reference transect 15.2m (50ft) west of the dock. Our analysis[2] of these data yielded three important findings (**Appendix Figure 1**). First, eelgrass shoot counts at all transects increased in the year immediately after the dock's construction, but significantly more so at the reference transect. Second, shoot counts declined in the final two years of the study to the point where all transects – including the reference and dock centerline transects – had indistinguishable shoot counts in the final year. Third, the centerline transect and, to a lesser degree, the west transect displayed a dulled increase in eelgrass shoot counts and a more rapid decline in shoot counts compared to the reference and east transects. Although these data are only from a single dock, in sum they illustrate how natural variation complicates identifying impacts of SOWS. Our analysis found that (1) eelgrass densities can vary substantially across years and (2) SOWS may dull natural eelgrass cycles, both immediately underneath the SOWS and nearby.

A study on a joint-use SOWS (SOWS used by more than one property owner) at Henry Island surveyed for eelgrass for one year before SOWS construction and three years post-construction at one transect under the SOWS footprint, a transect on either side of the SOWS footprint, and a control transect near the SOWS footprint (Fairbanks 2010). Substantial variation in eelgrass shoot density among years across all transects obscured assessing potential impacts of the SOWS on eelgrass. However, Fairbanks (2010) calculated a 'worst-case' scenario from the third year of post-construction monitoring. This calculation estimated that the dock may have resulted in a maximum loss of 7.6 eelgrass shoots/m^2 or 1,060 total eelgrass shoots. Importantly, as part of the HPA permit for this dock, an existing mooring buoy near the dock location was concurrently removed as in-kind, on-site mitigation of potential eelgrass loss due to the dock. Pre- and post-removal surveys concurrent with the dock monitoring found that removing the mooring buoy resulted in the gain of 1,538 eelgrass shoots, which putatively more than compensated for the other SOWS' impacts to eelgrass (Fairbanks 2010).

Research from outside the Puget Sound area further documents the effects of residential structures on common eelgrass (the same species as in Puget Sound). In Sweden, Eriander et al. (2017) found a significant reduction (42-64%) of eelgrass surface-area (as estimated visually) associated with shading from a mixture of SOWS and large OWS. The average distance from the OWS where 100% surface area coverage was reached was 7.3m for floating and 5.7m for

[1] Under RCW 34.05.271 these unpublished data are classified as category vi: Data from primary research, monitoring activities, or other sources, but that has not been incorporated as part of documents reviewed under the processes described in (i), (ii), (iii), and (iv) of this subsection.

[2] We used a generalized linear model (GLM) with a poisson distribution to analyze eelgrass shoot count data. Our model tested for a statistical interaction between the various transects and across years. Using both a reverse model selection approach and information theoretic approach with AICc model selection, we identified a model including this interaction as best fitting the data. This interaction showed that shoot counts varied across time, but differently across transects. To better understand differences across time and transects, we performed subsequent poisson GLMs to analyze differences (1) between each transect at each time interval and (2) differences across time for each transect. Tukey's post-hoc comparisons across these subsequent models identified differences among transects for each year and across years for each transect (Appendix Figure 1). We determined statistical significance at $p < 0.05$.

elevated docks, demonstrating impacts to eelgrass beyond the OWS footprint. Similarly, in Massachusetts, Burdick and Short (1999) found depressed eelgrass shoot density and canopy structure associated with docks, however, elevated docks had less impact. Studies on other seagrasses (*Halodule wrightii* and *Syringodium filiforme*) in Florida and Texas found similar decreases in cover and shoot densities associated with shading from SOWS (Shafer 1999, Beal and Schmit 2000). While not from Puget Sound, these additional studies highlight that shading cast by SOWS has a relatively ubiquitous, general impact on eelgrass and seagrasses more generally.

In sum, eelgrass is regularly impacted by SOWS and shading from SOWS likely contributes partly to eelgrass loss. However, impacts to eelgrass by SOWS are not consistent within and across studies, suggesting that multiple factors (e.g., SOWS height, orientation) can influence the outcome of SOWS installation on eelgrass. Moreover, which factors and the relative influence of each factor remain unquantified in Puget Sound (Fresh et al. 2006). Notably, functional grating alone is insufficient to fully ameliorate potential shading impacts from SOWS on eelgrass. Anecdotal expert observations in resurveying a SOWS that Fresh et al. (1995, 2001, 2006) originally monitored suggest that eelgrass may fully recolonize beneath SOWS ~ two decades post-construction, though the eelgrass may acclimate and grow back in a shorter, denser growth form than is typically seen in Puget Sound (Chris Betcher, personal communication). Whether eelgrass recolonization beneath SOWS commonly occurs remains unclear and requires studies that revisit older SOWS installations. Additionally, the mooring buoy removal by Fairbanks (2010) should motivate studies that assess the efficacy of restoration and mitigation activities that encourage eelgrass regeneration.

Macroalgae

To our knowledge, little work has examined the effects of SOWS on marine macroalgae in Puget Sound. Conversations with regional experts suggests that a diversity of macroalgae – including the genera *Alaria*, *Costaria*, *Gracilariopsis*, and *Cryptosiphonia* – persist and may even benefit from SOWS installations due to the enhanced physical structure (Chris Betcher, Leo Bodensteiner, Eric Eisenhardt, Amy Leitman, Nam Siu, and Beth Tate, personal communications). Although the number of studies on algae and SOWS are limited, sugar kelp (*Saccharina latissima*) appears to be relatively common and better-studied.

One study that evaluated SOWS effects found that sugar kelp cover and biomass under three SOWS was consistently and markedly less than in each paired control (Szypulski 2018). Specifically, sugar kelp reductions associated with SOWS were observed for both kelp cover (medians at dock = 0.0-20.4%, medians at paired controls = 96.2-100%) and biomass (medians at dock = 0.0-199.6g, medians at paired controls = 282.1-565.9g). In one instance, kelp cover increased with increasing distance from a SOWS, suggesting a gradient of impact to sugar kelp as a function of the distance to a SOWS. Overall, sugar kelp distribution and cover were negatively associated with SOWS and Szypulski (2018) suggested that kelp reduction was due to reduced light measured under the docks. However, there are important limitations to this study that limit inferences to be made. In particular, the study is correlational and lacked monitoring before and after SOWS construction. This makes it impossible to know if control sites differed from SOWS sites in kelp biomass and cover prior to SOWS construction. Additionally, the study may not be particularly applicable to or representative of most Puget Sound SOWS because all docks occurred in state parks, rather than privately-owned shorelines that are more common in the region. Differences between state parks docks and private docks may include, for example, different dock dimensions, the presence and extent of shoreline armoring, and intensity of human and boat use that may confound interpretations of the studied SOWS impacts. Furthermore, although state park docks are likely not as large as large commercial and industrial docks or ferry terminals, they are likely larger than more typical private, residential SOWS.

Unpublished data provided by Marine Surveys & Assessments[3] indicates a different pattern from Szypulski (2018). In 2010, Marine Surveys & Assessments used transects in late May 2010 to survey for sugar kelp under and on three groups of existing private, single-family SOWS and two nearby reference (control) sites adjacent to each SOWS. One reference site for each existing SOWS included the footprint of a proposed SOWS that was not yet constructed. We analyzed[4] Marine Surveys & Assessment's transect data and found that, across all three study areas, there were more sugar kelp stipes under and on SOWS than at the reference sites (**Appendix Figure 2**). However, our analysis also found substantial variation in stipe counts among study sites that may be due to large differences in current strength (Amy Leitman, personal communication). Like Szypulski (2018), this study is limited by a similarly small sample size and no before-and-after construction monitoring. Additionally, we were unable to discern from the data what proportion of stipe counts were under versus on the SOWS. However, these results may be more generalizable to most SOWS in Puget Sound because the data are from single-family SOWS, rather than state park SOWS. Even so, substantial differences in methodology (e.g., stipes counts under and on SOWS versus video monitoring of kelp cover) between these data and those from Szypulski (2018) make data comparisons challenging.

We also analyzed[5] data from another Marine Surveys & Assessments study that monitored sugar kelp beneath a single residential SOWS and a nearby reference site one year prior to construction and for four years post-construction from late July to early August each year. Our analysis found that the SOWS had more sugar kelp stipes compared to the reference site, including prior to SOWS construction (**Appendix Figure 3**). However, sugar kelp increased at both sites over time, but similarly so at the reference and SOWS sites. Although the SOWS site showed a proportionally larger increase in sugar kelp stipes count over time compared to the reference site, this proportional increase was not statistically significant. Taken together, these two studies by Marine Surveys & Assessments suggest that SOWS have a neutral or positive impact on sugar kelp recruitment. But in conjunction with Szypulski (2018), this work suggests large variation in sugar kelp cover across regions in Puget Sound and the need for before-and-after monitoring at various SOWS in different environmental conditions to adequately assess the impact of SOWS on macroalgae.

Notably, the only kelp species reported from Szypulski (2018) and Marine Surveys & Assessments was sugar kelp, a subcanopy species. This is notable because there are 22 species of

[3] Under RCW 34.05.271 these unpublished data are classified as category vi: Data from primary research, monitoring activities, or other sources, but that has not been incorporated as part of documents reviewed under the processes described in (i), (ii), (iii), and (iv) of this subsection.

[4] We used a generalized linear mixed effects model with a poisson distribution for stipe count data. Our model nested transect segments within each reference or SOWS site in each study area as 'random' effects, and treated study area and treatment (references vs SOWS) as fixed effects. A likelihood ratio test showed that SOWS had higher sugar kelp stipes counts than did reference sites ($p = 0.04$). This model also showed a high level of among-study area variation ($p = 7.8$ e-06)

[5] As with the Jen-Jay, Inc. data above, we used a poisson GLM to analyze whether sugar kelp stipes counts differed between a SOWS and nearby reference site pre-construction, immediately post-construction, and both 2- and 4-years post-construction. Our analysis found no significant interaction between site (SOWS vs reference) and year ($p = 0.52$), however, likelihood ratio tests found that both site and year were significant ($p < 0.0001$). This analysis found that the SOWS site always had higher stipes counts, even before construction, but the presence of the SOWS did not negatively or positively impact sugar kelp.

kelp in Washington state and, of these, only the two often-floating canopy species (giant kelp [*Macrocystis pyrifera*] and bull kelp [*Nereocystis luetkeana*]) are well-studied in the region, with little research attention for subcanopy, prostrate kelp species (Mumford 2007). Although there are few other data on kelp and SOWS, our conversations with topic experts suggest agreement about the large negative impacts of SOWS on eelgrass and canopy kelp (although we are unaware of relevant canopy kelp data), but highlights contrasting perspectives for the effects of SOWS on subcanopy kelp and other macroalgae. Specifically, across our consulted experts, experiences range from near total loss of all kelp to little effect of SOWS on persistence of subcanopy kelp under SOWS, and even enhanced kelp growth in some cases. Anecdotes also suggest that, when SOWS are not regularly cleaned, some kelp species may experience substantial growth on the artificial substrates of SOWS to the point of significantly enhancing the shadow footprint and negatively impacting eelgrass (Chris Betcher and Beth Tate, Jen-Jay, Inc.). The frequency of SOWS cleaning and the prevalence of SOWS with substantial kelp growth throughout Puget Sound remains, to our knowledge, undocumented.

Given the paucity of reported data on macroalgae and SOWS and the contrasting experiences of SOWS impacts, there is a need for research that addresses if, to what extent, and under what environmental conditions (e.g., currents, substrates, and different SOWS heights, decking material, orientation) macroalgae are impacted by SOWS. Furthermore, existing guidance for eelgrass and macroalgae surveys may be insufficient to adequately characterize annual algae species that vary spatially year-to-year, algal species that grow vertically and cannot be measured by two-dimensional surveys of cover, and successional patterns of algal community composition over time (Nam Siu, Chris Betcher, and Beth Tate, personal communications.). In sum, the negative impacts of SOWS to eelgrass are well understood, although what mitigation measures might benefit eelgrass are still poorly explored. Further, the impacts of SOWS on macroalgae are largely unstudied.

6. SALMONIDS

<u>Marine SOWS</u>

To our knowledge, only two studies have addressed the relationship between marine SOWS and fishes in Puget Sound. Toft et al. (2013) provides a case study on the effects of SOWS on salmon in an estuarine setting. This study monitored the biological responses of removing a SOWS at the Salmon Bay Natural Area, a relatively undeveloped shoreline in Seattle where freshwater and saltwater mix near the Hiram Chittenden Locks downstream of Lake Washington. Snorkel surveys revealed that juvenile salmon migrating towards the ocean avoided the SOWS footprint, being absent beneath the SOWS. After removal of the SOWS, juvenile Chinook (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*) leaving Lake Washington through the locks and chum salmon (*O. keta*) migrating along the Puget Sound shoreline were as prevalent beneath the SOWS' former footprint as at the nearby reference shoreline (Toft et al. 2013). This study provided experimental evidence that SOWS can affect juvenile salmon behavior in nearshore environments and that SOWS removal may improve salmon migratory habitat. However, we note that this is a single site and the mixing of freshwater and saltwater at the Salmon Bay Natural Area could obscure the generalizability of this case study to most SOWS in Puget Sound.

The sugar kelp study by Szypulski (2018) also aimed to monitor the presence of fish under SOWS. Although Szypulski (2018) employed two methods – video monitoring and baited "Squidpops" (small pieces of squid attached to submerged stakes) – to monitor fish, neither approach produced substantial data on fish in general and no data on salmon. The video monitoring under SOWS and nearby control sites without SOWS were used to assess fish presence, abundance, and diversity. Most fish observed in Szypulski's (2018) camera analysis were shiner perch (*Cymatogaster aggregata*), which were often concentrated near SOWS compared to control sites. As mentioned above (Section 4, *Macroalgae*), this study did not include a before-and-after assessment to confirm changes in fish communities after SOWS construction (i.e., were fish species present prior to SOWS construction that are now absent?). Additionally, the short-term (~2 hour) video monitoring may have been insufficient to adequately monitor for fish presence, which could explain the relatively depauperate fish observations for both SOWS and reference sites. In addition to video monitoring, Szypulski (2018) used baited Squidpops to assess differences in fish presence and abundance around SOWS versus nearby control sites, inferring fish presence using missing bait as a proxy for foraging. However, few Squidpops were missing over the course of this study (either at SOWS or control sites), limiting inferences about fish abundance and SOWS. We note that even if bait had been missing, this approach cannot definitively determine that foraging fish caused bait to disappear or identify fish species. Further, as mentioned above, the public context of the three study sites may influence fish presence and behavior (including at nearby control sites) differently than for private SOWS if, for example, boat traffic is higher at these public SOWS. This study's limited data are largely inconclusive with respect to the effects of marine SOWS on fishes.

Evidence from large marine OWS

Although studies of fish associations with SOWS in Puget Sound are limited, there is a more robust scientific literature on large OWS, particularly elevated large OWS. Ferry terminals are one such large OWS that have been particularly well-studied for fishes in Puget Sound. A single dive survey at each of five Puget Sound Ferry terminals showed that, although fish community composition varied across terminals, juvenile Chinook salmon were noted to swim freely underneath the Kingston ferry terminal, and a single juvenile blackmouth (residualized Chinook salmon) was also seen resting underneath the terminal (Simenstad et al 1999). Surveys by Williams et al. (2003) at the Mukilteo ferry terminal also found that chum and pink salmon fry moved freely under the shaded portion of the OWS. Schrefler et al. (1999) similarly concluded that the Port Townsend ferry terminal was not a barrier to Chinook migration, but also offered a more nuanced description of the effect of large OWS shading. Specifically, a one-time experimental release of 1,000 Chinook fry combined with surface observations, underwater video, and hydroacoustics found that the released salmon migrated to the ferry terminal, stopped at the shadow line beneath the terminal, fed near the water's surface at the shadow line, and subsequently followed the shadow line beneath and across the terminal as the sun set and moved the shadow's position (Schreffler et al. 1999).

A more comprehensive study by Southard et al. (2006) combined acoustic tagging, snorkel surveys, and surface observations at 10 Puget Sound ferry terminals to show that juvenile salmon tended to congregate adjacent to ferry terminals and rarely went beneath the structures. Juvenile chum salmon schools only crossed under two of 10 terminals, and most often showed milling behavior, swam in circles at the edges of the terminals, and rarely crossing shadow lines. Snorkel surveys also found that juvenile Chinook and coho salmon were rarely found under terminals or at reference sites; rather, salmon were often found at edges of ferry terminals, evidence that large OWS cause juvenile salmon to pause their migrations or congregate adjacent to OWS. Acoustic monitoring of tagged juvenile Chinook and coho salmon in this study similarly found that only half of the marked fish crossed under the terminal and most did so at night when there was no shadow effect from the OWS. Across these various survey methods, when juvenile salmon moved under structures, they did so by moving more rapidly than normal and often in the evening, when the light impacts of the structure were less pronounced or during the daytime at low tide, when water levels under the structure are lower and allow more light to reach the water surface (Southard et al. 2006). The authors concluded that ferry terminals are an occasional barrier to migrating salmon, and that the degree to which large OWS act as barriers likely depends on factors like OWS design, tides, and time of day.

Follow-up research at the Port Townsend ferry terminal mirrored the conclusions of Southard et al. (2006) and observed no salmon moving beneath large OWS, even when artificial lighting was employed (Ono et al. 2010, Ono and Simenstad 2014). These studies additionally extrapolated that behavioral changes when encountering large OWS could cause several hours of migratory delay for each large OWS per day (Ono et al. 2010, Ono and Simenstad 2014). If this same principle is applicable to SOWS, then this may be of particular concern considering the larger number of SOWS likely to be encountered by migrating salmon throughout Puget Sound. The cumulative impacts could be comparable to or more pronounced than a large OWS. Additional evidence that juvenile salmon avoid SOWS in freshwater (see below) may further suggest that juvenile salmon will avoid marine SOWS too.

Beyond behavioral changes associated with ferry terminals, work by Haas et al. (2002) at three Puget Sound ferry terminals found that species composition was altered and that the abundance and diversity of juvenile salmon prey items was dramatically reduced under and near these large OWS as compared to control areas not affected by OWS. A subsequent study of three large urban piers and three ferry terminals similarly found that these large OWS were associated with a reduced abundance and altered community composition of small invertebrates that salmon prey on, although several harpacticoid copepod species were relatively immune to the impacts of OWS shading (Cordell et al. 2017). These studies suggest large OWS directly reduce the quality of the foraging habitat for migrating salmon.

Additionally, it has regularly been hypothesized that OWS concentrate predators of salmon and cause higher predation rates, however, few data have been collected to test this (Simenstad et al. 1999, Carrasquero 2001, Fresh et al. 2003). Surveys at six ferry terminals in Puget Sound found no or negligible evidence that (1) predatory mammals, birds, and fishes were associated with large OWS or (2) predators were disproportionately targeting juvenile salmon near ferry terminals (Williams et al. 2003). In other words, ferry terminals can alter salmon behavior, delay migrations, and reduce food availability, but there is limited evidence, to our knowledge, that they concentrate salmon predators or result in higher salmon predation rates. However, we note that William et al.'s (2003) study occurred two decades ago and changes in predator abundance and composition (Chasco et al. 2017a,b) may result in an alternate present-day predation scenario in Puget Sound. Whether OWS concentrate predators remains an unanswered issue, largely because assessing predator community and predation rate differences between OWS and reference sites is logistically challenging and expensive.

Some work in Puget Sound has also addressed fish associations with other types of large OWS besides ferry terminals. An observational study in Seattle found that juvenile salmonids were concentrated near, but rarely under, the edges of apartment and business complexes built on overwater piers. These juvenile salmonids were most often found schooling (hovering or swimming) (Toft et al. 2007). Although Toft et al. (2007) observed little foraging activity by juvenile salmon, the feeding activity that they witnessed almost always occurred near the large OWS or at deep riprap. Beyond the small number of foraging observations, the sample size of this study was relatively small (n=3), and two of these three sites were located spatially nearby (and so were not statistically independent) and were also near a freshwater input. Such freshwater input may influence salmon behavior due to osmotic differences (Handeland et al. 1996), and Toft et al. (2007) noted that the freshwater inputs may confound behavior analyses, especially given the prevalence of schooling behavior near Lake Washington's outmigration corridor. Because of such potential spatial non-independence and freshwater influences, it is unclear how generalizable these findings are to most large marine OWS along the Puget Sound shoreline. Furthermore, the authors note they could not discern from their study design why juvenile salmonids concentrated near large OWS. Specifically, do large OWS (1) act as a barrier that pauses movement or (2) provide some benefit (e.g., relatively high-quality foraging habitat) that salmon prefer and congregate at? Because of this ambiguity, it is unclear whether the concentration of salmon near the large OWS has a negative, neutral, or positive impact, especially as predation was not examined.

Another study found that salmon presence and feeding was greatly reduced under three large piers in Seattle compared to three control sites, but juvenile salmon presence and feeding was concentrated near piers, rather than in open water (Munsch et al. 2014). Like data on ferry terminals (Haas et al. 2002), work by Munsch et al. (2014) suggests that habitat directly beneath large piers is of poor foraging quality for juvenile salmon, likely because of light limitation. Emerging work suggests that 'eco-engineering' approaches that aim to restore urbanized shorelines in Puget Sound by incorporating glass light penetrating elements into large piers, elevating seafloors (reducing depth), and texturing seawalls can buffer some of the light-mediated effects on salmon presence, behavior, and foraging (Sawyer et al. 2020). Although research consistently indicates that large OWS alter salmon presence and behavior, new restoration approaches may help mediate some of these impacts by increasing the foraging quality and permeability of large OWS shadows to salmon migration.

Direct empirical evidence of mortality associated with OWS is rare. Acoustic tagging data in Hood Canal found that the Hood Canal Floating Bridge (a unique type of large OWS formed by submerged pontoons that occur across 95% of the bridge length and extend 3.6m deep) slowed down and impeded migratory behavior in salmon (Moore et al. 2013). The study additionally inferred that the floating bridge directly or indirectly caused 4-36% of the mortality of migrating steelhead smolts (Moore et al. 2013). While it is unclear whether mortality associated with the bridge is due to increased predation and/ or other consequences of migratory delays (e.g., physiologic stress), these acoustic tagging data suggest that some types of OWS may substantially increase juvenile salmonid mortality. Notably, this study occurred more recently than Williams et al. (2003), and so may better reflect the increases in pinniped prevalence in Puget Sound that are complicating salmon recovery (Chasco et al. 2017a,b). In sum, the above studies illustrate that a range of large OWS can alter salmon behavior and migration, impair salmon foraging habitat, and may also increase mortality.

Evidence from freshwater SOWS

Work in freshwater systems also provides evidence that OWS (typically small, not large, OWS) may impact fishes. One report suggests that smallmouth bass (*Micropterus dolomieu*), predators of juvenile salmon, in Lake Washington and Lake Union are disproportionately concentrated within 2m of OWS (Fresh et al. 2003). However, this report only summarizes observations and provides minimal methodological information and few data. Tabor and Piakowski (2002) and Tabor et al. (2011) found that juvenile Chinook were rarely found under OWS in Lake Washington, but instead were often found adjacent to OWS or in open water. Although Tabor et al. (2011) apparently measured OWS width, these data were not reported. However, the studied SOWS predominated in the southern part of the lake and were of sizes that were likely relevant to our review of marine SOWS (Roger Tabor, personal communication).

Additionally, Tabor and Piakowski (2002) employed a short-term OWS experiment by constructing temporary OWS made of vinyl tarps (on a wooden frame) and supported overwater by a float (10m wide along the shoreline, 5m long, and 0.3-0.4m above the water). This experiment also found that juvenile salmon avoided the experimental freshwater OWS compared to nearby, unmanipulated control shorelines (Tabor and Piakowski 2011). We note that the dimensions of these experimental OWS are similar in size to marine SOWS that are the focus of our review. Because of this, it is possible that juvenile salmon may avoid marine SOWS as they appear to do in freshwater. Beyond the Puget Sound region, work elsewhere also suggests that smaller fishes tend to avoid OWS. For instance, Able et al. (2013) found that small, schooling fishes in general avoided a large pier in the Hudson River estuary of New York, perhaps in response to larger predatory fish (e.g., striped bass, *Morone saxatilis*), that were slightly more abundant under the pier than in more open waters.

7. LIMITATIONS FROM LARGE OWS AND FRESHWATER STUDIES

In general, it is unclear to what extent we can extrapolate findings from large OWS as size differences may engender different environmental impacts compared to SOWS. Substantial differences in size and shape between SOWS and large OWS likely results in important differences in the spatial extent and duration of diminished light penetration into the water. Additionally, small and large OWS differ in length and the extent to which the structures extend into deeper water. Notably, large OWS typically extend beyond shallow water habitats which may present a more substantial impact to salmon behavior, migration, and survival. Whereas salmon in nearshore environments may more readily move around SOWS, they may be less likely to do so for longer, large OWS. This is likely a pronounced problem for large OWS like the Hood Canal Floating Bridge studied by Moore et al (2013). This bridge casts a continuous shadow across the canal (shore-to-shore) and conceivably acts as a more substantial behavioral barrier to salmon than SOWS or other large OWS like ferry terminals that are elevated and have only pilings underwater. Moreover, some large OWS like ferry terminals may armor the shoreline and purposefully increase water depth nearshore to accommodate ferry landings. Furthermore, although our review did not encompass human use intensity differences, large OWS likely have substantially different human activity (ferries versus private boats, more frequent boat movements) which may have impacts to habitat conditions and salmon behavior beyond a given structure's presence.

Furthermore, inferences about the impacts of SOWS in freshwater environments may not readily translate to marine habitats. For instance, the suite of predators differs between these environments, and so ecological differences between freshwater and marine – and northeast (e.g., Able et al. 2013) versus northwest – predator communities, may result in different predation rates near and under OWS. Notably, fish predator impacts may be more pronounced in freshwater environments, whereas impacts from avian or pinniped predators may be more pronounced in marine environments. Additionally, salmon life history and behavior are strongly tied to differences between freshwater and marine habitats (Quinn 2005). This life history variation may elicit different behavioral responses and impacts from OWS in different environments. In sum, studies on marine large OWS and freshwater OWS can help generate hypotheses for how SOWS impact marine nearshore habitats and salmon. However, due to physical and potential use differences between large and small OWS and ecological differences between marine and freshwater environments, there may be limited transferability of insights among different types of OWS and environments.

8. DATA GAPS

Studies of marine large OWS and freshwater SOWS provide evidence that, in general, OWS can reduce light, vegetation biomass and cover, and the abundance and species richness of secondary consumers. These structures can also alter juvenile salmonid migratory behavior and possibly increase their mortality. These issues remain largely unexplored for the over 8,200 SOWS in Puget Sound. Even so, SOWS may alter nearshore environments and species in a multitude of ways, including by altering physical structure. We emphasize that an absence of evidence of impacts from SOWS is not the same as the absence of impact. Whether SOWS negatively impact submerged aquatic vegetation (other than native eelgrass) and fishes in Puget Sound remain important questions to address. Furthermore, shoreline development associated with residential land uses is not limited to SOWS, but often also includes shoreline armoring. We did not identify any studies that quantitatively addressed the additive or interactive effects of shoreline armoring with SOWS. However, shoreline armoring that creates deeper water around SOWS during high tide may amplify any potential impacts from SOWS. There remains an important need for targeted research on the impacts of SOWS to nearshore habitats, vegetation, and wildlife and on the mitigation or restoration actions that may mediate possible SOWS impacts.

Importantly, most studies to date compare impacts of OWS to adjacent, uncovered shorelines as controls. However, these adjacent control shorelines likely are also degraded habitat due to shoreline development and human use. Because of this, control shorelines in many studies may lack the natural features that historically were prevalent in Puget Sound shorelines, including overhanging vegetation that provided dappled shade and wracked large woody debris to benefit physical structure, refuge, and foraging habitat (Thom and Williams 2001, Holsman and Willig 2007). As such controls used in prior studies may not necessarily represent ideal conditions for salmon and other nearshore species. There remains a need to understand how SOWS impact shorelines relative to historical conditions, and whether SOWS design modifications or restoration actions can replicate aspects of historical conditions. An additional important step to conducting useful research is ensuring that SOWS have been installed properly. This requires two steps: (1) HPA permits are implemented correctly, i.e., permits are comprehensive and contain all important provisions, and (2) that permittees have complied with all HPA provisions.

The most comprehensive assessment to date on marine SOWS in the Puget Sound region is Szypulski (2018)'s study. This study provides evidence that marine SOWS limits light beneath the water surface and reduces sugar kelp cover and biomass in the Puget Sound nearshore environment. Even so, this study is limited in several important ways that may preclude generalizing results to the broader region. In addition to limitations noted previously, shorelines surrounding the SOWS studied by Szypulski (2018) are relatively undeveloped, whereas private SOWS are often adjacent to heavily armored shorelines (Tabor et al. 2011, Munsch et al. 2014, Toft et al. 2014). Although Szypulski (2018) considered this a strength of the study, the lack of comparison to SOWS with armored shorelines reduces the study's transferability to other SOWS in Puget Sound. Even with these limitations, the data from Szypulski (2018) – along with insights from regional experts – provide useful context to guide future research on SOWS.

Beyond limited research on the impacts of functional grating on light penetration (Fresh et al. 1995, 2001, 2006, Donoghue 2014, Gabriel and Donoghue 2016), there has been minimal work on how various design elements may mitigate potential impacts of SOWS in Puget Sound. A survey of 20 SOWS in Massachusetts found that shorter, east-west oriented docks had the largest negative effect on light penetration and eelgrass growth (Burdick and Short 1999). And a survey of 212 small, private docks in Massachusetts salt marshes recapitulated these results, also finding that deck height had the most consistent impact on light penetration and salt marsh vegetation; docks with shorter heights showed the greatest negative impact on light penetration and aquatic vegetation (Logan et al. 2017a). This study also found that other SOWS attributes were relevant. Specifically, older docks, east-west oriented docks, and classic plank (rather than grated decking) had stronger negative impacts on lighting and vegetation (Logan et al. 2017a). A subsequent experimental study in Massachusetts salt marshes confirmed that taller docks can substantially minimize or negate impacts to aquatic vegetation compared to docks with shorter heights, even though taller docks still reduced light penetration compared to uncovered, control areas (Logan et al. 2017b). Work on private SOWS in Sweden also found evidence that height influenced submerged aquatic vegetation. Specifically, floating docks had greater impacts to vegetation than docks on fixed pilings, presumably because floating docks are closer to the water and permit less light penetration (Eriander et al. 2017). No such studies have occurred in Puget Sound, but observational studies of existing SOWS combined with experimental SOWS installations would greatly inform which design elements provide the greatest mitigation of potential impacts of SOWS to habitat and juvenile salmon.

9. RESEARCH NEEDS

Below we outline a non-exhaustive list of research questions that could inform the potential biological and physical impacts of SOWS in Puget Sound and the human dimensions that may inform restoration and management priorities. These questions arise from insights gleaned from large marine OWS and freshwater SOWS studies and conversations with regional subject matter experts. Additionally, these questions address potential problems associated with SOWS beyond light-mediated impacts. Addressing these questions necessitates multiple types of studies including, for instance, (1) correlative, observational studies across a diversity of existing SOWS and environmental variables; (2) before-after-control-impact (BACI) experiments that capitalize on HPA-permitted SOWS to monitor impacts to habitat and salmon after SOWS construction, modification, or removal; and (3) experimental studies that construct artificial pseudo-SOWS (*sensu* Tabor and Piakowski 2002, Logan et al. 2017b) in a variety of environmental conditions (e.g., different regions, orientations, current strengths).

Critically, conversations with multiple subject matter experts suggests that current marine vegetation survey protocols are insufficient to detect changes in eelgrass or macroalgae. Future research should carefully design studies so that responses (or null results) can be confidently ascribed to impacts from SOWS and particular design features. Finally, we emphasize that most of the studies cited in our review are not published in the peer-reviewed literature; less than 50% of the cited references in our review had clearly gone through an independent peer-review process. Although agency reports have likely undergone a degree of peer review, it is often unclear what form of peer review (e.g., independent, internal) occurred. A comprehensive understanding of the impacts of SOWS on salmon and nearshore habitats would benefit from further support from the broader research community, as well as publishing results in peer-reviewed journals.

1) Do macroalgal species differ in their responses to SOWS? Do SOWS impact the structure and composition of macroalgal communities?

2) Do shadows cast by SOWS alter juvenile salmon behavior and migration?

3) How do SOWS influence salmon foraging habitat?

4) How do SOWS influence marine predators like pinnpeds, birds, coastal cutthroat trout (*Oncorhynchus c. clarki*), and bull trout (*Salvelinus confluentus*) that consume juvenile salmon? Can SOWS act as predator traps or refuges from predators for salmon?

5) Are there additive or interactive effects between SOWS and shoreline armoring? How does the removal of shoreline armoring influence the impact of SOWS? Does deeper water caused by armoring enhance predation on juvenile salmonids at SOWS?

6) Does the type of SOWS construction and/or SOWS age influence the potential impacts on marine vegetation and fish behavior and fitness?

7) What is the relative importance of SOWS design elements (e.g., height, width, aspect, decking material) in minimizing impacts on aquatic vegetation and fish use? How can these design elements be incorporated into future SOWS permitting or modifications to ameliorate potential SOWS impacts? Are the impacts of these design elements additive or synergistic? Does the degree of maintenance on or cleaning of SOWS influence impact?

8) Does boat moorage at SOWS extend the footprint and associated impacts of SOWS? Does the number of boats and the duration of boat moorage influence boat impacts? Are boat impacts limited to shading, or are there other impacts like propellor wash and scouring?

9) Does the density or proximity of multiple SOWS within a given shoreline region cause cumulative impacts of SOWS at local or regional scales in Puget Sound? Are there cumulative impacts Sound-wide, even if individual SOWS may have limited impacts?

10) How do natural variables like current strength, substrates (e.g., mudflats, shell hash, cobble), or geographic region within Puget Sound influence measured effects of SOWS?

11) Does existing state guidance on submerged aquatic vegetation monitoring adequately account for eelgrass and all forms of kelp, including annual kelp species? Do other survey approaches (e.g., PISCO surveys[6]) provide more comprehensive assessment of the impacts of SOWS installations on nearshore environments?

12) Do impacts of SOWS shading on vegetation extend beyond the presence and abundance of eelgrass and macroalgae and impact these species' ecosystem functions, such as in carbon cycling?

13) Are there inequitable impacts and benefits of SOWS to different human communities?

14) What are SOWS owners' concerns about potential impacts of SOWS on nearshore environments?

15) Why do SOWS owners have SOWS instead of using communal or public OWS? What incentives would encourage communal dock use? What would motivate a SOWS owner to modify or remove SOWS if it benefited Puget Sound and salmon?

16) Have permitting and regulatory changes altered the willingness of private homeowners to build new SOWS?

[6] http://www.piscoweb.org/kelp-forest-sampling-protocols

10. ACKNOWLEDGEMENTS

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(Parenthetical categories are from RCW 34.05.271)[7]

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[7] (i) Independent peer review: Review is overseen by an independent third party;
(ii)Internal peer review: Review by staff internal to the department of fish and wildlife;
(iii) External peer review: Review by persons that are external to and selected by the department of fish and wildlife;
(iv) Open review: Documented open public review process that is not limited to invited organizations or individuals;
(v) Legal and policy document: Documents related to the legal framework for the significant agency action
(vi) Data from primary research, monitoring activities, or other sources, but that has not been incorporated as part of documents
(vii) Records of the best professional judgment of department of fish and wildlife employees or other individuals; or
(viii) Other: Sources of information that do not fit into categories i - vii.

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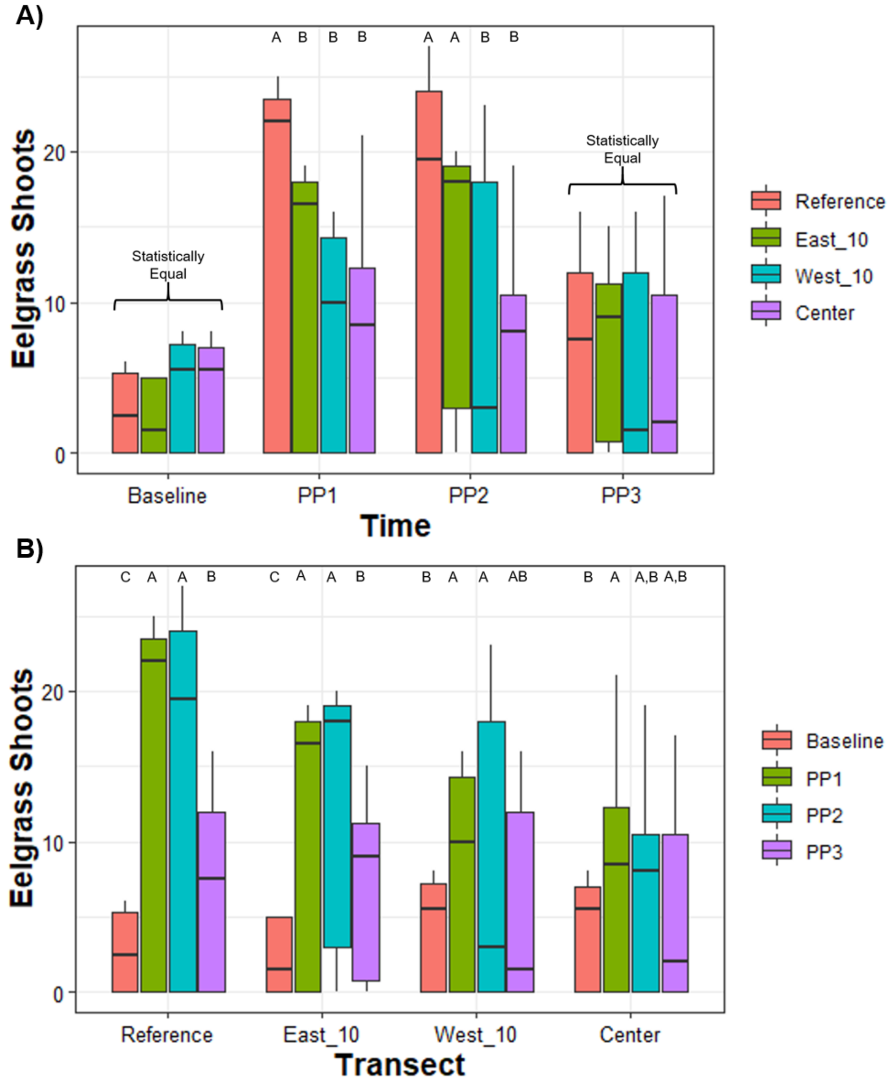
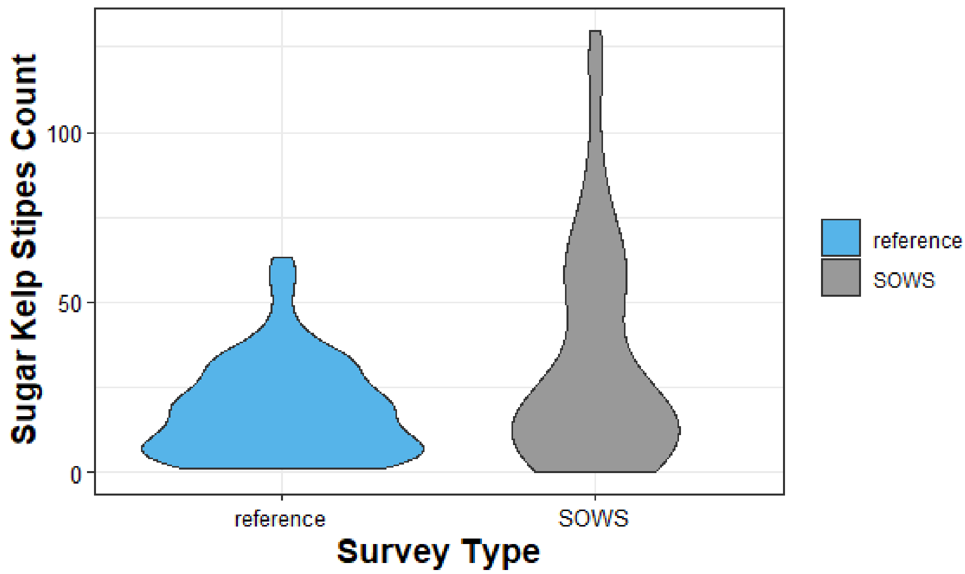
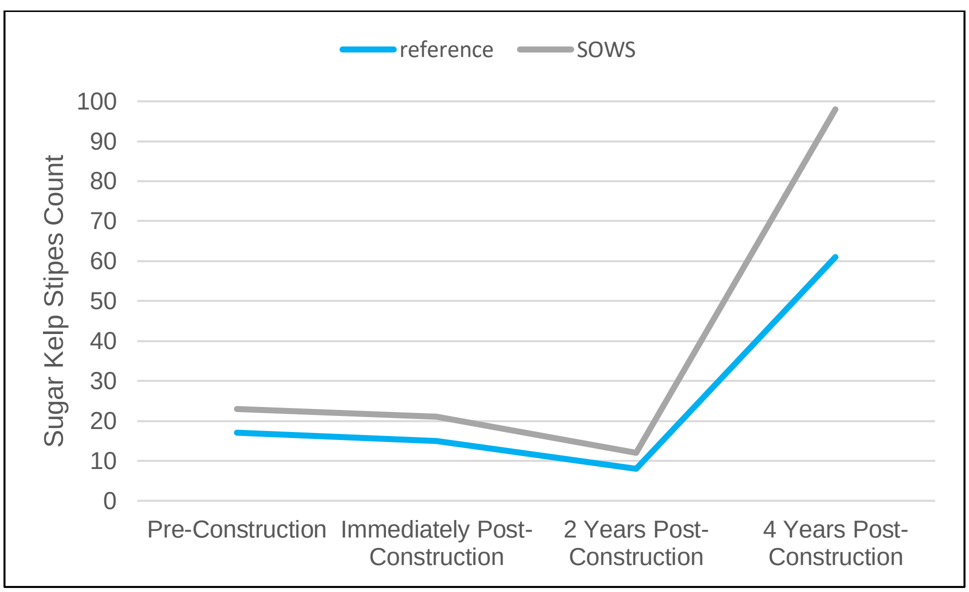
12. APPENDIX



Appendix Figure 1. Eelgrass (*Zostera maxima*) shoot count data at SOWS (private dock) demonstrate that eelgrass beds exhibit substantial natural variation, but that SOWS can dull natural increases in eelgrass, both immediately under and adjacent to the dock. Data are from a baseline year in 1993 and three subsequent Post-Project years (PP1, PP2, PP3) after construction. Included in the data are a center transect beneath the dock, a transect 10ft (3m) east and west of the dock, and a reference transect 50ft (15.2m) west of the dock. A statistical interaction in a generalized linear model (GLM) with a poisson distribution showed that eelgrass shoot counts differed over time, but differently for each transect. Subsequent poisson GLMs and Tukey's post-hoc comparisons performed for each transect and each year separately found substantial variation in shoot counts between transects within a year (A) and across years for each transect (B). Letters over each group of boxplots represent Tukey's post-hoc groupings. Boxplots with the same letters are statistically equivalent, whereas boxplots with different letters are statistically different. Boxplots with multiple letters are statistically indistinguishable from two different groupings. Note that Tukey's groupings are only comparable within a set of boxplots, but not between sets within or between panels. Data provided by Jen-Jay, Inc.



Appendix Figure 2. Sugar kelp (*Saccharina latissima*) stipe counts at each of three existing Puget Sound SOWS (private docks) and six reference sites (n = 2 reference sites near each SOWS). Presented are violin plots which illustrate the data as kernel density distributions. A poisson generalized linear mixed effects model found that, in general, stipes counts were higher on and under SOWS compared to nearby reference sites, but there was also substantial variation among the three study locations. Data provided by Marine Surveys & Assessments



Appendix Figure 3. Sugar kelp (*Saccharina latissima*) stipe counts beneath a SOWS (private dock) and nearby reference site pre-construction, immediately post-construction, and 2- and 4-years post-construction. A poisson generalized-linear model found that the SOWS site had higher stipe counts, even prior to construction. Although sugar kelp stipe counts changed over time, they did so in a proportionally similar way at both sites. Data are from a single replicate transect each year and are stipe counts within a 66.9m^2 area at both the reference and SOWS sites.