Technical Report

Comparison of light transmitted through different types of decking used in nearshore over-water structures

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Aquatic Assessment and Monitoring Team

Summary

The Washington Department of Natural Resources (DNR) is challenged with finding a sustainable balance between water dependent uses and environmental protection of state-owned aquatic lands. DNR therefore has an interest is ensuring that overwater structures are designed to maximize light available to the nearshore aquatic resources. An investigation was conducted to quantify and compare light attenuated by overwater structures constructed of different decking types that are currently available from various vendors. The decking types differed in the percentage of open space, the shape of the open spaces, and the vertical thickness of the decking material. Light sensors were submerged in water below and beside five different deck types, each in a separate tank, and compared with light reaching unobstructed sensors in a control tank. The experiments were designed to evaluate the effect of each decking type, deck elevation above the water surface, and orientation of the decking material open spaces on light attenuation. Results demonstrated that percentage open space alone is not a good predictor of light attenuated by the deck. There were significant differences in light beneath and beside different decking types, at different elevations and orientations. Elevation of the decks eighteen inches above the water resulted in significantly higher values of light reaching directly beneath the deck compared to decks at the water surface. In contrast, elevation of the decks reduced light reaching areas adjacent to the deck. Decks under certain conditions reduced the amount of light available beneath structures to below the threshold of light required for eelgrass (*Z. marina*) survival. Lower than threshold light levels where behavioral changes have been observed in juvenile salmon and herring occurred beneath and beside each deck type investigated in this study.

Introduction

Nearshore areas including the upland beach, intertidal, and subtidal zones are important habitat for primary producers, shellfish, shorebirds and fish. It is an active area where wave run-up and current flows transport sediment and particulates from source to deposition down drift. Nearshore environments above the beach, intertidal and subtidal have been heavily altered by construction of structures such as docks, marinas, and boat ramps to provide humans and boats easy access to the waters. Overwater structures can have effects on aquatic habitat during initial building of the structures, from the installed structures, and from ongoing use of the structures. Effects such as scour from boat wakes during operations can change beach slope, alter water flow and sediment transport patterns. Reduced ambient light conditions from the structure shading beneath and beside the structure can restrict photosynthesis and inhibit fish use. These shade impacts are long term and continue whether the structure is still being actively used or not.

Studies indicate that shading by overwater structures in the marine nearshore is deleterious to nearshore species and their habitat (Ono et al. 2010). Survival of juvenile Chinook and sockeye salmon was reduced in shaded areas (Helfman, 1981). Shading however was advantageous to their predators (Tabor et al., 2004). The opposite is demonstrated with increased light levels. It has been shown to decrease predation rates between northern pike minnow and juvenile Chinook (Petersen and Gadomski, 1994). Docks, piers, boat ramps and other overwater structures also shade submerged aquatic vegetation. This shading is sometimes significant enough to impede the sun's radiant energy from reaching the plants. This radiant energy, referred to as photosynthetically active radiation (PAR), is a measure of the flux of photons with wavelengths in the visible spectra (400 and 700 nm). PAR changes seasonally and varies depending on the latitude and time of day. Levels are greatest at mid day during the summer. PAR values that are adequate for one plant species survival may be insufficient for another. As a result of these and similar findings, the Department of Natural Resources (DNR) recommends maximizing natural light transmission through over-water structures. Techniques to maximize light transmission include: installing decking with open space, increasing elevation of structure above water surface, minimizing structure width, minimizing piling numbers and size, and orienting the longest dimension of a pier in the north-south direction.

Manufactures use different construction materials and designs for decking types, depending in large part on what uses the overwater structure will provide. Industrial piers and wharves, for example, must be able to support heavy vehicles driving and large cranes and equipment mounted on them. These are constructed to be stronger and sturdier than a pedestrian walkway. The decking characteristics - density and size of open space in the decking, number of support pilings required, thickness, strength and durability of the material used, must balance safety and functionality for its use as well as the environment.

Information regarding sunlight passage through different types of decking is limited. This study compares light transmitted in shaded areas beneath and adjacent to structures constructed of some of the more commonly used decking material in the surfaces of piers, docks and marinas in Washington. The major goals of this study are:
- To quantify and compare the amount of light reaching under water, beneath and beside different decking types;
- To quantify light transmitted (measured as PAR) through these decking types with change in elevation of the deck relative to water surface, and orientation of the open spaces relative to the arc of the sun ;

- To develop management recommendations for protection of nearshore organisms based on the findings.

Objectives

Compare PAR in shaded areas beneath and adjacent to overwater structures constructed of different decking materials to determine the relationship between decking type and PAR passing through the decking.

Measure and compare PAR beneath and adjacent to these structures when the deck is at the water surface and elevated eighteen inches above water surface.

Measure and compare light irradiance beneath these same over water structures oriented in north-south and in east-west orientations.

Compare PAR measured in each treatment to empirically observed ecological thresholds to assess the effects of decking type, orientation and elevation on the frequency at which transmitted PAR fails to reach the threshold.

Methods

To address the objectives while controlling for water depth and water clarity, the treatment scenarios were implemented using large portable water storage tanks filled to the same depth with clear, fresh water. The tanks needed to be large enough in width and length to contain the experimental decking structures and have enough remaining space to place a sensor beside them to measure light in the shade cast area adjacent to the structure. The walls needed to be relatively low to minimize their shading of the light sensors. The storage tanks were placed in a flat area with no tall buildings or trees that would obstruct the sunlight or shade any of the tanks.

Five Type II 250 gallons, 8'x 8' water storage AQUA (Aluminum Quick Assembly) tanks were acquired. These tanks are made from water proof tarp secured onto an exterior aluminum frame (Figure 1). The AQUA tanks were placed in a flat unshaded area outdoors at the DNR Tumwater compound then filled with clear fresh water to a depth of thirty inches.

Figure 1.   Type II AQUA tank with 250 gallon capacity and 34 inch tall sides.

Scale models (L=4'x W=4') of pier deck surfaces were constructed using each of five different decking materials. These decking materials varied in shape and amount of open space. The decking types included Fibergrate® molded with 70% open space (referred to as FM), Fibergrate® pultruded -60% open

space (FP), TrueDeck ™ SunWalk ™ 42% (SW), ThruFlow ™ 43% (TF),and Micro-Mesh ® 44 % (MM) and each is pictured in Figure 2. Samples of the decking material were obtained from the manufacturers. Two different length sets of legs were constructed for each structure that could be easily unbolted and exchanged to change elevation of the deck above the water surface. One set were 2.5 feet long, this allowed the bottom of the deck to be just at the water surface when structure was stood upright in the water tank filled to 30 inches depth. The other set of legs were 4 feet long, so the deck was 1.5 feet above the water surface when these legs were swapped in and the structures stood upright in the tanks. One decking structure was placed at the center of each tank. A sixth water tank filled with water, had no structure placed inside and was used as a control.
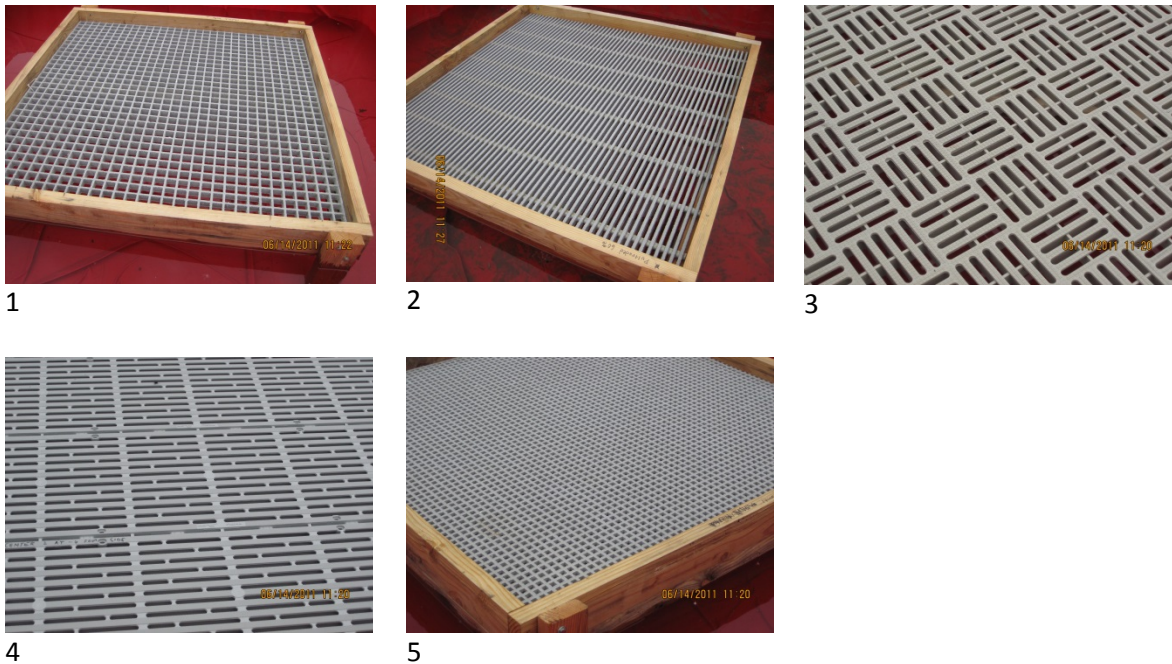

Figure 2. Decking types included in experiment 1) Fibergrate® molded with 70% open space (FM), 2)Fibergrate® pultruded -60% open space (FP), 3) TrueDeck ™ SunWalk ™ with 42% open space (SW), 4) ThruFlow ™ with 43% open space(TF), and, 5) Micro-Mesh® with 44 % open space (MM).

Twelve Odyssey ™ light sensors were calibrated over a twenty-four hour period to a manufacturer calibrated LI-COR® light meter. The Odyssey light sensors are designed to be submerged beneath water up to a depth of 20 meters. The sensors have an internal integrator and data recorder (Figure 3). The integrator produces a pulse output that is directly proportional to the light irradiance, or the photosynthetic photon flux density, entering the sensor. The user will define the period or 'scan-time' the internal counter is to accumulate pulse data. The accumulated value at the end of each scan-time is logged.

Figure 3. Odyssey™ PAR light sensor and data logging recorder contained in a single waterproof unit.

For this study, scan-time was programmed for a ten minute period. The instrument has two parts integrated into the receiving head, a sensor and an electronic integrator amplifier. The amplifier gives a pulse output, with a rate of pulse repetition that is proportional to the irradiance of the light energy reaching the sensor. These data are logged in 'operational amperage,' units. At the end of each scan interval, the total accumulated operational amperage counts from the integrator are recorded in the electronic logging board. The raw logged data, then, is treated as a unitless count that is proportional to the total PAR radiant energy received in the 10 minute interval (e.g., in units of Joules). Alternatively, the unitless count can be thought of as proportional to the total count of PAR quanta received in the 10 minute interval (e.g, units of moles of quanta). In the calibration process, these unitless counts are converted to a mean value of instantaneous PAR over the 10 minute interval in quantum flux units (e.g., units of μmol m^{-2} s^{-1})

Free-standing light sensor mounts were constructed out of clear Plexiglas material to reduce shading from mounts during deployment (Figure 4). In each tank one Odyssey light sensor was placed beneath the center of the decking, just below the water surface. A second Odyssey light sensor was placed in the shade cast area, 1 foot adjacent to east of the decking edge (a distance of 3.5 feet from the first sensor), three inches below the water surface. Two light sensors were placed in the control tank, one at the center of the tank, just below the water surface, and the other sensor 1.5 feet away from the first one, three inches below the water surface.

Figure 4. Submerged light (PAR)sensor supported by Plexiglas mount at bottom at AQUA tank.

Total PAR was measured beneath and adjacent to each decking for four different treatment scenarios (Figure 5). For each treatment, one sensor was deployed directly below each deck, with the sensor head at the water surface. The other sensor was beside each decking type with the sensor head at three inches below the water surface. Each treatment scenario lasted at least a period of four consecutive days.

The four treatments include:

1) Deck at the water surface, long dimension of decking open spaces oriented in North-South direction;
2) Deck at the water surface, long dimension of decking open spaces oriented in the East-West direction;
3) Deck at eighteen inches above water surface, long dimension of decking open spaces oriented in the North-South direction; and
4) Deck at eighteen inches above water surface, long dimension of decking open spaces oriented in the East-West direction.

There was a control tank with two light sensors placed at the same water depths as in the treatments. PAR was measured simultaneously in the control and treatment tanks.

Five treatment tanks with PAR sensors beneath and adjacent to each different deck structure

Control tank with PAR sensors at same water depths as those in treatment tanks
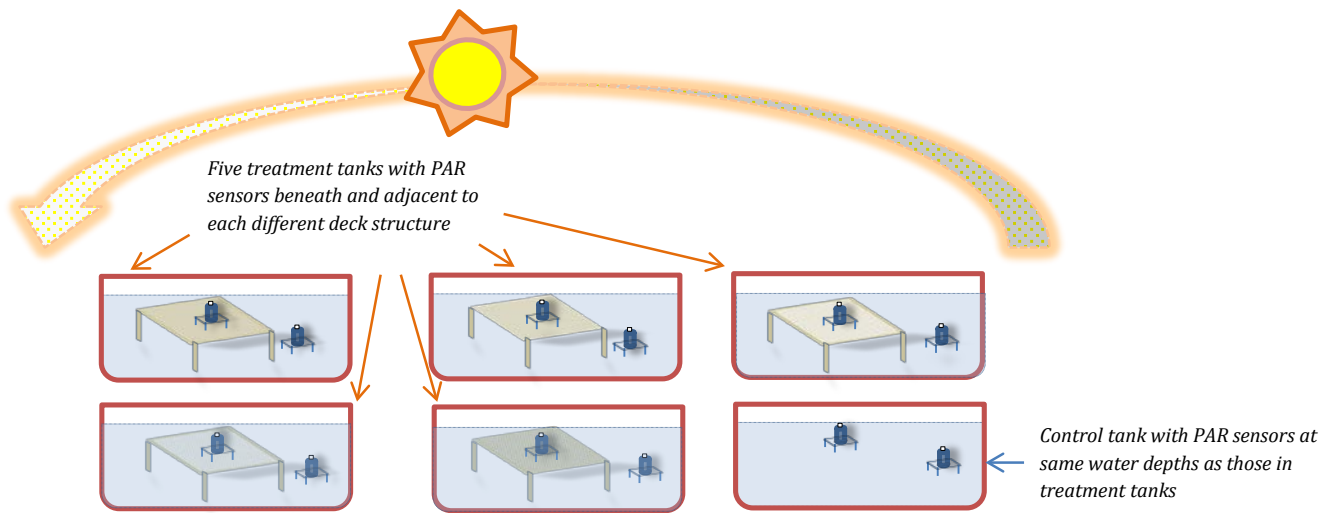
Figure 5. Schematic depicting a treatment scenario. All scenarios included six water tanks filled to the same water depth and twelve PAR sensors. Sensors collected data simultaneously throughout several days for each treatment, logging total PAR in 10-minute increments reaching each sensor as sun traveled through sky. Five of the water tanks contained a deck structure with two PAR sensors, one beneath the deck, just below the water surface, and one adjacent to the deck at three inches water depth. The sixth tank was the control tank. It contained no deck structure but had two logging PAR sensors placed at the same depths as the treatment tanks- one just below water surface and one at three inches depth.

Previous studies have considered the effect of the shape of the dock. Thinner, longer docks oriented in the north-south direction have been demonstrated to allow more sunlight to enter from the sides to reach beneath the dock as the sun traveled through the sky (Rondorf et al., 2010). In this study the experimental deck structures were square, which provided an opportunity to examine whether the orientation of the decking open spaces relative to arc of sun contributed significantly to the amount of sunlight measured beneath the dock. Some of the decking open spaces are symmetrical in two dimensions. Others are asymmetrical, with one dimension as much as twice as long as the other. For this treatment scenario, the longer dimensions of the open spaces were orientated in the north-south direction first, light was measured beneath and adjacent to the structure. Then the decking was turned 90 degrees so the longer dimension of the open space was oriented in the east-west direction, and irradiance was measured again beneath and adjacent to the structure. Each decking orientation was placed in two different elevations relative to the water surface. Irradiance beneath and adjacent to the

structures was measured when structures were just above the water surface, and again when they were elevated eighteen inches above water surface.

Results and Analysis

Instantaneous PAR measured at each sensor was summed over the entire day to give daily PAR (in units of mol m^{-2} day^{-1}). Daily PAR values measured in treatment tanks were divided by the simultaneously collected control PAR values measured by the sensors placed at the same depth in the control tank. In this way, differences in light resulting from changes in cloudiness or local visibility were normalized. These normalized proportion values of total daily PAR were compared and analyzed with respect to decking type, elevation and orientation. These proportional values were averaged over the days within each treatment to give average proportional daily PAR transmission and standard deviation. Plots depicting the average proportion of daily PAR transmitted and standard deviations for each decking by treatment are presented in Figure 6 and Figure 8. The non-normalized total daily and instantaneous PAR values measured in the treatment tanks were also evaluated. The magnitude of these values, and each simultaneously measured control value, were compared with minimal threshold PAR values that have been observed to be of ecological significance. This provided the opportunity to assess which decking, in which orientation, and, at which elevation above the water surface led to PAR conditions falling below these empirically observed standards. Proportional PAR measurements were compared and analyses of variance performed to assess whether differences were significant between: 1) deck at water surface versus deck elevated eighteen inches above water surface, 2) sensor beneath versus sensor beside structure, 3) long dimension of deck open spaces oriented N-S versus open spaces oriented E-W.

Sensors beneath the different deck types

It is immediately obvious from visual inspection of the results plotted in Figure 6 and Figure 8, that the lowest average proportion of sunlight for all decking types was measured when the decks were at the water surface and the sensors directly beneath the decks. The values of PAR measured under the structures with the deck at the water surface (Figure 6) ranged from 16 to 32 percent of the incident sunlight measured at the unobstructed control sensor. When the deck is elevated eighteen inches above the water surface, the proportion of total PAR measured beneath the structures increases, with averages ranging from 26 to 40 percent of the total PAR measured at the control.

It is also apparent that the relative differences between the different decking types measured with sensors beneath the decking remained consistent regardless of the treatment (Figure 6). The sensor beneath the deck constructed of Fibergrate® molded with 70% open space (FM) consistently allowed a greater proportion of PAR to reach the sensor than all the other decking types.

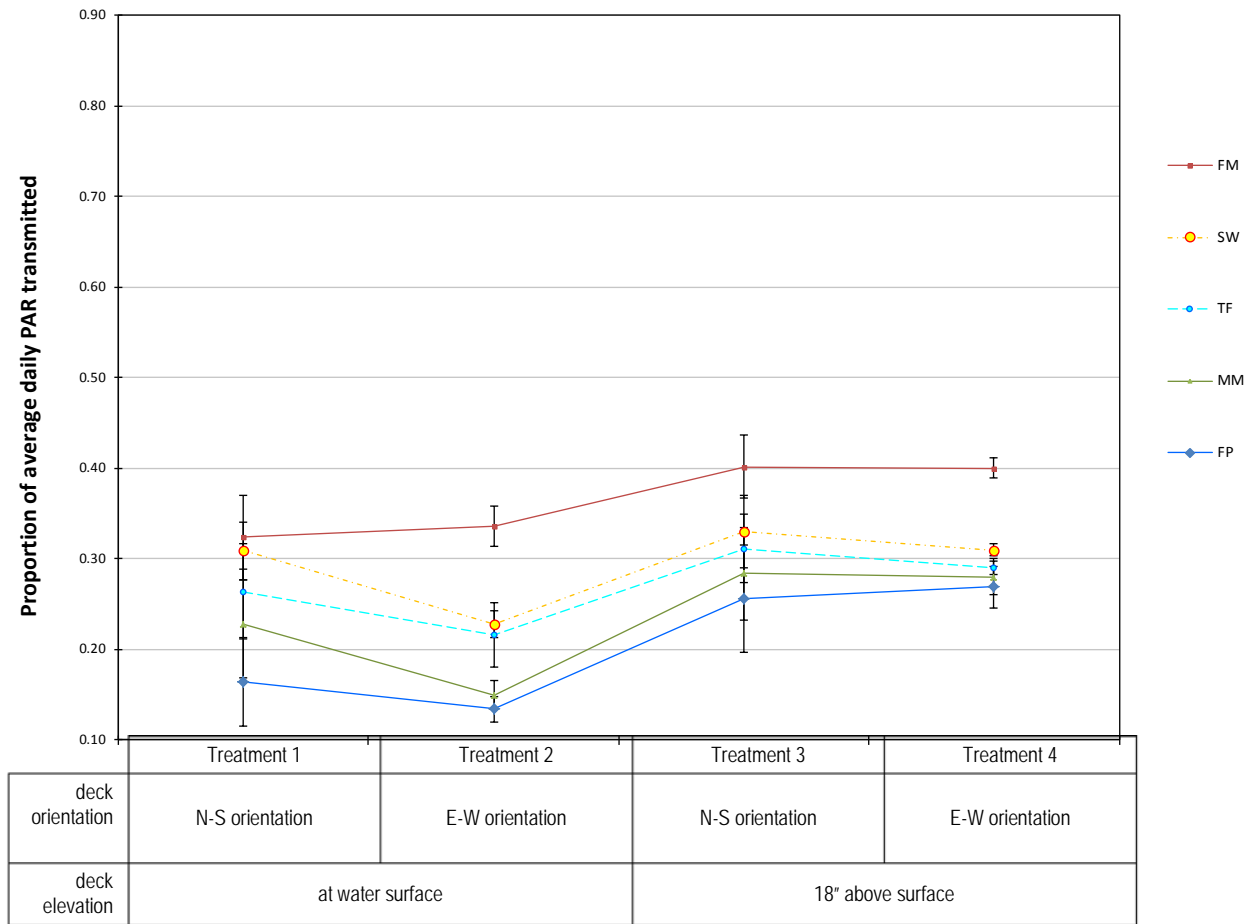## Proportion of average daily PAR measured beneath decking

Figure 6. Proportion of average total daily PAR (mol/m²/day) reaching sensors located beneath each decking type
Treatments are: 1) Deck at the water surface, long dimension of decking open spaces oriented in North-South orientation; 2) Deck at the water surface, long dimension of decking open spaces oriented in the East-West direction; 3) Deck at eighteen inches above water surface, long dimension of decking open spaces oriented in the North-South direction; and, 4) Deck at eighteen inches above water surface, long dimension of decking open spaces oriented in the East-West direction.

Although intuitively it may have seemed that a greater percentage open space would result in a greater proportion of light being transmitted beneath the deck. However, this is not the case. The relationship between increasing open space and amount of PAR transmitted below deck is depicted in Figure 7 below. It is obvious from this plot that increasing percentage open space does necessarily result in increased PAR transmission. There is not a consistent positive linear relationship between amount of open space and amount of light transmitted

Percentage of decking open space x proportion of average daily PAR transmitted beneath deck
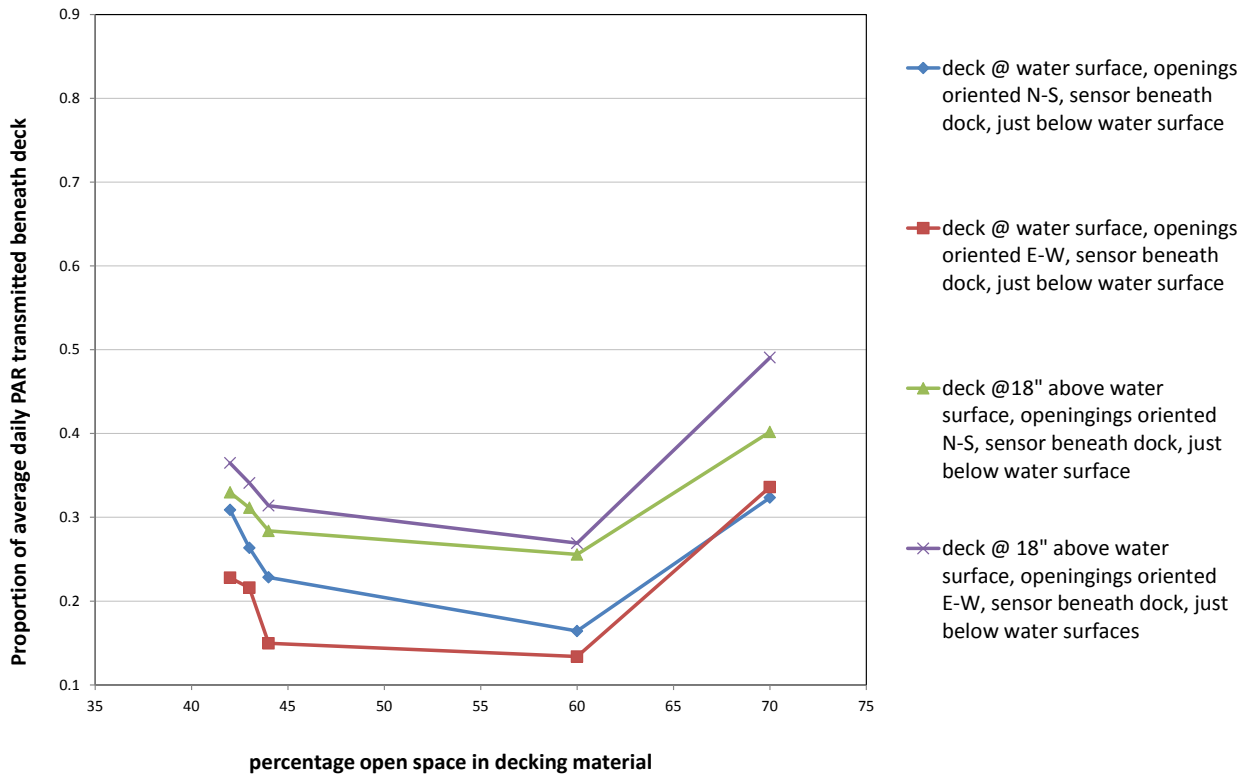

Figure 7. The proportion of light transmitted beneath deck with increasing percentage open space.

When two-way repeated measures ANOVAs without replication were performed to evaluate the difference in variance among the deck types and between the deck types in each treatment scenario, significant differences among the means were indicated. While these ANOVA results demonstrate that different decking types exposed to the same treatment allow significantly different amount of light to pass through, they don't indicate which groups differ significantly from each other. To evaluate this, Tukey's post-hoc ANOVA pair wise analysis of the means was performed. This analysis compares all possible pairs of means. It is based on a studentized range distribution, q, which is similar to the t distribution from the t test. A critical q value is determined based on the standard error and degrees of freedom. If the q calculated for a pair means is greater than the critical q, those means differ significantly from one another (Zar, 1999). This provided the ability to determine which decking types allowed a significantly greater amount of light to pass through the decking. Summarized results of the Tukey post-hoc pair-wise analysis are presented below in Table 1.**Error! Not a valid bookmark self-reference.**

Table 1. Summary of significant differences in PAR measured beneath the different decks determined from Tukey's post-hoc pair-wise analysis of ANOVAs applied to each treatment scenario.

Treatment 1	Treatment 2	Treatment 3	Treatment 4
Significantly different mean daily PAR measured	Significantly different mean daily PAR measured	Significantly different mean daily PAR measured	Significantly different mean daily PAR measured
FM>TF,MM, FP SW>TF,MM, FP	FM>SW,TF, MM, FP SW> MM, FP TF>MM, FP	FM>TF,MM, FP	FM>SW, TF,MM, FP

From the analysis results in

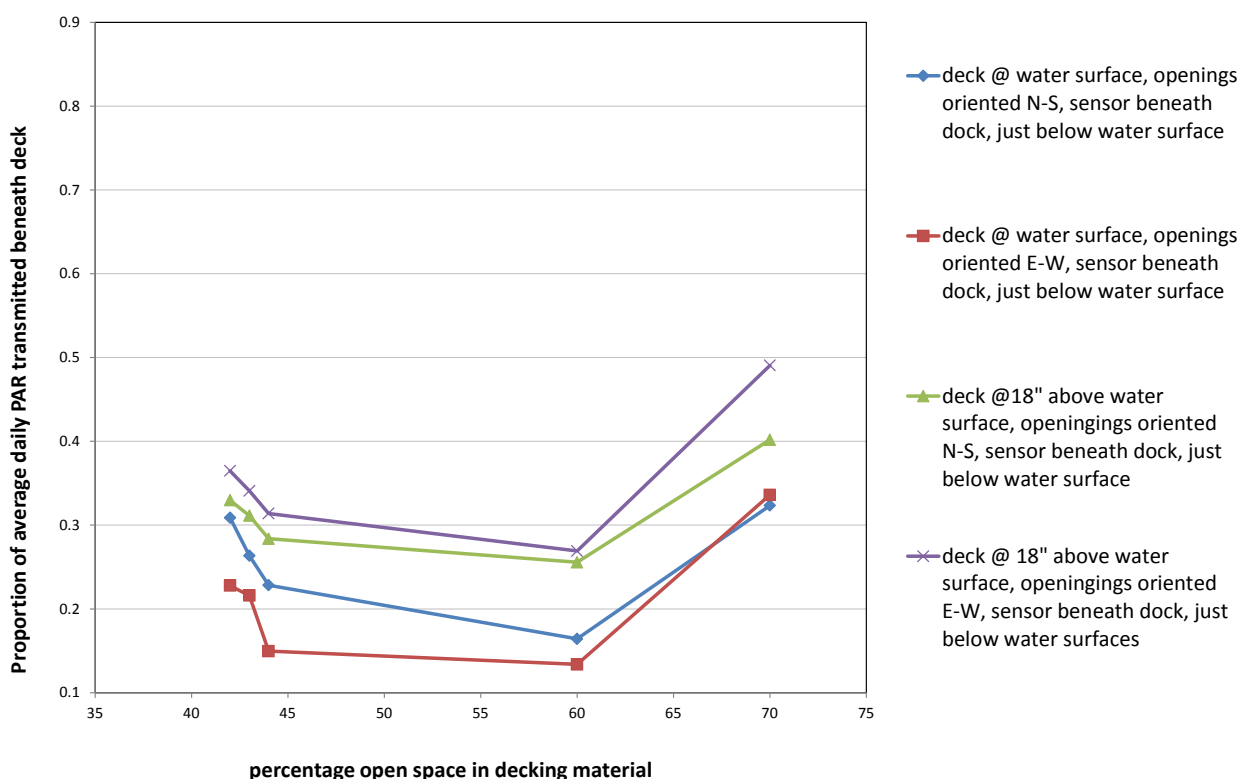**Percentage of decking open space x proportion of average daily PAR transmitted beneath deck**

Figure 7. The proportion of light transmitted beneath deck with increasing percentage open space.

When two-way repeated measures ANOVAs without replication were performed to evaluate the difference in variance among the deck types and between the deck types in each treatment scenario, significant differences among the means were indicated. While these ANOVA results demonstrate that different decking types exposed to the same treatment allow significantly different amount of light to pass through, they don't indicate which groups differ significantly from each other. To evaluate this, Tukey's post-hoc ANOVA pair wise analysis of the means was performed. This analysis compares all

possible pairs of means. It is based on a studentized range distribution, q, which is similar to the t distribution from the t test. A critical q value is determined based on the standard error and degrees of freedom. If the q calculated for a pair means is greater than the critical q, those means differ significantly from one another (Zar, 1999). This provided the ability to determine which decking types allowed a significantly greater amount of light to pass through the decking. Summarized results of the Tukey post-hoc pair-wise analysis are presented below in Table 1.**Error! Not a valid bookmark self-reference.**

Table 1, it is apparent that the FM deck type allows a significantly greater proportion of light to reach beneath the grating than the TF, MM and FP decks in all cases. The differences in PAR measured beneath the FM and SW decks are not significant for Treatment 1(deck at the water surface, long dimension of decking open spaces with north-south orientation), or Treatment 3, (deck at eighteen inches above water surface, long dimension of decking open spaces with north-south orientation), in spite of SW having twenty-eight percent less open space than FM. Deck types MM and FP performed similarly for each treatment. No significant differences in PAR were measured beneath these two deck types for any treatment, though the MM deck has less than fifteen percent open space than the FP deck. MM spacing shape is symmetrical while FP open space is asymmetrical, but changing the orientation of the open spaces with respect the arc the sun traveled did not have an effect that distinguished the amount of light passing through these two deck types. The FP deck material is a very thick (in the vertical dimension), as is the MM material. Additionally, the size of the individual open spaces in the MM deck material is very small relative to the thickness of the mesh which may cause a large amount of light to be deflected back skyward rather than traveling through the open spaces and reaching below the structure.

Sensors beside the different deck types

Results plotted in Figure 8 indicate the proportion of sunlight reaching the sensors located adjacent to the deck is higher when the decks are at the water surface than when the decks are elevated above the water. Values of PAR measured beside decks at the water surface ranged from 70 to 89 percent of PAR measured at the unobstructed control sensor. When the deck is elevated eighteen inches above the water surface, the proportion of total PAR measured beside the structures decreased, with mean total daily PAR ranging from 40 to 57 percent of the total PAR measured at the control. This is opposite of what was observed for the sensors located beneath the deck. The proportion of sunlight reaching the sensors beside each of the different deck types does not follow a pattern of relative consistency across the treatment types. For the first two treatments (when deck is at the water surface), the FP deck allows the greatest proportion of sunlight to reach beside the deck. However when the decks are elevated eighteen inches above the water, the lowest values of PAR were measured beside the FP deck.

The relationship between increasing open space and the amount of PAR transmitted beside the deck is not a direct positive one. The results plotted in Figure 9 show that increasing percentage open space does necessarily result in increased PAR transmission. There is not a consistent positive linear relationship between percentage of open space and amount of light transmitted.

Proportion of average daily PAR measured beside decking

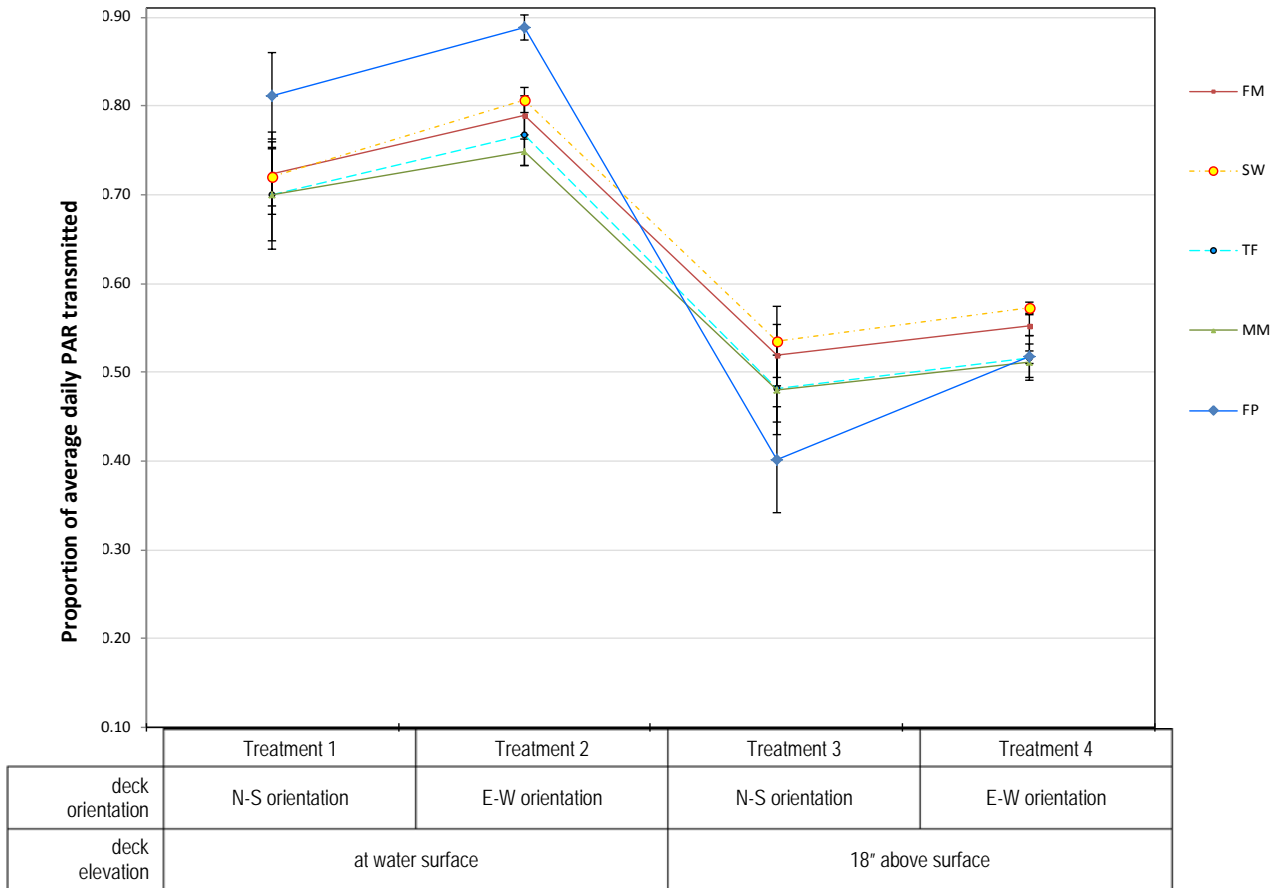|	Treatment 1	Treatment 2	Treatment 3	Treatment 4
deck orientation	N-S orientation	E-W orientation	N-S orientation	E-W orientation
deck elevation	at water surface		18″ above surface	

Figure 8. Proportion of average total daily PAR (mol/m²/day) reaching sensors located beside each decking type.
Treatments are: 1) Deck at the water surface, long dimension of decking open spaces oriented in North-South orientation; 2) Deck at the water surface, long dimension of decking open spaces oriented in the East-West direction; 3) Deck at eighteen inches above water surface, long dimension of decking open spaces oriented in the North-South direction; and, 4) Deck at eighteen inches above water surface, long dimension of decking open spaces oriented in the East-West direction

Percentage of decking open space X proportion of average daily PAR transmitted beside deck
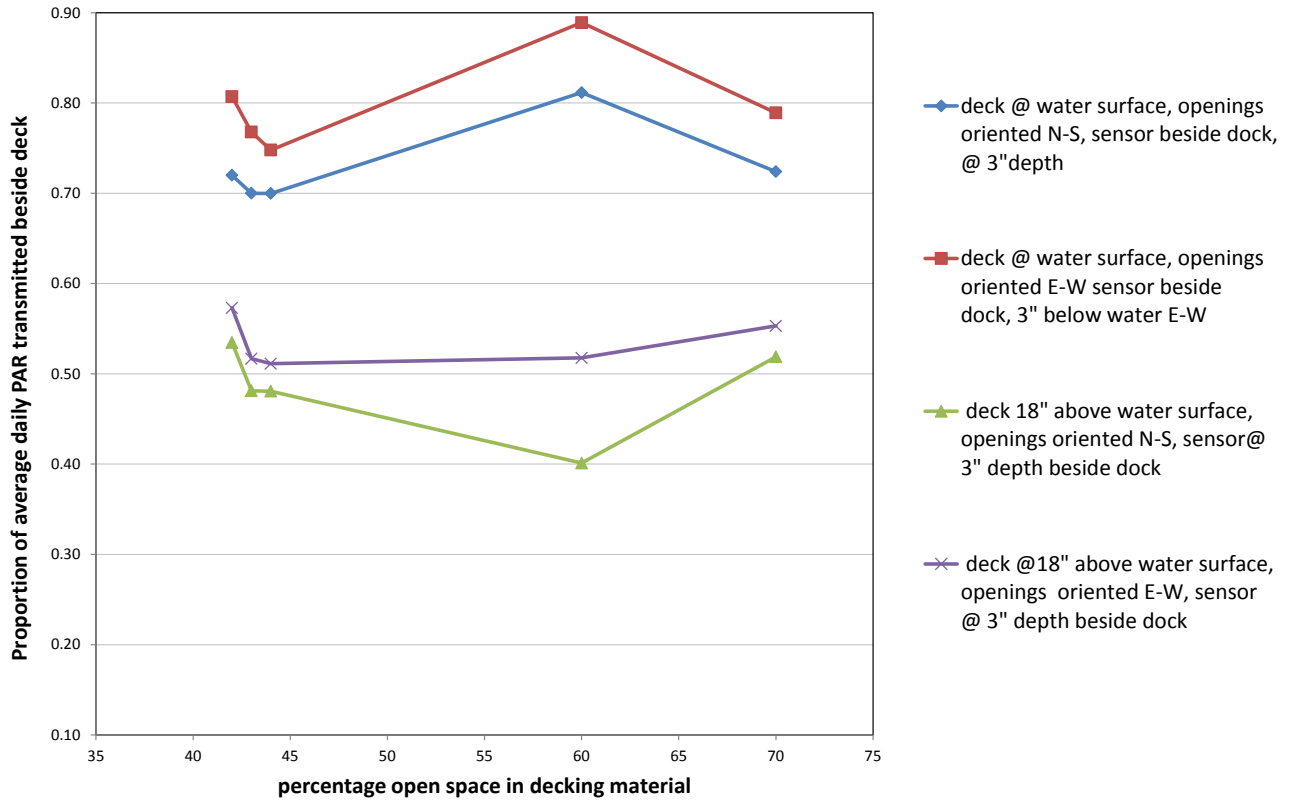

Figure 9. The proportion of light transmitted beside the deck with increasing percentage open space.

Table 2 Summary of significant differences in PAR measured beside the different decks determined from Tukey's post-hoc pair-wise analysis of ANOVAs applied to each treatment scenario.

Treatment 1	Treatment 2	Treatment 3	Treatment 4
Significantly different mean daily PAR measured	Significantly different mean daily PAR measured	Significantly different mean daily PAR measured	Significantly different mean daily PAR measured
FP>TF,MM	FP>SW,FM, TF, MM	SW>TF,MM, FP FM>TF,MM, FP	SW >TF,MM, FP

The Tukey pair-wise analyses results summarized in Table 2 show the FP deck type allows a significantly greater proportion of light to reach beside the deck than the TF and MM deck types do under Treatment 1. PAR measured beside deck types SW, FM, TF and MM are all significantly lower than PAR measured beside the FP deck for Treatment 2. With sixty percent open space, the FP deck type has the second highest percentage of open space among all the decks. In contrast, for Treatments 3 and 4, where the decks are elevated eighteen inches above the water, the highest values were measured beside the SW deck, and the lowest values measured beside the FP deck, though the SW deck contains eighteen percent less open space than the FP deck. These findings may be explained by considering and

comparing the characteristics of these two decks. The open spaces of the SW deck are asymmetrical but are placed in an alternating, repeated pattern to become symmetrical (Figure 2). It is a very thin (<0.25"), light decking material. The open spaces of the FP deck are asymmetrical, and the decking is quite thick (>1.0"). When elevated above the water level, the FP deck casts a more intense and larger shadow than the SW deck.

Comparing sensors beneath and beside PAR transmission

Summarized results of single factor analyses of variance (ANOVAs) are presented in Table 3, Table 4, and Table 5. These results indicate that regardless of the orientation of the open space, mean total daily PAR measured at the sensors located beneath the deck are significantly lower when the deck is at the water surface compared to when the deck is raised eighteen inches above the water surface.   This difference is significant at α =.05 when open spaces are oriented east-west and at α = .10 when open spaces are oriented north-south. Regardless of the orientation of the open space, ANOVA results indicate mean total daily PAR measured at the sensor located beside the deck is significantly higher when the deck is at the water surface compared to PAR measured when the deck is raised eighteen inches above the water surface at α =.05.

When the open spaces were oriented in the east-west direction, a significantly greater proportion of PAR was measured beside the decks, regardless of whether the decks were at the water surface or elevated eighteen inches above the water.

Table 3. ANOVA results comparing PAR measured when deck is at water surface and deck placed 18" above water surface.

Sensor position and deck open space orientation	Deck @ H_2O surface	Deck 18" above H_2O surface	ANOVA Significant difference
Beneath N-S	.26 ± .16	.32 ± .06	Yes @ α = .10
Beneath E-W	.21 ± .10	.31 ± .06	Yes @ α = .05
Beside N-S	.73 ± .18	.48 ± .06	Yes @ α = .05
Beside E-W	.80 ± .10	.53 ± .06	Yes @ α = .05

Table 4. ANOVA results comparing PAR measured from sensor beside deck and sensor beneath deck

Deck elevation and open space orientation	Sensor beside deck	Sensor beneath deck	ANOVA Significant difference
@ H_2O surface N-S	.73 ±.18	.26 ±.16	Yes @ α =.05
@ H_2O surface E-W	.80 ±.10	.21 ±.06	Yes @ α =.05
18" above H_2O surface N-S	.48 ±.06	.32 ±.06	Yes @ α =.05
18" above H_2O surface E-W	.53 ±.06	.31 ±.06	Yes @ α =.05

Table 5. ANOVA results comparing PAR measured with open spaces oriented N-S and E-W

Sensor position and deck elevation	N-S open space orientation	E-W open space orientation	ANOVA Significant difference
Beneath @ H_2O surface	.26 ±.16	.21 ±.10	No @ α = .10
Beneath 18" above H_2O surface	.32 ±.06	.31 ±.06	No @ α = .10
Beside @H_2O surface	.73 ±.18	.80 ±.10	Yes @ α = .05
Beside 18" above H_2O surface	.48 ±.06	.53 ±.06	Yes @ α = .05

Comparing PAR values beneath and beside deck types to ecological thresholds

There are two empirically derived ecological threshold values of PAR that are compared to the values measured in this experimental work. It is clear from the results presented above that over water structures constructed with any of the five decking types investigated in this study will reduce the light available under and beside the structures. Comparison of these measured values to some relevant threshold values of PAR will help demonstrate whether the magnitude of the light reduction is of ecological significance.

Previous research has demonstrated that reduction in light can limit the growth and reproduction of submerged aquatic plants such as seagrasses, including eelgrass *Zostera marina* (Burdick and Short 1999, Shafer 1999, Smith and Mechid 1999). *Z. marina* is a flowering perennial (but may also grow as an annual) nearshore aquatic plant. It is the dominant seagrass in coastal and estuarine areas of Washington State, found in both intertidal and subtidal areas. This plant is an important member of the coastal ecosystem because it helps to physically form the habitat and it plays a critical role in providing sheltering and spawning grounds for many other species including Pacific herring (Haegele and Schweigert 1985), Dungeness crab (McMillan, et. al 1995; and Williamson, 2006), juvenile and migrating salmonids (Fresh 2006) and the harpacticoid copepods salmon feed on (Fujiwara and Highsmith, 1997; Haas, et al. 2002). Because of the recognized important ecological role of *Z. marina,* there has been considerable study in the Pacific Northwest to understand the status and trends of its distribution and how best to sustainably manage and protect the species. A study designed to understand the minimal light needed for eelgrass plants to survive indicated PAR values of at least 3 mol/m^2/day, on average, during spring and summer were required (Thom et al., 2008). This empirical ecological threshold value was compared with the mean daily total PAR values measured beneath and beside the deck types exposed to the four different treatments in this study. The other PAR value comparison is to an instantaneous threshold of 2 μmol/m^2/sec (converted from empirically measured values reported in Lux units see Appendix A for conversion method) which is the light intensity where juvenile salmon and herring larvae (*Clupea harengus*) have been observed to generally stop feeding (Ali and Hoar 1959, Blaxter, 1966), and where juvenile chum stop actively swimming (Suzuki et al., 2007).

The threshold value of 3 mol/m^2/day, the minimum required PAR for *Z. marina* survival is plotted together with the mean total values of PAR for each day of the four treatments that were measured by sensors placed beneath (Figure 10) and beside each deck (Figure 11). There are a number of occurrences apparent in plots for treatments 1, 2, and 4 of Figure 10 where the measured mean total daily PAR values are below the threshold value. These are PAR values measured beneath the FP deck type. One tailed Student T tests performed on these data indicated that the measured mean total daily PAR values were not significantly lower than the threshold value. It is important to recognize that the sensors placed beneath the deck were measuring light incident just at the water surface. The majority of eelgrass in Puget Sound is distributed in the lower intertidal and subtidal depths. Typically sunlight must travel through water column depths of inches to feet before reaching the photosynthetic leaves of eelgrass. This point will be further elaborated on later in the discussion section.   None of the PAR values measured with the sensor placed beside the deck (Figure 11) were lower than the minimal threshold value required for *Z. marina* survival.

The instantaneous PAR values of 2 μmol/ m^2/sec, the threshold below which behavior changes have been observed in salmon and herring were compared to the average instantaneous PAR values logged with the light sensor over ten-minute intervals. Instances where the control sensor recorded a value above the threshold, while a treatment sensor beneath or beside each deck recorded a value lower than

the threshold were identified and tallied. All these ten minute periods were summed and divided by the total time that above -threshold PAR values were measured at the control sensor.   The percentage of time above-threshold light was available but was prevented from reaching beneath or beside each deck for each treatment scenario was calculated. All deck types in all treatment scenarios blocked adequate light from reaching the water for some portion of the day. The maximum percentage time this occurred for each treatment and deck are plotted in Figure 12 - for sensors beneath deck, and in Figure 13, for sensors beside decks. There was a greater percentage of time (ranging between 2-13 %) where measured PAR values were below threshold values beneath the decks than beside the decks. This percentage of time corresponds to a range of twenty minutes to two hours of a typical mid June day in Olympia, with nearly 16 hours of daylight). The periods of day where light beneath the dock was below the 2 µmol/ m^2/sec threshold was when the sun was low on the horizon- in the early morning and early evening. At the beside-deck sensor, the percentage of time PAR values were measured below threshold ranged from 0-3% (or zero to thirty minutes of the 16 hours of daylight). Decks at the water surface had a greater impact on preventing adequate light reaching below the deck than decks elevated eighteen inches above the water surface. Deck types FP and MM had the greatest percentage of time below the threshold relative to the other deck types. Just the relative amount of time PAR was measured below the threshold value of 2 µmol/ m^2/sec is compared among decks. It is assumed that the greater amount of time each deck attenuates the light below the threshold PAR, the more harmful this is for fish- forcing them to expend energy avoiding the shaded areas. However, what the magnitude of ecological significance is for fish with reduced time exposure to adequate PAR in the early morning and evening hours is beyond the scope of this study.
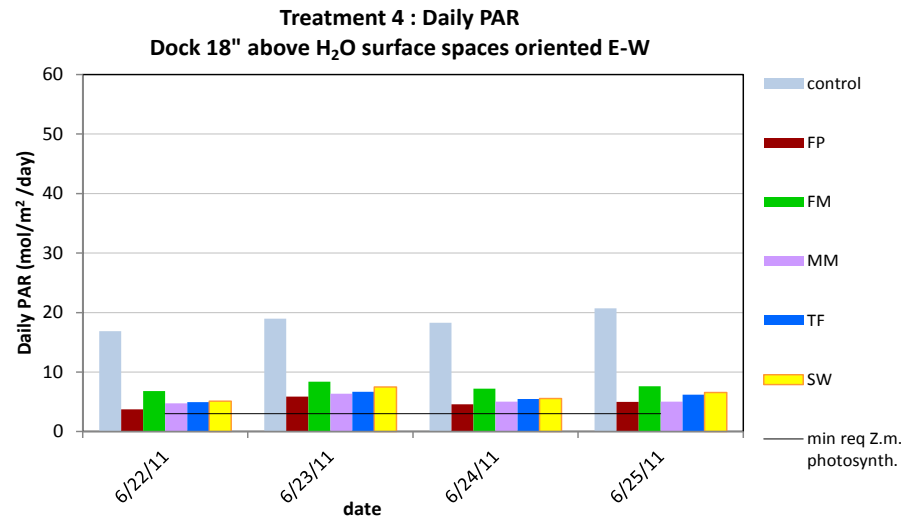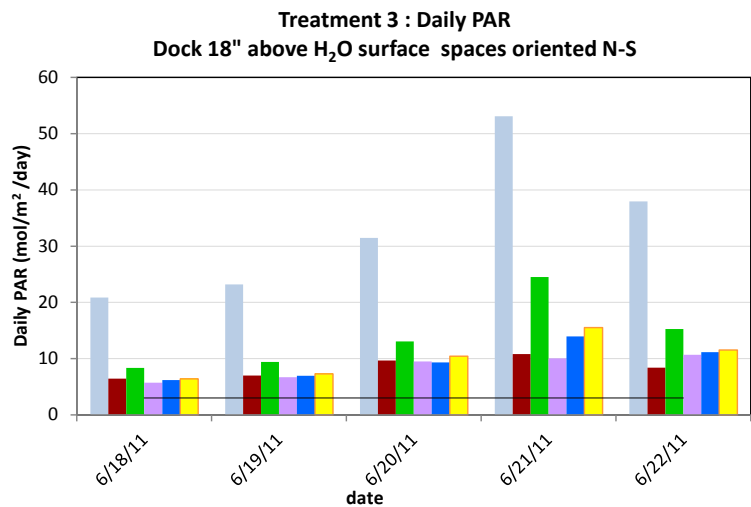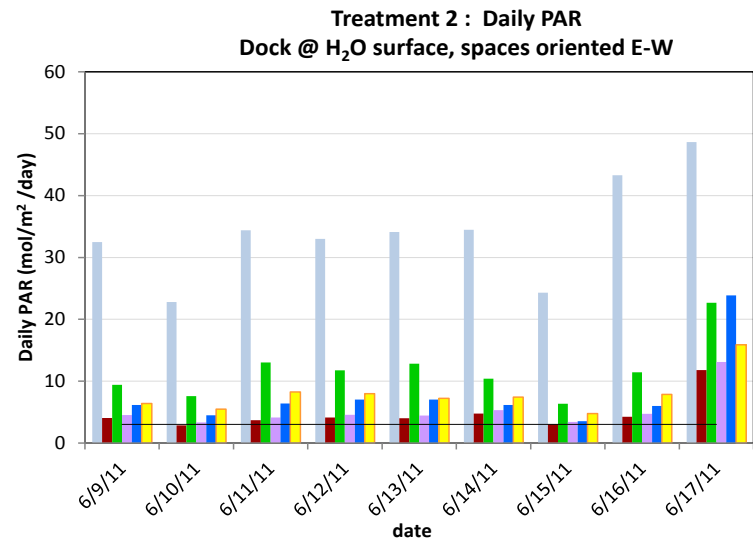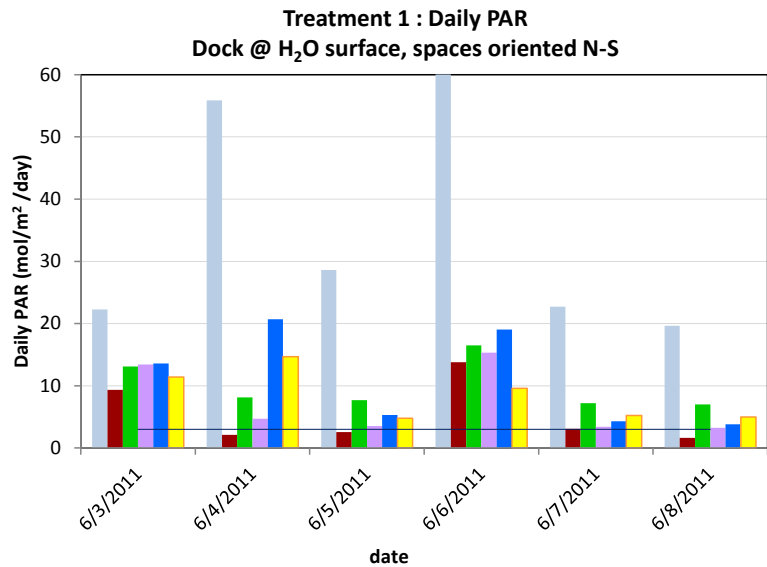
Figure 10. Mean total daily PAR measured beneath each deck type, just at the water surface for four different treatment scenarios. The horizontal black lines represent the minimum daily PAR required for *Z. marina*.
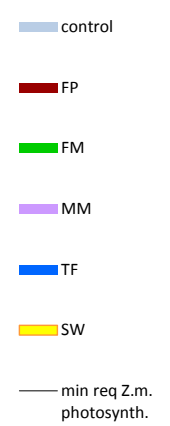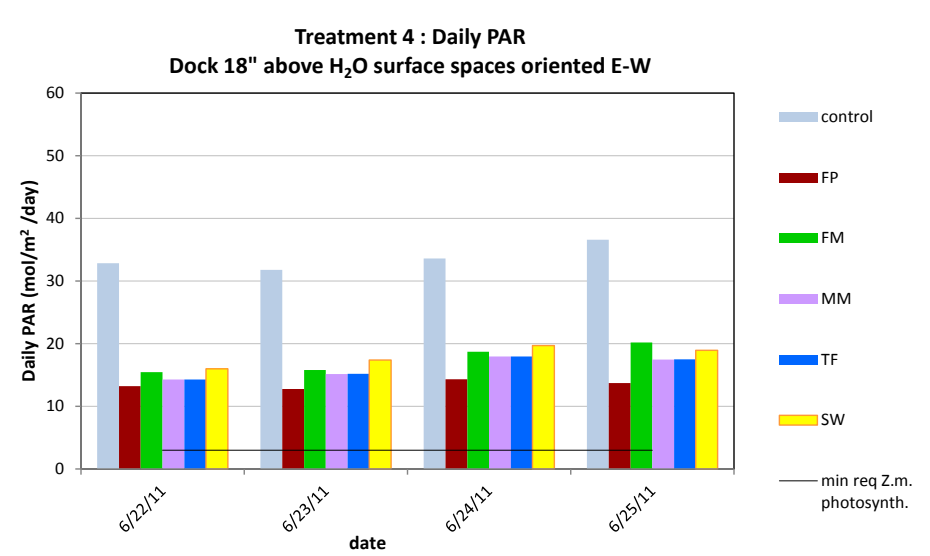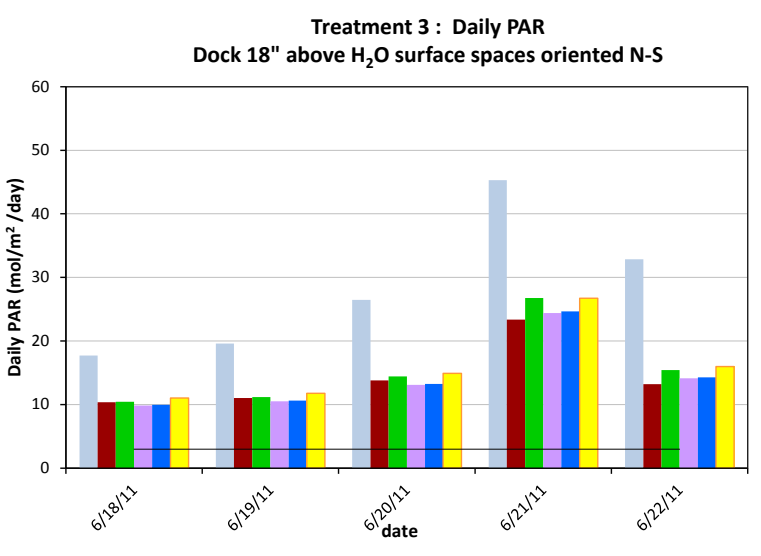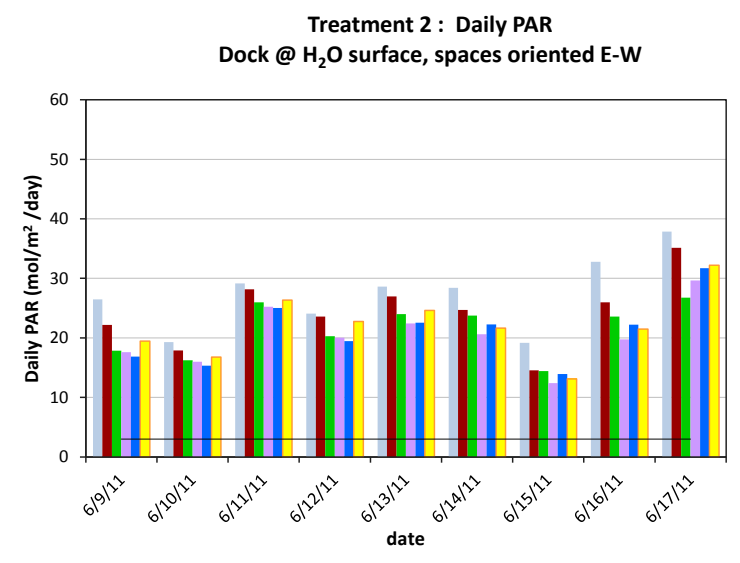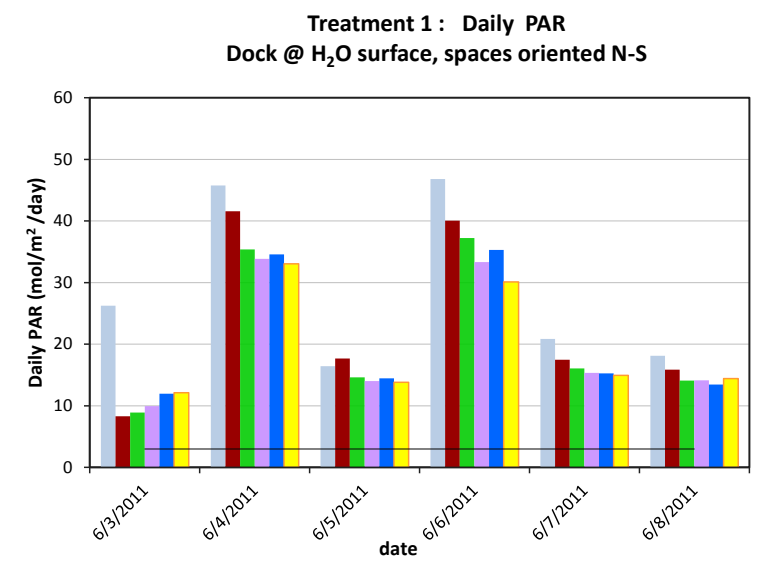
Figure 11. Daily total PAR measured beside each deck type, at three inches water depth, for four different treatment scenarios. The horizontal black lines represent the minimum daily PAR required for *Z. marina*.
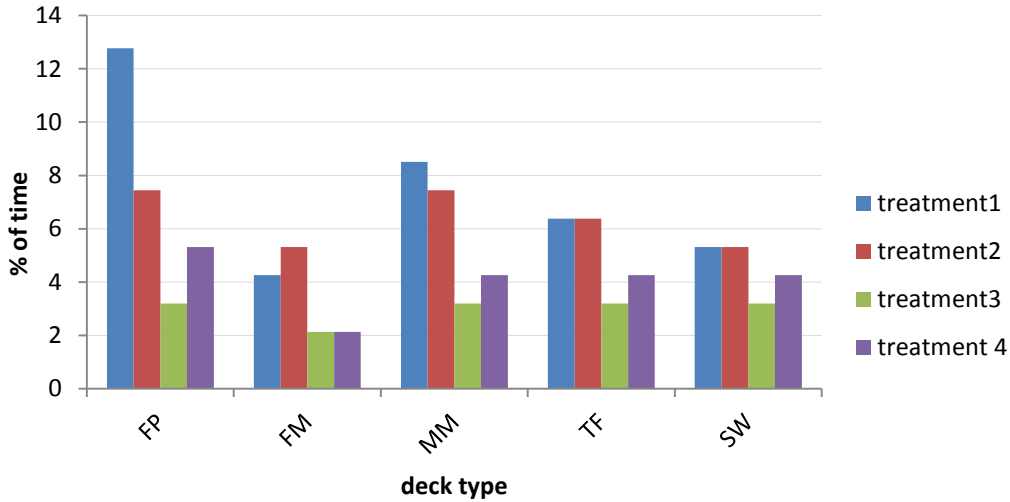
Figure 12. Percentage of time measured for each treatment where the control sensor measured daily PAR values above fish behavior changing threshold of 2 µmol/m²/sec while sensor beneath each deck type measured below this threshold.

Treatments are: 1) Deck at the water surface, long dimension of decking open spaces oriented in North-South direction; 2) Deck at the water surface, long dimension of decking open spaces oriented in the East-West direction; 3) Deck at eighteen inches above water surface, long dimension of decking open spaces oriented in the North-South direction; and 4) Deck at eighteen inches above water surface, long dimension of decking open spaces oriented in the East-West direction
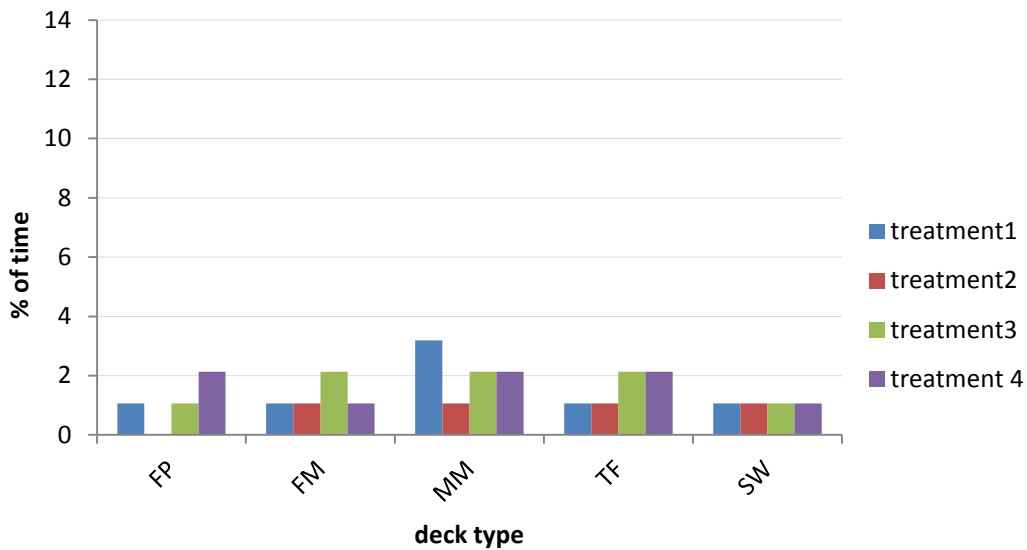

Figure 13. Percentage of time measured for each treatment where the control sensor measured daily PAR values above fish behavior changing threshold of 2 µmol/m²/sec while sensor beside each deck type measured below this threshold.

Discussion

The most important factor for maximizing light beneath decks is elevating the deck above the water surface. For all deck types this resulted in a significantly greater proportion of light reaching the sensors beneath the decks (Figure 6).

Raising the deck above water decreased the proportion of light reaching the sensors beside the deck (Figure 8). A raised deck will cast a larger shadow so it makes physical sense that the sensor next to the deck would have a higher likelihood of being shaded with an elevated deck. Raising the deck does create a larger shade footprint around the deck, but this shading did not significantly reduce the light availability below the ecological thresholds tested for the configurations tested. While the decrease in proportion of light reaching beside the dock is greater than the increase in proportion beneath the deck after elevation, it seems more critical that the minimum ecological threshold values of 3 mol/m^2/day and 2 μmol/m^2/sec be met or exceeded than values of light intensity that are already sufficiently high be increased.

There is not a positive linear relationship between amount of open space and the amount of shade cast beneath and beside a deck (Figure 7and Figure 9). The FM deck type had seventy percent open space, the greatest percentage of open space among all the deck types. The largest proportion of light reached beneath the FM deck when decks were at the water surface. However, this amount was not significantly different than the light allowed through by SW deck type, which was only forty two percent open space. The shape of the open space, the size of the open space and thickness of the decking material all affect the amount of light that passes through a deck top. If there is a high density of open space but the size of the open space is very small, such as in the MM deck type, much of the light may be deflected and reflected upwards rather than down beneath the deck.

The orientation of the open space with respect to the arc of the sun traveled does influence the amount of light that is able to reach through the deck surface. Significantly greater PAR values were measured beside the deck when the open spaces were in the E-W direction. When the deck was at the water surface, significantly greater PAR was measured beside the FP deck relative to all the other deck types. However, when the decks were raised above the water surface, greater PAR was measured beside the SW deck. Both the FP and SW decks have oblong open spaces. The FP is a thicker decking material than the SW decking. The open spaces in FP decking run the length of the deck, so are large and long. The open spaces in SW decking are not that large (<4.0") - but the decking design is an alternating pattern of the direction of the oblong spaces. This design appears to reduce the shading that is cast beyond the footprint of the structure.

Although none of the deck types reduced the amount of light reaching beneath the structure significantly below the eelgrass threshold PAR value, some of the values measured were just below or barely met the threshold value. These values were measured beneath the decks just at the water surface. In most locations in Washington, eelgrass grows in the lower intertidal and subtidal. This means light must travel through the water column before it reaches the eelgrass leaves where photosynthesis occurs. There is an important reduction of light intensity and loss of color with increasing water depth. The underwater light intensity at different depths follows the Beer-Lambert Law:

$$I_z / I_o = e^{-kz}$$

Where: I_z, = the intensity of light at depth z,

I_o = the intensity of light at the ocean surface
k = the light attenuation or extinction coefficient
(Monteith and Unsworth 2007).

This formula indicates that light intensity decreases exponentially with water depth. The relative decrease of light intensity and loss of color is also influenced by the water composition—turbidity, presence of phytoplankton, and suspended matter—which is taken into account by the attenuation (extinction) coefficient. This means that if mean total daily PAR values measured at the water surface are below the threshold value needed for eelgrass survival, once the reduced light travels through the water column to reach eelgrass, even if it is traveling just a few inches, it will be significantly below the threshold PAR value. If there are empirically measured extinction coefficients for Washington marine waters in areas of known eelgrass distribution and depth, it would be a useful next step to apply the Beer-Lambert equation with the PAR values measured at the water surface under these different deck types.

All deck types in all treatment scenarios blocked adequate light required for undisturbed fish behavior for some portion of the day. There was a greater percentage of time (ranging between 2-13 %~ 20 min to 2 hrs 16 hr daylight) where measured PAR values were below threshold values beneath the decks than beside the decks.

Management Recommendations

- Require decks to be elevated above the water surface. Though this does increase the shaded amount of nearshore area, the intensity of this expanded shading does not appear to reduce light availability below the ecological significant thresholds evaluated in this study. Elevating the deck above the water surface increases the light available under the deck by allowing light to enter from the sides – often increasing the light intensity above the critical threshold values. Raising structures also reduces the intensity of the light-to-shade line when moving from beside to beneath the deck. Deleterious effects on fish behavior have been observed with respect to the intensity of the light-to-shade line (Ono 2010)

- Implementing a stewardship measure that relies just on a minimum percentage open space criteria is not an effective management method to minimize reduction of light beneath and adjacent to docks. Instead, requiring that a proportion of the incident radiant light reach the water surface below or adjacent to a dock would better account for the other parameters effecting light transmission including the shape, size and density of the open spaces. Shafer (1999) found in Florida that seagrass did not grow under docks if light levels reaching the surface were less than fourteen percent of the incident radiation.

- The long dimensions of the structure itself should be oriented in the north-south direction, to maximize incident light from the sides reaching beneath the deck. However, by orienting the longer dimension of the open spaces in the east-west direction when decks are elevated above the water reduces the shading beside structures of some decking types.

- Encourage use of the thinnest deck material and largest open spaces possible while still providing for safety, strength, and durability necessary for the structure's primary use.

- It appears possible to modify the design and placement of over water structures adequately to avoid reducing available light below the mean total daily PAR threshold required for eelgrass survival. Modifications to avoid falling below the instantaneous PAR threshold where fish behavioral changes are observed are more complex. While the plants require a minimum flux of photons over a day (Thom 2008), the fish respond more rapidly to finer scale differences in light availability (Ono et al. 2010). The results from this study show that light availability is reduced below the ecological threshold of 2 μmol/m^2/sec beneath and beside every decking in nearly all treatment scenarios.

Suggested Next Steps

- In this investigation, the required threshold value of PAR necessary for eelgrass survival was compared to light measured just below the water surface. However, the majority of eelgrass in Washington is found at some depth below the water surface. The light reaching the water surface will be further reduced before reaching the eelgrass canopy depending on the depth of the water the light must travel through and the light extinction properties of the water (e.g. amount of phytoplankton and suspended sediment in the water). Empirical data of the light extinction coefficients in Puget Sound and outer coast estuaries is limited. Where eelgrass distribution and depth data is known, extinction coefficients should be sampled using secchi disk or submersible light extinction meter. These data can be analyzed with the results of this light-deck study and to predict light availability at eelgrass canopy water depths beneath and beside the decks. Using the relationship on light attenuation with depth described in the Beer-Lambert law, whether PAR values above the critical threshold of 3 mol/m^2/day are reaching eelgrass beneath and beside the decking types.

- Existing, operational docks constructed of the deck materials investigated in this study should be instrumented with light meters beneath and beside and monitored in-situ over several peak solar irradiance days and compared with the study findings. Relative differences among the deck types should remain consistent, unless dock designs are very dissimilar. It would be useful if multiple docks constructed of the same materials but different designs could be investigated to evaluate how dock design (such as height of siding) might influence shade effects.

- PAR values should be measured beneath and beside opaque and floating docks that are planned to be modified to include decking with open space and increased elevation above the water. After the modifications are constructed PAR values should be monitored at the same locations beside and beneath the updated structures and changes in submerged aquatic vegetation distribution and density documented. Comparing the 'before' and 'after' values will provide the information needed to evaluate the effectiveness of the modifications.

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