ZOSTERA MARINA *AND SEA LEVEL RISE:*

ESTIMATING FUTURE HABITAT AVAILABILITY ON ARMORED AND UNARMORED SHORELINES IN THE PUGET SOUND.

by

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ABSTRACT

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Global sea level rise is a growing concern for coastal environments and poses significant risks to many habitats and species. *Zostera marina* habitat in the Puget Sound, however, has been predicted to expand in the event of sea level rise (SLR) due to the elevation range of its subtidal habitat. Shoreline armoring is extensive along Puget Sound shorelines and occurs at many locations where eelgrass is present. This study used geographic information system (GIS) analysis of publicly available survey data and digital elevation models to summarize the spatial extent of eelgrass and armoring in the Puget Sound. It then used site analysis and inundation models of armored and unarmored site pairs in the Central Puget Sound. Armoring was found to occur on 30% of shorelines where eelgrass has been observed. Individual study sites showed considerable variability in characteristics and SLR projections. Habitat expansion was projected by the year 2100 for 3 sites and losses were modeled at 1 site. Differences in habitat changes between armored and unarmored site pairs were variable and did not suggest any patterns of armoring impacts. Elevation profiles from each site indicate that slope and profile shape may be a predictor of habitat loss or gain. Overall, the analysis showed that while total area of habitat change at small scale locations is variable, the ideal depth range of eelgrass habitat will shift closer to armored surfaces and their potential influences.

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Introduction

The most recent Intergovernmental Panel on Climate Change (IPCC) report projections show that there will likely be a between 0.43 m and 0.84 m rise in global mean sea level (GMSL) by the year 2100 (Oppenheimer et al., 2019). Some projections are over 1m rise in GMSL (Oppenheimer et al., 2019). Many studies in the Puget Sound have attempted to model or quantify affects from sea level rise (SLR) on nearshore and intertidal habitats and have projected massive losses of some habitat types (Glick et al., 2007). In contrast to these losses of habitat, potential eelgrass habitat has been modeled to expand with sea level rise in some cases (Kairis & Rybczyk, 2009; Smith & Liedtke, 2022).

The eelgrass *Zostera marina* is a subtidal seagrass species that provides essential habitat in the Puget Sound for many species including salmonids. Specifically, juvenile salmon as well as feeder fish use this habitat to forage for invertebrates during vulnerable transitional stages (Kennedy et al., 2018). Eelgrass is also considered by the Washington State Department of Natural Resources to be a vital sign of the health of Puget Sound waters because of its sensitivity to environmental pressures like temperature, light availability and physical disturbance (Christiaen et al., 2022). Despite its sensitivity, healthy eelgrass can also provide significant ecosystem services such as carbon storage, reduction of sediment resuspension, and mitigation of ocean acidification (Christiaen et al., 2022).

Due to its significance in the ecosystem, *Z. marina* is well studied from a variety of angles. However, many studies of SLR focus on intertidal species rather than subtidal nearshore species as they are less at risk from inundation. The models that are widely used to predict these changes rely on the assumption of conversion of nearshore habitat on a basis of elevation. In some cases, though, these models generalize or omit erosion, accretion data and the effects of shoreline armoring on these processes (Kairis & Rybczyk, 2009; Smith & Liedtke, 2022).

Shoreline armoring of various types exist on about 30% of Puget sound shorelines (Morley et al., 2012). These structures can form a barrier between sediment sources to shorelines and reflect wave energy, which can lead to increasing beach sediment size and lowering beach elevation (Smith & Liedtke, 2022; Thom & Williams, 2001). Studies of SLR that discuss shoreline armoring recognize these structures as a physical barrier to landward migration of species. While armoring does present a barrier, it also is recognized to alter shoreline substrate, elevation, and slope. Nonetheless, the existing studies of eelgrass habitat response to SLR do not appear to address shoreline armoring or its affects to habitat quality (Kairis & Rybczyk, 2009).

Shoreline armoring is widespread in the Puget Sound and efforts are taking place to remove barriers and restore natural shorelines. However, with the increasing threat of rising water, landowners may decide to place more barriers to protect their assets (Smith & Liedtke, 2022). Understanding the extent of the environmental risk from shoreline armoring is important for conservationists and decision makers considering removal or construction of barriers as well as locations for eelgrass preservation and restoration efforts.

The purpose of this study was to find to what extent shoreward migration of eelgrass in response to sea level rise will be affected by shoreline armoring in the Puget Sound. The study used GIS spatial analysis and the open source Sea Level Affecting Marshes Model (SLAMM) to examine armored shorelines near eelgrass habitat (Clough et al., 2016). The extent of eelgrass habitat in Puget Sound that may be affected by shoreline armoring was quantified, and several site pairs were selected for more focused analysis. Site pairs of armored and unarmored beaches 1-5 km in length were chosen with the methods of Dethier et al. (2016) by attempting to match geomorphic and bathymetric characteristics, location in the same drift cell and close proximity of the pair member (Dethier et al., 2016). At each site elevation profiles measure were created to measure beach slope, width, and armor elevation before raster analysis was used to estimate habitat change under three SLR scenarios. These spatial measurements and elevation analyses provide a preliminary exploration of the spatial relationship between shoreline armoring and *Zostera marina* communities and may serve as a basis for more robust studies.

Literature Review

The topics of sea level rise, shoreline armoring, and the seagrass *Zostera marina* are each well studied with a wealth of literature spanning decades. An overview of the current knowledge about them is necessary to support any research into their interactions. This literature review will provide a basic background of each subject before detailing the intersecting literature and its implications. First the review will introduce *Zostera marina* and its significance in the Puget Sound region. Next the problem of sea level rise, its effects, and current predictions will be outlined. Thirdly, shoreline armoring and its effects will be described, as well as its extent in Puget Sound. The fourth section will bring the three previous topics together in a review of what is known specifically about how eelgrass may be affected by Sea Level Rise in the presence of an armored shoreline. The last section will be a brief conclusion that will describe gaps in the literature and where my study could add knowledge for the benefit of conservationists, shoreline habitat managers, and future researchers.

Ecology of Zostera marina

Zostera marina, or eelgrass, is one of the most widespread native seagrasses in the Puget Sound. It is a monecious flowering plant belonging to the Family *Zosteraceae* (Hitchcock & Cronquist, 2018). They have perennial rhizomes, flowering stems, and vegetative leaves that are around 80 cm in length, though morphology can vary greatly depending on physical and environmental conditions (Moore & Short, 2006). *Z. marina* grows in lower intertidal to subtidal nearshore habitats and in Puget Sound it can be found everywhere but in the southernmost inlets (Christiaen et al., 2022). Generally, *Z. marina* grows in beds that are unoccupied by other seagrass species, but in some cases the non-native *Nanozostera japonica* (commonly known as

Zostera japonica) overlaps its habitat in and mixed stands or a mosaic of bed patches (Hannam, 2013; Hitchcock & Cronquist, 2018).

Eelgrass can be found on fine, soft substrates like sand and muddy sediments of beaches and tidal flats. The primary limiting factors of its distribution are substrate, light availability, and desiccation (Hannam et al., 2015; Moore & Short, 2006). At the lower end of its depth range it is limited by light penetration and at the upper end by exposure and desiccation during low tides (Christiaen et al., 2022; Hannam, 2013; Hannam et al., 2015).

Eelgrass habitat depth distribution can vary between locations and shoreline types. On flat shorelines eelgrass depth range can be shallower than at steeper fringing beds, but eelgrass at fringe beds can also grow at deeper depths (Hannam et al., 2015). Washington State Department of Natural Resources Submerged Vegetation Monitoring Program (SVMP) has found that in Puget Sound, *Z. marina* occurs between +1.4 m and -12.0 m MLLW with an preferred depth range of 0 to -2 m MLLW (Hannam et al., 2015). They calculate that over 60% of eelgrass is subtidal, or 1 meter below MLLW (Hannam et al., 2015).

Z. marina has several ecosystem services that it provides to the Puget Sound region. It is an essential habitat for fish and provides both cover and foraging opportunities. Several species of salmon and beach spawning forage fish use eelgrass extensively in their juvenile stages as they transition from freshwater to marine habitats (Dumbauld et al., 2015). Due to its importance to juveniles of many species, eelgrass habitat is sometimes referred to as a nursery habitat (Moore & Short, 2006). Eelgrass beds increase beach complexity by providing habitat and substrate for benthic invertebrates and epiphytes, which in turn provide food for fish and waterfowl (Duffy et al., 2005; Moore & Short, 2006).

Eelgrass is highly productive, and its biomass contributes to carbon storage through deposition in marine sediment. They also provide beach stabilization with their root systems and increased water clarity by decreasing resuspension of sediment (Christiaen et al., 2022; Moore & Short, 2006). Eelgrass has even been recognized to benefit water quality by limiting harmful algae and bacteria as well as provide some mitigation for ocean acidification (Christiaen et al., 2022; Pacella et al., 2018). In contrast to these abilities to mitigate climate change, eelgrass can be very sensitive to certain environmental influences like increasing water temperature and elevated nutrient input. Eutrophic conditions can affect the seagrass by decreasing light availability through phytoplankton blooms and algal overgrowth (Christiaen et al., 2022; Moore & Short, 2006). Because of its widespread distribution and significance in Puget Sound, *Zostera marina* is used as an indicator of ecosystem health. It is monitored closely by the state of Washington and is the subject many studies and restoration efforts. (Cereghino et al., 2012; Christiaen et al., 2022).

Sea Level Rise

Causes and effects of sea level rise

Sea level rise is a climate change phenomenon that is a cause of concern for coastal regions around the world. The Global Mean Sea Level (GMSL) is increasing and has accelerated from 1.4 mm per year during 1901-1990 to 3.6 mm per year between 2006-2015 (Oppenheimer et al., 2019). Rising temperatures from anthropogenic climate change have shifted the balance of multiple interconnected hydrologic processes that control the flow and storage of water around the globe. The warming atmosphere causes both thermal expansion of the ocean water as well as the loss of water stored in the form of ice. Thermal expansion occurs as rising temperature decreases the density of the water, resulting in a greater volume without any increase in mass

(National Research Council et al., 2012; Oppenheimer et al., 2019). Yet, ocean mass is also increasing due to the addition of stored water. Most of the fresh water on the earth is stored in the Antarctic and Greenland ice sheets. These ice sheets can increase sea level through sub surface melting, loss of ice at marine edges, and loss of surface mass from ablation (National Research Council et al., 2012; Oppenheimer et al., 2019). Like the ice sheets, glaciers also contribute to sea level through melting of their stored water and have, to date, added more mass to the ocean than both the Antarctic and Greenland ice sheets (Oppenheimer et al., 2019). However, the total mass of glacial water storage is only a fraction of the ice sheets capacity to add to sea level rise (National Research Council et al., 2012; Oppenheimer et al., 2019).

Climate induced SLR will expose coastal and nearshore habitats to a variety of effects including inundation, salinization, erosion, and more frequent extreme sea level events (Glick et al., 2007; Miller et al., 2019; Oppenheimer et al., 2019). As water levels rise, habitats can transition to new types, are forced to migrate landward, or are converted to open water. Inland habitat that is not inundated may also be influenced as groundwater can become salinated and the water table can rise. Subtidal habitat may be affected by reduced light availability and erosion. In some cases sedimentation and accretion may accumulate quickly enough for nearshore habitats to match rising water levels, but as rates of SLR are increasing, this process may be outpaced (Fagherazzi et al., 2020; Moritsch et al., 2022; Poppe & Rybczyk, 2022). There is still a great deal of uncertainty in how nearshore vegetation will respond to lateral and horizontal migration (Fagherazzi et al., 2020). Migration of coastal habitats is a natural process in response to changes in water level and shoreline conditions, but the rapid pace of SLR and anthropogenic modifications of the coastlines may restrict this ability (Glick et al., 2007; Oppenheimer et al., 2019; Thom & Williams, 2001).

The most recent IPCC report projections show that there will likely be between a 0.43 m (low emission scenario RCP2.6) and 0.84 m (high emission scenario RCP8.5) rise in Global Mean Sea Level by the year 2100 (Oppenheimer et al., 2019). However, Sea level will not occur proportionately around the globe due to geodynamic processes. The shifting distribution of water to the ocean from storage in ice and on land, will influence the gravity, shape, and rotation of the earth. These variations will cause disproportionate sea level changes at the regional scale (Oppenheimer et al., 2019). Geologic processes like uplift and subsidence can also affect sea level relative to the land at the regional level. Human activity can also influence regional sea level by causing Anthropogenic subsidence through extraction of groundwater and hydrocarbon (Candela & Koster, 2022; Miller et al., 2019; Oppenheimer et al., 2019). While GMSL is a good measure for explaining sea level rise in general, localized studies are necessary for predicting effects of SLR at the regional and local levels (Miller et al., 2019). The IPCC estimates that regional variation can be ±30% around the global mean, with greater than 30% departure possible in regions with rapid vertical movement of the land (Oppenheimer et al., 2019). Regional calculations of sea level rise have both Absolute Sea Level (ASL) and Relative Sea Level (RSL) to consider. ASL is the average height of the ocean as compared to a fixed baseline like the center of the earth, while RSL is the average height of the ocean compared to a fixed point on the land (Miller et al., 2019). Washington State may have local variations in absolute sea level rise of around 10cm by 2100, but there is greater potential for variation due to vertical uplift and subsidence (Miller et al., 2019). Regional rates of vertical land movement for the entire state have been estimated at about +0.10 cm per year, but more localized studies have shown that there are areas in the Central Puget Sound that may experience subsidence by the end of the century (Miller et al., 2019; National Research Council et al., 2012). The Washington

Coast Resilience Project collected and modeled data from 171 locations around the state, allowing them to show these more local projections (Miller et al., 2019). For example, they project RSL at an inner Puget Sound location (Tacoma) at between +2.1 ft (low emission scenario RCP4.5 central estimate) and +2.5 ft (high emission scenario RCP8.5 central estimate), and a Coastal location (Neah bay) at between +0.5 ft (RCP4.5 central estimate) and 1.0 ft (RCP8.5 central estimate) (Miller et al., 2019).

Shoreline Armoring

What is shoreline armoring?

As coastlines are developed, modifications are made to the shoreline for several purposes including controlling wave energy and stabilizing the shore. Armoring is a method of shoreline stabilization used to protect land from natural physical processes like erosion, inundation, and storm surge. Typically armoring is placed to protect structures and development in upland areas that may be affected by erosion or flooding.

There are many different forms of armoring that are used depending on the location and the level of protection intended. Some forms of armoring like sea walls create barriers against the water with concrete that are impermeable and very reflective of wave energy (Shipman et al., 2010; Thom & Williams, 2001). Similarly, bulkheads are wall like structures made of concrete or wood that both hold back erosion from the land and protect from waves. Another common form of armoring is called revetment. This style is made of thick layers of permeable stones that are commonly deposited from the upper shore at the high water line all the way down to the low water line (Thom & Williams, 2001). Revetments are generally more simple to construct and can follow the natural contour of the shoreline. Riprap is the most common type of revetment and is composed of random stone rubble, but there are other types formed from interlocking concrete or metal cages filled with stone. (Shipman et al., 2010; Thom & Williams, 2001).

Extent of Armoring in Puget Sound

Puget Sound is one of the largest estuaries in the country and is extensively armored along its shorelines. Around a third of the approximate 4000 km of estuarine coast has some form of armoring due to the urbanization and industrialization of the region (Shipman et al., 2010). A review in 2001 reported that 1.7 miles of shoreline are armored per year in the Puget Sound (Thom & Williams, 2001). The expanding urbanization of Puget Sound in combination with rising sea levels has caused concern that armoring will continue despite the potential ecological harm that it may cause (Dethier et al., 2016, 2017; Smith & Liedtke, 2022). Restoration and removal of armored shore is becoming more widespread but there is also evidence that new armoring is often being placed without permitting or proper adherence to regulatory standards (Dethier et al., 2017; Kinney et al., 2015).

Physical effects of Armoring

The intended purpose of armoring is to interrupt the natural progression of physical processes like erosion, but there are consequences of this interruption. Impoundment blocks the supply of sediment to the fronting shore and possibly to other shorelines connected by currents and drift cells (Simenstad et al., 2011; Thom & Williams, 2001). Armoring can lead to erosion of the beach surface if its sediment supply is blocked, and longshore transport continues to move material from the shore (Shipman et al., 2010). The hard surfaces of armoring structures reflect wave energy away from the shore or back onto the beach surface. Reflected wave energy can resuspend sediments and allow currents to draw them away from the beach in a process called scour, resulting in a coarser substrate and lowered beach elevation. As the wave energy is redirected, it may also cause scouring effects on adjacent shores (Shipman et al., 2010). Scour and impoundment at armored locations results in vertical but not horizontal erosion, which can lead to narrowing of the beach and steepening of its slope (Shipman et al., 2010)

The severity and speed of sediment supply changes may vary greatly by location and extent of armoring. A study by Dethier et al. in 2016 found that differences in sediment size between armored and unarmored beaches were difficult to distinguish at the local scale, but were significant at the regional scale (Dethier et al., 2016). They were able to conclude that drift cells that were extensively armored had larger sediment grain size. This may confirm the theory of Thom and Williams that there are thresholds of drift cell armoring extent beyond which sediment supply loss becomes significant (Thom & Williams, 2001). Both Thom and Williams and Dethier et al. suggest that there are likely cumulative effects of extensive armoring at the larger regional and temporal scales (Dethier et al., 2016; Thom & Williams, 2001).

Z. marina *habitat change and response to sea level rise.*

Projected future habitat area.

Unlike many habitats on Puget Sound shorelines, eelgrass habitat has been projected to expand as sea level rise occurs. This is to be expected if we consider that loss of terrestrial habitat from inundation results in a corresponding expansion of marine habitat. Some of the most concerning effects of SLR (including inundation, salinization, and storm surge) are not a significant issue for *Z. marina* due to its subtidal habitat range. As a result of its depth range, eelgrass habitat change is not often the focus of modeling. For example, the National Wildlife Federation used the SLAMM model to estimate habitat changes over 10 large areas of the Pacific Northwest, but the only habitat type in the model that covers eelgrass is “estuarine open water”. The study showed an overall expansion of estuarine open water in all scenarios, but this is an imprecise measure when considering that only a fraction of the open water depth profile fits eelgrass's narrow elevation range of 1 to -14 m MLLW (Glick et al., 2007).

Smith and Liedke also used the SLAMM model in their study and overlaid eelgrass habitat data to make up for the lack of corresponding habitat type in the model. At their site they projected potential eelgrass habitat gains of over 10% for a 0.4 m SLR scenario and over 22% for a 1 m scenario by the year 2100 (Smith & Liedtke, 2022). They noted that this habitat expansion was contrary to their initial hypothesis, but also acknowledged the many unaccounted variables of erosion, accretion, and changes in wave energy (Smith & Liedtke, 2022).

In 2009, Kairis & Rybczyk used a relative elevation model to project eelgrass productivity and coverage in Padilla Bay. Their results also predicted overall increases in habitat by 2100 in all but the highest of eight SLR scenarios (Kairis & Rybczyk, 2009). They do note that the large buffer of flats surrounding existing eelgrass habitat is a major factor in its ability to expand unchecked in their model (Kairis & Rybczyk, 2009). This may suggest that bays and locations with gently sloping beaches will have more resilient eelgrass habitat. Another consideration that the authors note is that the ability of eelgrass to migrate laterally is slower than the predicted rate of expansion (Kairis & Rybczyk, 2009). However, eelgrass can spread over large distances through seed dispersal and spread of reproductive shoots, so is possible that lateral spreading rate may not present an issue (Kairis & Rybczyk, 2009; Moore & Short, 2006).

Each of these projections of sea level rise account for a variety of variables to predict water depth and even changes in shore elevations, but some of these variables can be influenced by shoreline armoring in ways that might affect predictions of eelgrass habitat change. Some of these variables include accretion, substrate, and slope. Accretion is the process of material deposition that builds and expands shorelines and as a result changes depth profiles and habitat distribution. Substrate refers to the material composition and size of the shore's surface, which can determine its suitability as habitat. Slope simply describes the angle of the beach surface, which can affect exposure to wave energy and determines the width of the available habitat along the shoreline. Changes in each of these variables are difficult to accurately predict, but they are known to be vulnerable to shoreline armoring as well as important for eelgrass habitat suitability.

Accretion

The geomorphic processes that form beaches in the Puget Sound play an important role in determining how eelgrass habitat is distributed along shorelines. Finlayson (2006) characterized the majority of Puget Sound beaches as low energy with a composite profile consisting of a steep foreshore and a low-tide terrace. They are typically mixed sediment beaches with a distinct transition of sediment coarseness between the foreshore and the terrace (Finlayson, 2006). However, variations in the profiles and sediment characteristics between locations are variable with some uncertainty in which oceanographic and geomorphic factors are most important in their formation (Finlayson, 2006).

The Puget Sound has a unique tidal climate with a diurnal pattern and wide tidal range. This pattern focuses tidal and wave energy on the upper foreshore. The concentration of energy results in the majority of sediment transport and elevation changes occurring in the upper shore with very little on the terrace and the subtidal zone (Finlayson, 2006)

Fringing eelgrass beds may be more susceptible to SLR because they may lack the direct sediment input that delta beds receive to vertically shift their habitat (Dethier et al., 2017; Finlayson, 2006). These areas rely on erosion and longshore transport of material to create suitable fine substrate for eelgrass habitat. As many of the shorelines in Puget Sound have some sort of armoring, erosion and the natural geomorphic process of beach creation will be impeded.

It is possible that near deltas of freshwater input some effects of SLR could be counteracted or slowed to a degree by sediment deposition (Fagherazzi et al., 2020; Poppe & Rybczyk, 2022). If the sediment supply remains high enough, the beach surface might increase in height along with the increasing depth. In 2009 a study of Padilla Bay in Puget Sound by Kairis and Rybczyk found that accretion rates in that location would not keep pace with SLR (Kairis & Rybczyk, 2009). Also, a more recent study that modeled sediment deposition on eelgrass beds in Padilla bay suggested that there would likely be negative affects to eelgrass if sediment concentrations were increased to the level required to match SLR (Poppe & Rybczyk, 2022). They found that almost four times the current suspended sediment concentration would be needed to keep pace with SLR. That level of suspended sediment could reduce light penetration and inhibit eelgrass growth potential (Poppe & Rybczyk, 2022). However, eelgrass was modeled to significantly expand its habitat shoreward in Padilla bay despite the lack of accretion (Kairis & Rybczyk, 2009).

Substrate

Accretion rates and sediment concentrations not only affect beach elevation, but the composition of the beach surface material. This material, or substrate, is very important when determining habitat suitability for seagrasses. Due to shoreline armoring and the accelerated speed of climate induced sea level rise, the substrate at the ideal tidal depth for eelgrass may not remain suitable as the range shifts landward. Shoreline armoring can reduce the deposition of fine materials on beaches by blocking material input from the land which may result in more coarse and rocky substrates (Dethier et al., 2017; Finlayson, 2006; Shipman et al., 2010). The severity of armoring impacts like coarsening of beach sediments is thought to be dependent on the location of the structure along the beach profile (Shipman et al., 2010). Rising sea level will bring the preferred habitat depth range closer to barriers and increase the risk of coarsening substrate. However, substrate grain size is variable between locations and is dependent on a variety of factors that influence accretion that are difficult to predict.

In a study on Bainbridge Island, Smith and Liedtke found that upper beach mean sediment size was smaller on an armored site as compared to an adjacent unarmored site, though the low wide terrace was very similar between the two (Smith & Liedtke, 2022). They concluded that the difference in mean grain size did likely indicate effects from shoreline armoring like scour and wave reflection. In that study they modeled increases of eelgrass habitat in all three SLR scenarios that they used, but they recognized that physical processes like accretion and scour were unaccounted for in the model, and that the unarmored site demonstrated greater plasticity (Smith & Liedtke, 2022).

Slope

Changes in variables like accretion and substrate can often be very difficult to measure or predict depending on the study scale or timeline, but slope can be related to both and can be easier to use as a predictor of accretion, erosion, and substrate. On armored shorelines there is also the possibility of erosion resulting from increasing storm surge and wave energy caused by SLR, as well as armoring induced wave scour and increased wave energy (Finlayson, 2006; Shipman et al., 2010). As is the intention of armoring, this erosion does not widen the beach landwards, but occurs on the beach surface. This process results in a steeper beach slope. Increasing depth can also result in greater wave energy and sediment resuspension that could decrease light penetration and reduce photosynthetic potential (Kairis & Rybczyk, 2009; Moore & Short, 2006).

The studies that model eelgrass habitat expansion tend to do so at very flat sites like Padilla Bay because they contain a large percentage of the eelgrass beds in the Puget sound. Sound wide surveys have found that around 50% of eelgrass is found at locations with “Flats” type profiles like Padilla bay in the Northern Puget sound, and the rest is located on narrower “Fringe” sites (Christiaen et al., 2019). At Padilla bay and similar delta sites there is very little change in slope between current and projected habitat (Kairis & Rybczyk, 2009; Poppe & Rybczyk, 2022). However, at fringing sites where eelgrass beds are smaller, there has been less modeling. At these locations there may be a more drastic transition from the low wide terrace to the steeper slope of the foreshore.

Steeper slopes may not necessarily be a limiting factor for eelgrass habitat, but they are associated with more coarse substrate and higher wave energy (Finlayson, 2006; Moore & Short, 2006). A greater slope will also decrease the overall surface area of available habitat in *Z. marina’s* preferred depth range, though this effect may be negligible depending on the degree of slope change and the scale of study.

Conclusion

Eelgrass is an essential species for Puget Sound habitats and an important indicator of ecosystem health. Current literature and modeling suggest that SLR may increase available habitat area, yet complex variables like accretion, erosion, and sediment supply add uncertainty to these predictions. Shoreline Armoring exacerbates this uncertainty by its influence on these geomorphic variables. Few studies attempt to address the effects of shoreline armoring on eelgrass habitat. My study will attempt to better understand future eelgrass habitat availability by linking the science of SLR modeling to the developing research of armored shores.

Methods

The goal of this project was to estimate the amount of *Z. marina* habitat that may be influenced by shoreline armoring, model potential future habitat availability, and compare SLR models at armored and unarmored habitat locations. The following methods section covers the project data sources, study region, and analysis techniques. The methods described show the steps that were taken to obtain eelgrass and armoring coverage statistics, select study sites, collect site characteristics, and estimate habitat change with SLR inundation models.

Data sources

The primary spatial data sources for this research project were obtained from several sources including the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP), the WSDNR Submerged Vegetation Monitoring Program (SVMP), ShoreZone, and the United States Geological Survey (USGS).

Data from the PSNERP was downloaded in a geodatabase (GDB) file structure which contained all of the vector data layers and tables used in the PSNERP comprehensive change analysis published in 2011. (Simenstad et al.). The data type and quality that the PSNERP used to create this geodatabase ranges widely, but only two layers were used in this study. Drift cell line features were used in the selection of study sites. Armoring line features from this dataset were adapted from the ShoreZone study as well as other sources with a date range between 1994 and 2008 (Anchor QEA, 2009).

SVMP data was also obtained in a GDB that contains all of the programs survey data from the years 2000 to 2020 (Christiaen et al., 2022). These layers include study site polygons, generalized eelgrass polygons, and survey transects. These layers were used for the estimation of eelgrass presence and site selection.

ShoreZone inventory data was also used to fill in gaps of unsurveyed shoreline from the other sources when necessary. As the survey was completed between 1994-2000, the Shorezone data is relatively old and may not be reliable for many uses due to the collection methods. This data was collected via aerial videography and manually interpreted to create a comprehensive survey of shoreline characteristics. The high potential for human error in this method makes it necessary to treat it with a degree of uncertainty (Berry et al., 2001). Despite these uncertainties, it is in some cases the most comprehensive and complete survey of Puget Sound shoreline characteristics that is available at this time. The SVMP has not yet collected data on all the Puget Sound shoreline and so this dataset became useful in the estimation of eelgrass coverage and in study site selection.

Elevation data was obtained from the US Geological Survey and NOAA. The USGS has created an integrated topobathymetric digital elevation model (TBDEM) with 1 meter resolution for their Coastal National Elevation Database (CoNED). This elevation model combines data from 186 sources into a single model that prioritized the most recent and accurate data available (OCM Partners, 2023).

All data was downloaded to ArcGIS Pro v. 3.0 for exploration, analysis, and data management. All layers used or were transformed to the projected coordinate system UTM 1983 Zone 10 with a vertical coordinate system of NAVD88. Horizontal and vertical units were set to meters.

Study area

The study area was adapted from the study area of the Submerged Vegetation Monitoring Program (Christiaen et al., 2022). The study area of the entire Puget Sound region extends from the United States-Canada border in the North, to the full southern extent of the Puget Sound. It also encompasses the San Juan Islands and the US shoreline along the strait of Juan De Fuca to the end of Cape Flattery.

The Puget Sound region was divided into subregions for the selection of small scale site pairs. The South Puget Sound (SPS) includes the basin and all the inlets south of the Tacoma Narrows (Figure 1). The Central Puget Sound (CPS) extends from the Tacoma Narrows to the opening of Admiralty Inlet into the Strait of Juan de Fuca. North Puget Sound (NPS) includes Whidbey Basin, the US coastline of the Salish sea North of Admiralty Inlet. The regions including the San Juan Islands and the stretch of the Strait of Juan de Fuca from the Pacific Ocean to Admiral were excluded from use in the small scale site analysis due to their difference in shoreline characteristics, presence of eelgrass and armoring, as well as the limitations of time.

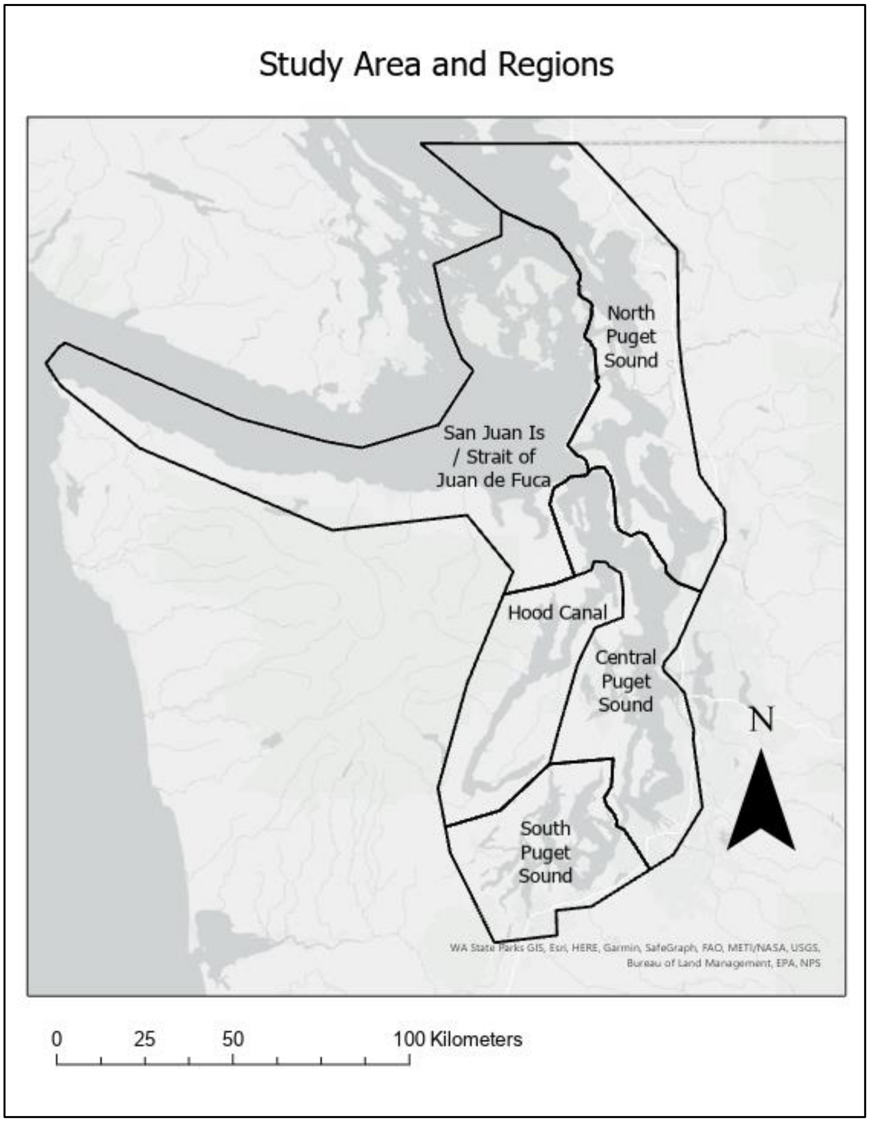


Figure 1: Puget Sound study area. Summary statistics include all areas within all regions.

Summary Statistics and Elevation Profiles

Summary statistics of the extent of eelgrass and armoring in the PS region were collected using vector data from the SVMP and the PSNERP. Line features were used to calculate length of shoreline segments that were reported to have eelgrass presence. The line features were manually edited with the trimming tool to only extend to the boundary of the study area polygons. The SVMP dataset provided shoreline segments with vegetation codes corresponding to *Zostera marina* habitat, but some locations have not been surveyed and have a nodata value that cannot be assumed to have no *Z. marina* presence. To supplement this data set on shore segments with no data, the PSNERP eelgrass data which is derived from the Shorezone Project was used to estimate eelgrass extent.

Armoring presence was obtained from PSNERP as a line feature attribute. The armoring attribute is only a Yes/No option assigned to shoreline segments. The PSNERP used Shorezone data to calculate this attribute and the "Yes" value was only assigned to line segments with 50% or more armoring coverage (Anchor QEA, 2009; Simenstad et al., 2011).

Shoreline profiles were created with ArcGIS Pro using the CoNED DEM as the elevation source. Line features of 4 transects per site pair were drawn from 6 m to -2 m MLLW at sites 1 and 3 and from 6 m to 0.5 m MLLW at site 2. Contours line features were generated at each required elevation to ensure accurate snapping of transect endpoints. The lines were manually drawn at an approximate 150 to 200 m interval and an approximate right angle from the shoreline. The line vertices were densified to 0.5 m intervals and elevation values were interpolated from the MLLW corrected DEM. Profile charts were then created from each set of line features. Additional statistics like slope and distances were measured along the transect lines and elevation contours with exploratory analysis tools and recorded in Excel.

Site Selection

Smaller scale sites were chosen out of these regions in order to characterize the eelgrass habitat in the Puget Sound. Due to the restriction of time and the narrow selection parameters, only 4 sites in the Central Puget Sound region were able to be used in the study. Site pairs of armored and unarmored beaches 2 km or less in length that have evidence of *Z. marina* presence were selected with the criteria used by Dethier et al. (2016) by attempting to match geomorphic and bathymetric characteristics, location in the same drift cell and close proximity of the pair member.

Sites selection used the eelgrass and armoring line features to select study site polygons from the SVMP database. In each region sites were filtered by the presence of eelgrass and armoring, then filtered by their proximity to a site with eelgrass but no armor. These remaining site pairs were selected by their occurrence in the same drift cell and drift direction, then they were manually filtered for similar direction of shore face. Site pairs that occurred in different drift cells or were in differing zones of the same drift cell, for example convergence zones or divergence zones, were discarded. Pairs that had shorelines oriented in significantly differing directions were also discarded from the selections. Site 1 is located on Maury Island at the coordinates 122.400°W 47.400°N. Site 2 is located at Magnolia Bluff, Seattle at the coordinates 122.427°W 47.654°N. Site 3 is located near Brownsville at the coordinates 122.613°W 47.667°N. Site 4 is on Ledgewood Beach, Whidbey Island at the coordinates 122.608°W 48.146°N (Figure 2).

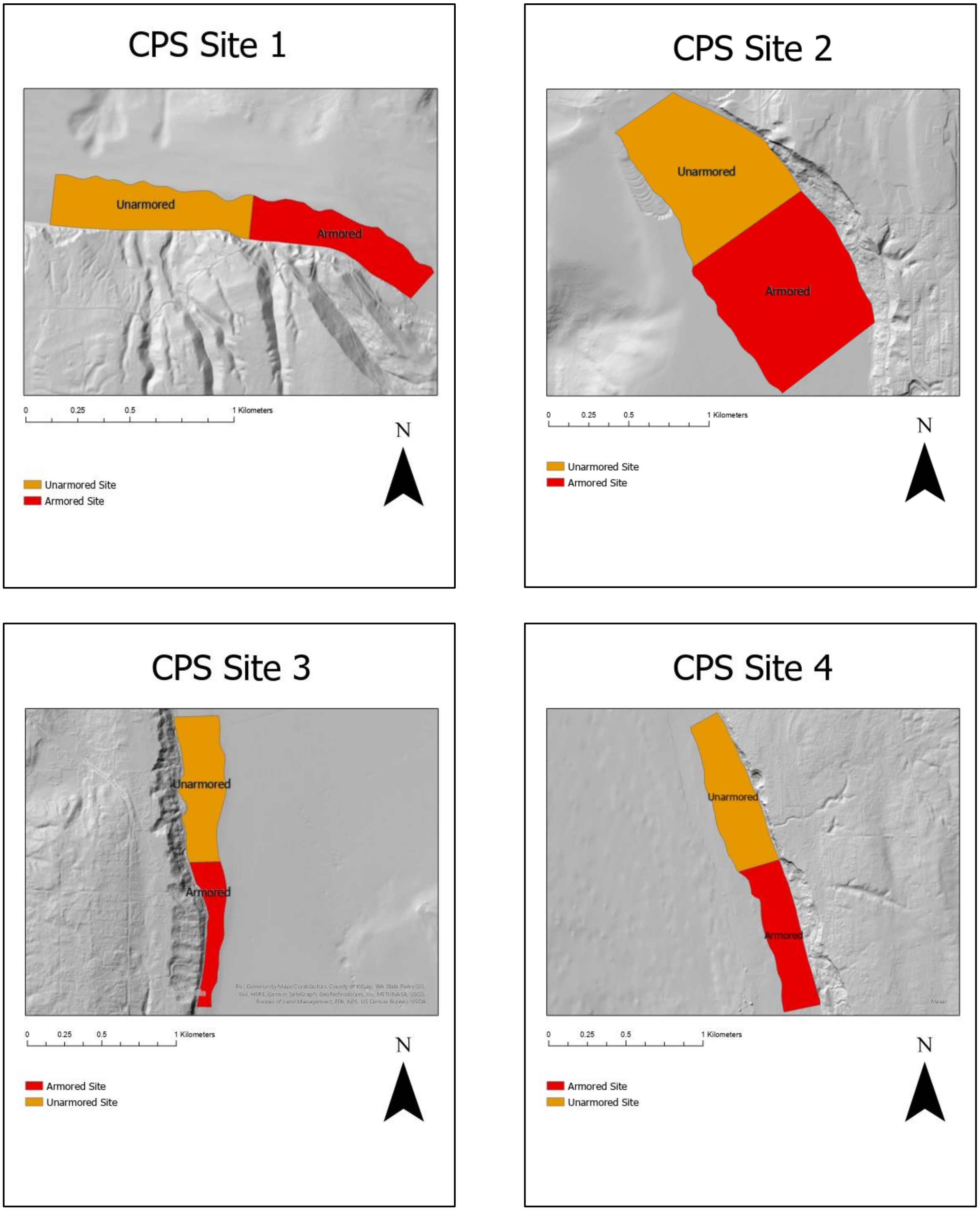


Figure 2: Central Puget Sound Site pair selections.

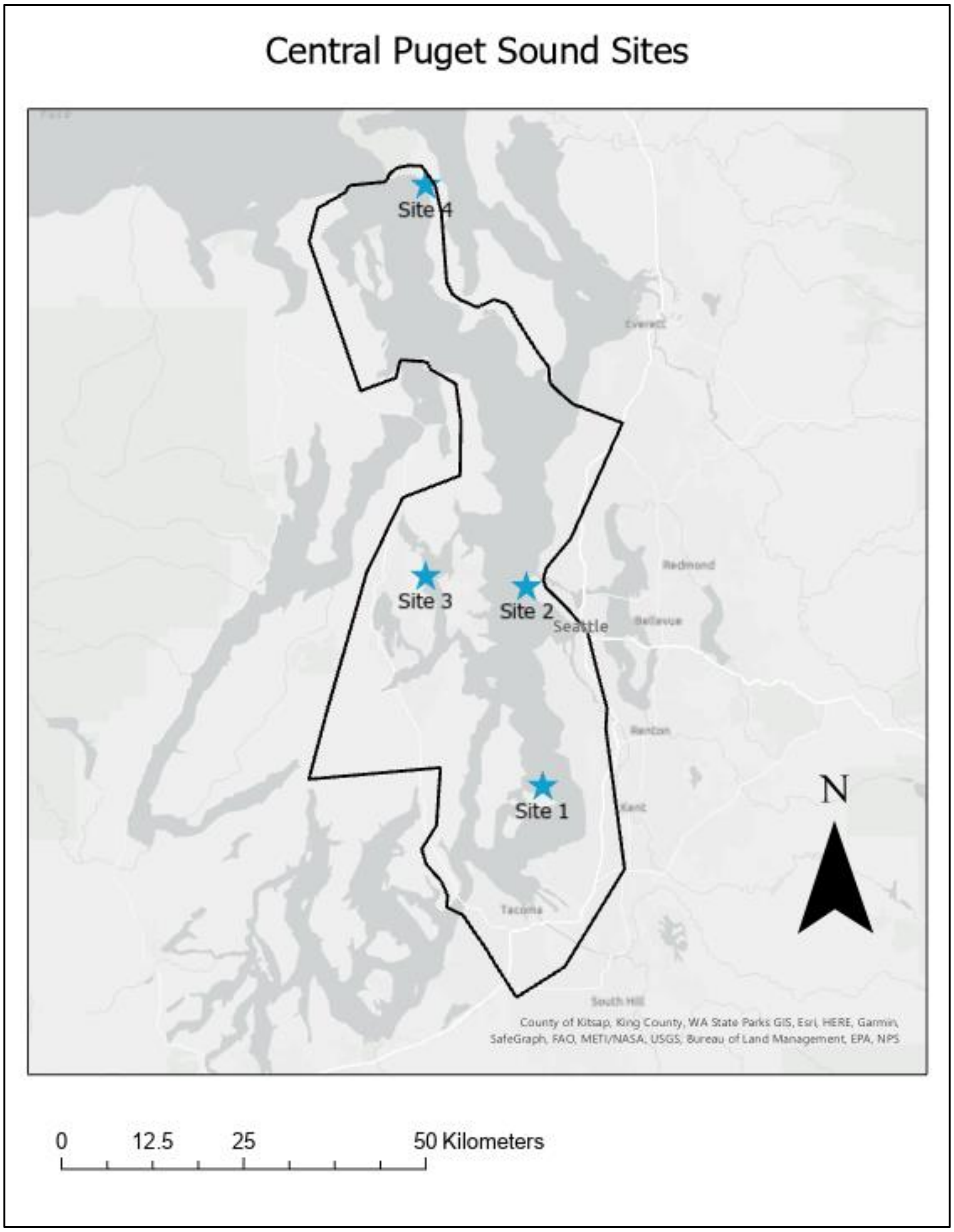


Figure 3: Central Puget sound study site pair locations as indicated by the blue stars.

ArcGIS Pro modeling

Estimating eelgrass habitat change was completed with elevation analysis using raster datasets. ArcGIS Pro was used to perform raster analysis of digital elevation models and create inundation models of preferred *Z. marina* habitat depth range. The CoNED elevation model was used as the source data for these models. Local NOAA tidal datums, IPCC projected SLR data, and habitat ranges defined by the SVMP were used to calculate potential *Z. marina* habitat coverage layers (Hannam et al., 2015; Oppenheimer et al., 2019).

The raster calculator geoprocessing tool was used to correct the DEM from NAVD88 to MLLW so that the elevation model would correspond to the *Z. marina* habitat range values. Datum correction values were obtained from the Tacoma and Seattle NOAA tidal gage stations (National Oceanic and Atmospheric Administration, 2020). The DEM raster was then processed with the raster calculator by separately adding each scenario's sea level rise value to simulate the change in MLLW by 2100. The DEM collection date was 2015 and the IPCC scenario base year was in 2005, so a correction was also applied to each scenario SLR value to account for sea level rise that had already occurred between 2005 and 2015. The correction calculation used 2.07 mm per year from the mean annual sea level rise over the past century reported by local NOAA tidal gauge data (Table 1).

The cells within the depth ranges of eelgrass habitat were selected from each corrected DEM with the raster calculator to estimate habitat coverage in each scenario. Calculations were run with the RCP 2.6, 4.5, and 8.5 scenarios as well as the base MLLW datum corrected DEM. Elevation range for *Z. marina* habitat was set at the preferred depth of between 0 m and -2 m MLLW as described by the SVMP (Hannam et al., 2015). To separately calculate area for the armored and unarmored site pairs, the Extract by Mask geoprocessing tool was used to select the raster cells within their respective site polygons. The source DEM cell size was 1 meter so area could be calculated with cell count values obtained from attribute tables. Resulting area values were input into Excel for data management and calculation of percent change.

Table 1: IPCC scenario projected SLR values and date corrected values

IPCC Scenario	SLR (m)	SLRcorr (m)
RCP 2.6	0.43	0.4093
RCP 4.5	0.55	0.5293
RCP 8.5	0.84	0.8193

SLAMM modeling

The Sea Level Affecting Marshes Model (SLAMM) was used to model SLR and habitat change with an erosion model component. The program required an elevation model, slope layer, and land cover class layer in the numeric SLAMM format. Each of these layers was required to be in the ASCII raster format with the identical location, dimension, and projected coordinate system (Clough et al., 2016). The DEM at each site pair was clipped to a standardized extent that encompassed both the armored and unarmored site and a slope layer was generated. The Raster Calculator was used to apply a vertical datum correction and define 0 elevation as the local Mean Tide Level as defined by the local NOAA tidal gauge (National Oceanic and Atmospheric Administration, 2020). The Tacoma and Seattle tidal gauges were used for sites in the CPS region (Table 2).

Table 2: Tidal datums and corrections using nearest NOAA tidal gauge.

Location	MTL	NAVD88	NAVD88corr	Sites
Tacoma	2.094	0.729	1.365	CPS 1
Seattle	2.032	0.715	1.317	CPS 2, 3 and 4

To fulfil the requirement for land cover class layers a Washington State National Wetlands Index (NWI) was obtained from the U.S. Fish & Wildlife Service (USFWS, 2023). The NWI layer was reclassed to SLAMM Classic categories and converted to raster format. The NWI dataset only included wetland polygons and required manual classification of dry land categories into the converted raster. The site DEM, slope layer and NWI categories were then converted to the ASCII file format and input into SLAMM.

The SLAMM model was run with custom sea level rise scenarios as the programs preset options use data and SLR scenarios originating from the 2001 IPCC report. To match the 2019 IPCC report, the custom SLR scenarios were set with a base year of 2005 and used the median values of global mean sea level rise (GMSL) in the 2046-2065 and 2100 projections for three Representative Concentration Pathways (RCP) (Oppenheimer et al., 2019). Custom scenarios of RCP 2.6, 4.5, and 8.5 were input as well as a preset 1 m scenario. The site parameters were set using a combination of default settings, data from NOAA, and from settings described in Glick et al. (2007) and Smith and Liedtke Outputs were saved as both tabular and GIS data formats.

Results

Summary Shoreline Statistics

Examination of shoreline surveys found that the study region contained over 3900 kilometers of shoreline with 1071 km of armored shore and 1701 km of shoreline with eelgrass. Within the entire Puget Sound study region about 27% of the shorelines are armored on 50% or more of the shoreline segment, and 43% of the total shoreline has been surveyed to have eelgrass presence. Of these shores with reported eelgrass presence, 30% have armoring on 50% or more of the shoreline segment.

Table 3: Summary statistics calculated in ArcGIS Pro from spatial survey data. Armored shore refers to shoreline segments that are armored on 50% or more of their length.

Summary Shoreline Statistics						
Total Shoreline (km)	Total Armored Shoreline (km)	Total Shoreline with Eelgrass (km)	Total Armored Shore with Eelgrass (km)	Percentage of Shore Armored	Percentage of Shore with eelgrass	Percentage Eelgrass shoreline with armor
3962.07	1071.14	1701.82	512.32	27%	43%	30%

ArcGIS Pro projections

The projections of habitat change from ArcGIS analysis are focused on the narrow depth range of preferred habitat and generally follow the expected patterns of change and habitat expansion from each SLR scenario. In 3 out of 4 sites, the SLR projections resulted in expansion of potential habitat. As expected, the RCP 2.6 scenario showed the least percent change in habitat and the RCP 8.5 showed the greatest changes at all sites and scenarios.

Table 4: Results from ArcGIS Pro SLR raster analysis modeling. All scenarios use the DEM year of 2015 as the base year and 2100 as the projected year. "Depth" refers to the elevation range used as an estimation of preferred Z. marina *habitat. "ChangeDiffArmor/non" is the difference between the percentage habitat change of the armored and non-armored site pair in the same scenario. Negative values are in bold italic.*

Central Puget Sound ArcGIS Projections of Eelgrass Habitat Change by 2100									
Region	Site	Armor	Depth	Scenario	Year	Area (sq. m)	GainLoss	PCT change	ChangeDiffArmor/non
CPS	1	Armor	0m to-2m	Base	2015	65,700			
CPS	1	Non	0m to-2m	Base	2015	65,500			
CPS	1	Armor	0m to-2m	RCP2.6	2100	80,858	15,158	0.231	0.142
CPS	1	Non	0m to-2m	RCP2.6	2100	71,338	5,838	0.089	***-0.142***
CPS	1	Armor	0m to-2m	RCP4.5	2100	85,566	19,866	0.302	0.162
CPS	1	Non	0m to-2m	RCP4.5	2100	74,685	9,185	0.140	***-0.162***
CPS	1	Armor	0m to-2m	RCP8.5	2100	109,957	44,257	0.674	0.129
CPS	1	Non	0m to-2m	RCP8.5	2100	101,159	35,659	0.544	***-0.129***
Region	Site	Armor	Depth	Scenario	Year	Area (sq. m)	GainLoss	PCT change	ChangeDiffArmor/non
CPS	2	Armor	0m to-2m	Base	2015	147,449			
CPS	2	Non	0m to-2m	Base	2015	80,308			
CPS	2	Armor	0m to-2m	RCP2.6	2100	212,558	65,109	0.442	***-0.074***
CPS	2	Non	0m to-2m	RCP2.6	2100	121,745	41,437	0.516	0.074
CPS	2	Armor	0m to-2m	RCP4.5	2100	240,722	93,273	0.633	***-0.215***
CPS	2	Non	0m to-2m	RCP4.5	2100	148,369	68,061	0.847	0.215
CPS	2	Armor	0m to-2m	RCP8.5	2100	413,362	265,913	1.803	***-0.743***
CPS	2	Non	0m to-2m	RCP8.5	2100	284,796	204,488	2.546	0.743
Region	Site	Armor	Depth	Scenario	Year	Area (sq. m)	GainLoss	PCT change	ChangeDiffArmor/non
CPS	3	Armor	0m to-2m	Base	2015	40,140			
CPS	3	Non	0m to-2m	Base	2015	81,861			
CPS	3	Armor	0m to-2m	RCP2.6	2100	47,896	7,756	0.193	***-0.028***
CPS	3	Non	0m to-2m	RCP2.6	2100	99,949	18,088	0.221	0.028
CPS	3	Armor	0m to-2m	RCP4.5	2100	51,171	11,031	0.275	***-0.043***
CPS	3	Non	0m to-2m	RCP4.5	2100	107,903	26,042	0.318	0.043
CPS	3	Armor	0m to-2m	RCP8.5	2100	55,148	15,008	0.374	***-0.072***
CPS	3	Non	0m to-2m	RCP8.5	2100	118,376	36,515	0.446	0.072
Region	Site	Armor	Depth	Scenario	Year	Area (sq. m)	GainLoss	PCT change	ChangeDiffArmor/non
CPS	4	Armor	0m to-2m	Base	2015	39,516			
CPS	4	Non	0m to-2m	Base	2015	40,853			
CPS	4	Armor	0m to-2m	RCP2.6	2100	34,571	(4,945)	***-0.125***	0.055
CPS	4	Non	0m to-2m	RCP2.6	2100	33,501	(7,352)	***-0.180***	***-0.055***
CPS	4	Armor	0m to-2m	RCP4.5	2100	32,343	(7,173)	***-0.182***	0.058
CPS	4	Non	0m to-2m	RCP4.5	2100	31,054	(9,799)	***-0.240***	***-0.058***
CPS	4	Armor	0m to-2m	RCP8.5	2100	28,657	(10,859)	***-0.275***	0.053
CPS	4	Non	0m to-2m	RCP8.5	2100	27,456	(13,397)	***-0.328***	***-0.053***

At site 1 the armored beach showed greater habitat expansion than the unarmored beach in each scenario. In each scenario the armored site showed 13-16% more change than the unarmored site (Table 4). In the RCP 8.5 scenario, differences in percent change between the armored and unarmored beaches were less than in RCP 2.6 and 4.5, indicating that the differences in change may be reduced with greater increases in water height.

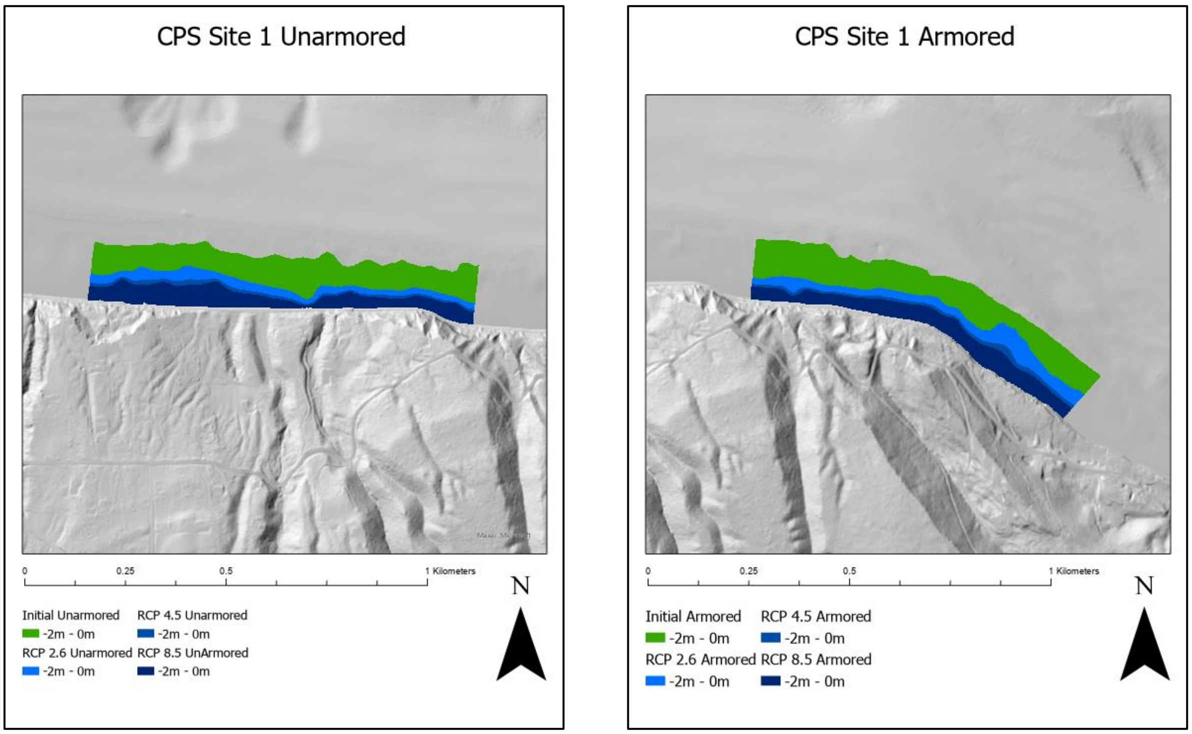


Figure 4: CPS site 1 unarmored and armored beaches projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible. Individual projections availible in Appendix A.

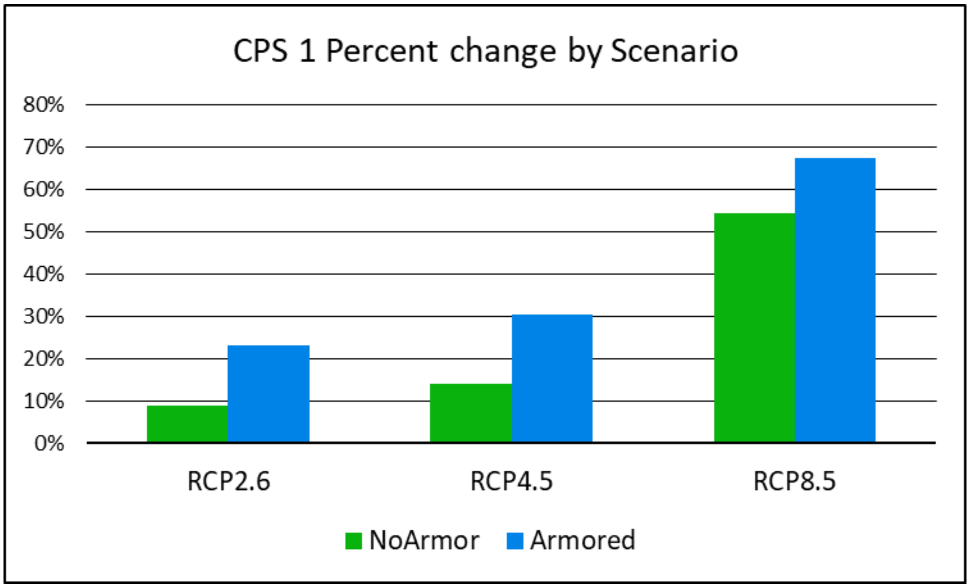


Figure 5: Percentage of habitat change between non-armored and armored beaches at CPS site 1.

Site 2 results aligned with expectations and showed greater habitat expansion at the unarmored site than the armored site in every scenario. The difference between the armored and unarmored sites percent change was relatively larger in the higher severity scenarios. In RCP 2.6 the difference between the two was only 7%, but in RCP 4.5 and 8.5 the differences were 22% and 74%. The RCP 8.5 scenario at site 2 showed the greatest habitat expansion out of all sites with 180% gain at the armored site and 255% gain at the unarmored site (Table 4).

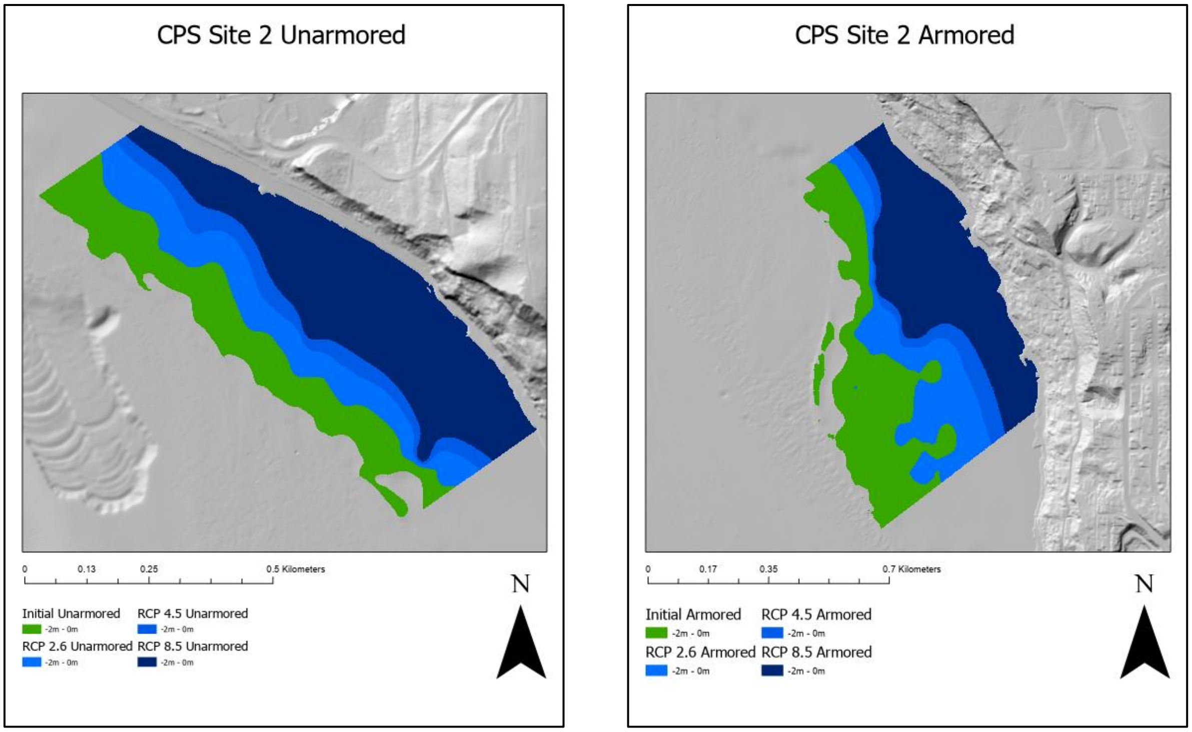


Figure 6: CPS site 2 unarmored and armored beaches projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible. Individual projections availible in Appendix A.

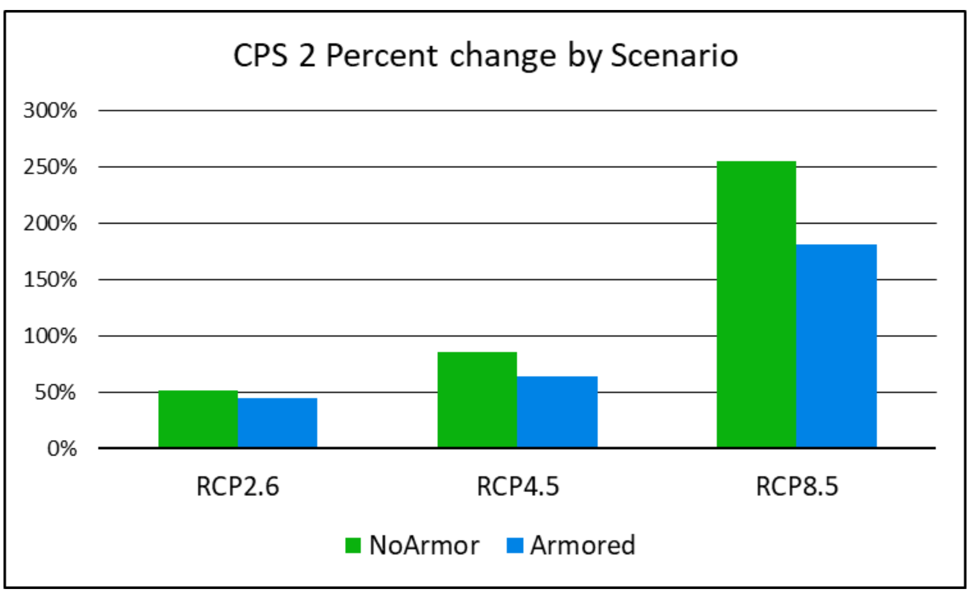


Figure 7: Percentage habitat change between non-armored and armored beaches at CPS site 2.

Site 3 also showed expected habitat expansion with more gain at the unarmored site than the armored site. The difference between percent change at armored and unarmored sites followed a similar pattern to site 2, but the difference between scenarios was less severe. RCP 2.6 showed a difference of 3% followed by 4% in RCP 4.5 and 7% in RCP 8.5 (Table 4). At site 3 there was also the lowest percent change in RCP 8.5 compared to sites 1 and 2 (Table 4).

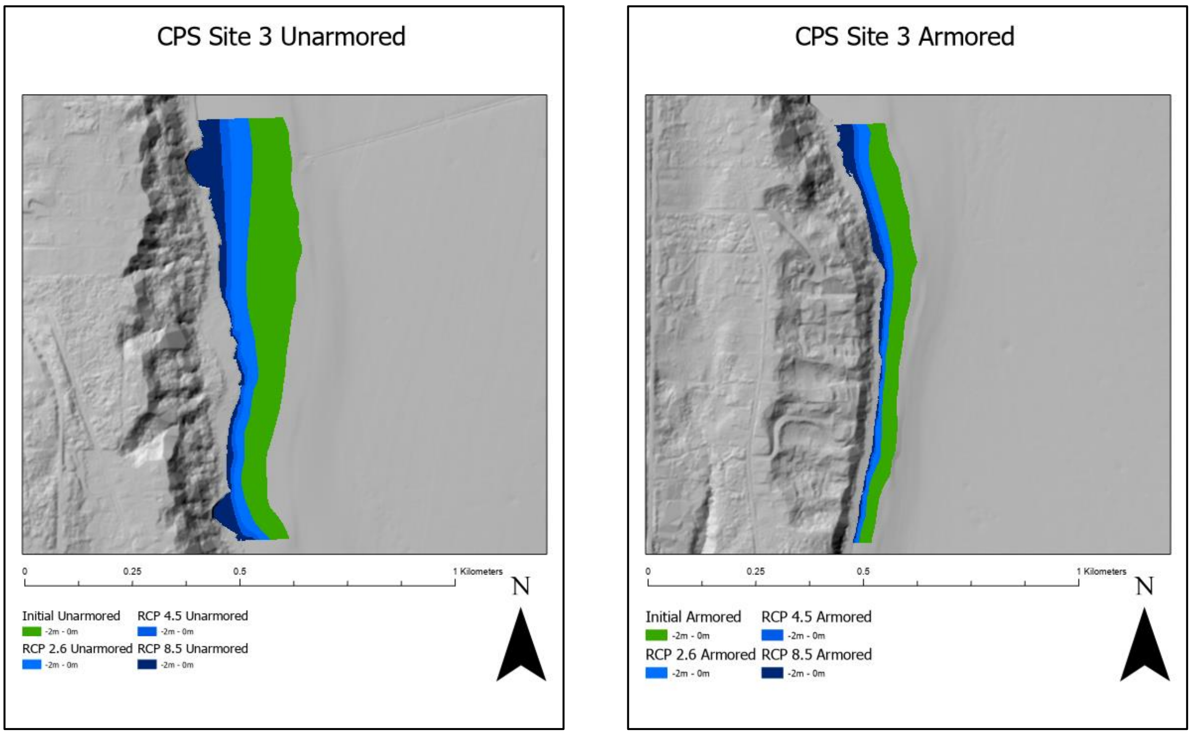


Figure 8: CPS site 3 unarmored and armored beaches projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible. Individual projections availible in Appendix A.

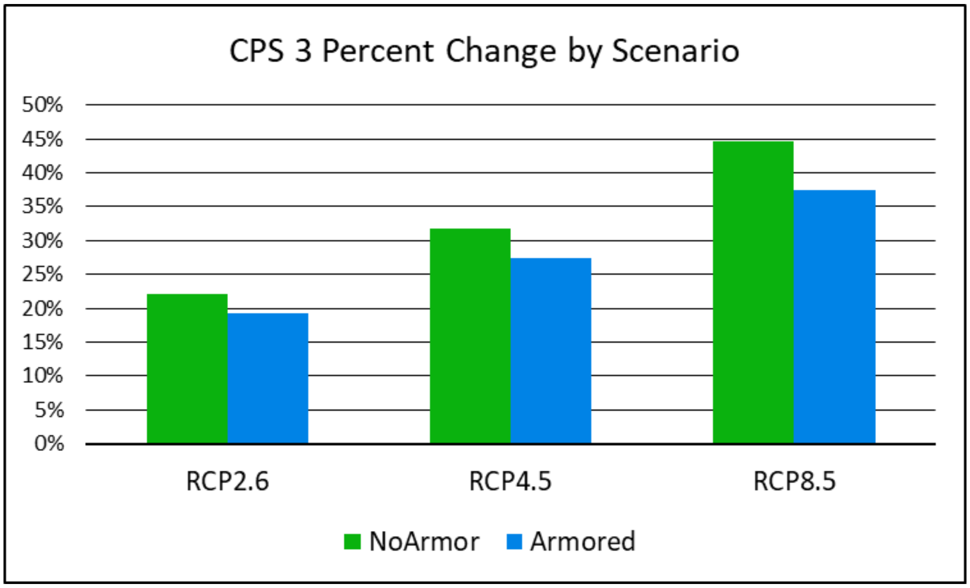
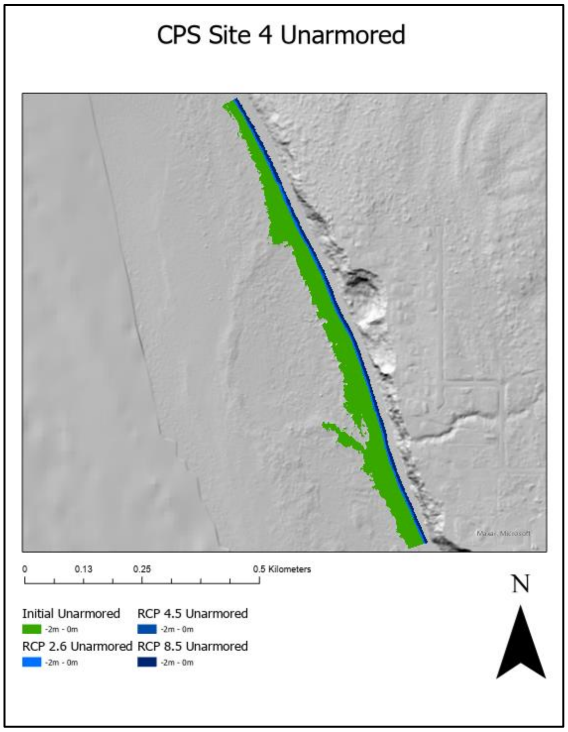


Figure 9: Percentage habitat change between non-armored and armored beaches at CPS site 3.

At site 4 the results were nearly opposite from the other 3 sites. Every scenario at this location projected losses of habitat by 2100. The RCP 2.6 scenario showed the least amount of loss with a 13% decrease in area at the armored site and 18% at the unarmored. RCP 8.5 showed the greatest losses with 28% decrease at the armored site and 33% at the unarmored site. In each scenario the non-armored site had over 5% more losses than the armored site (Table 4).



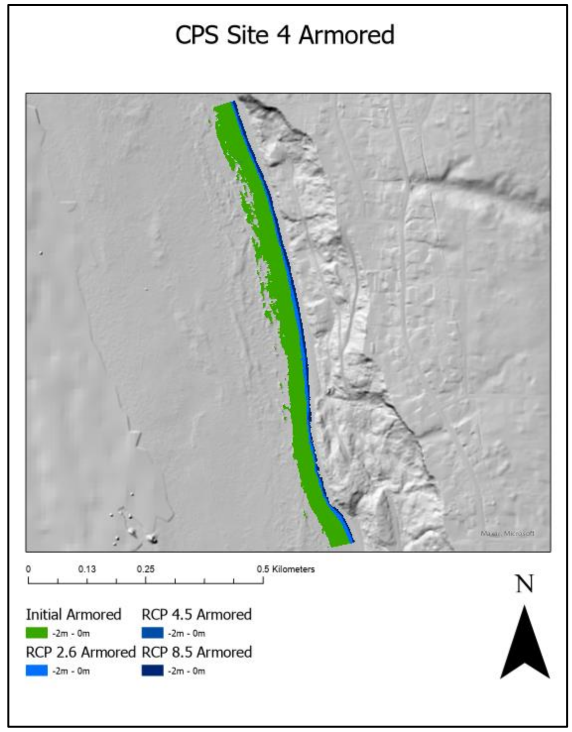


Figure 10: CPS site 4 unarmored and armored beaches projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible. Individual projections availible in Appendix A

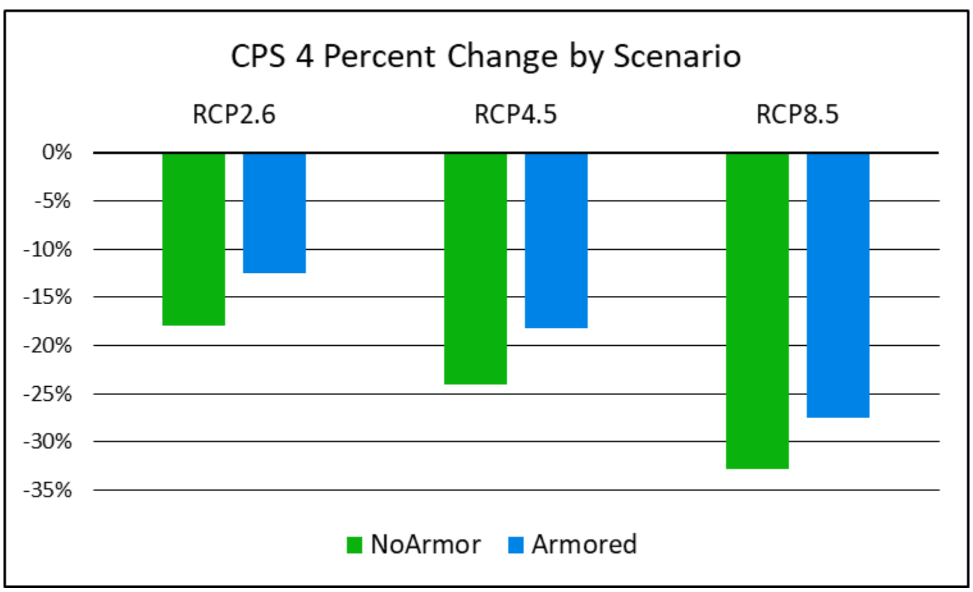


Figure 11: Percentage habitat change between non-armored and armored beaches at CPS site 4.

During the analysis of these results, it became apparent that a distinct pattern of steep elevation change was occurring near mean low water. This pattern forms a small band or seam along the shoreline at each site that is likely where the topographic and bathymetric elevation models were stitched together to form the original CoNED dataset. This seam appears to be about 2-4 m wide, spanning from around 0.6 to 1-meter MLLW elevation, but the depth and width vary between locations. The seam runs just above the edge of the RCP 8.5 coverage in every scenario. The CoNED metadata explains that the edges between these datasets were blended with the best available methods using several generalization and interpolation tools that maintained a 1 m resolution and a smooth transition at the seamlines (OCM Partners, 2023). At the regional level, a seamline with one meter or less elevation difference would not be a major issue for most applications, but a SLR inundation model focused at low tidal and subtidal elevations could be hindered by this boundary.

Profiles

Each site that was examined in the Central Puget Sound had a significantly different shoreline profile. To visualize both the transitions from upland to foreshore as well as from foreshore to the low wide terrace, the profiles at 1, 3, and 4 were drawn from 6m elevation to -2 m MLLW. To better represent the transitions at site 2 the profile was drawn from 6 m to 0.5m because the greater width of the terrace at this location.

Foreshore and terrace width can be estimated from most of these profiles as well as slope. However, the seamline in the DEM runs along this transition point and obscures the accurate measurement of any of these parameters. At sites 2 and 3 there is enough unobscured foreshore to estimate slope and widths and get a general picture of the beach profile. In the case of site 1, the seam is over 2 m high and covers the majority of the foreshore, so it is difficult to estimate a slope or width. To measure slope and widths at sites 2, 3, and 4, the average foreshore transition elevation of 1.22 m MLLW from Finlayson (2006) was used as an estimation to differentiate between foreshore and terrace.

Table 5: Profile characteristics of site transects. Slope is measured in percent slope. Foreshore is estimated between MHW and transition elevation. Terrace is estimated between transition elevation and -2 m. "Avg Slope" refers to average slope between MHW and -2 m "Armorheight" refers to the approximate MLLW elevation in meters of the base of shore armoring. "NA" = Not Applicable.

Profile Characteristics									
Site #	**Armor**	**Transect**	**Foreshore (m)**	**FS slope**	**Terrace (m)**	**T slope**	**Transition Elevation**	**Avg. Slope**	**Armorheight**
1	N	1	NA	NA	NA	3.1	NA	4.0	NA
1	N	2	NA	NA	NA	3.3	NA	4.0	NA
1	N	3	NA	NA	NA	2.7	NA	4.1	NA
1	N	4	NA	NA	NA	4.0	NA	5.5	NA
1	Y	1	NA	NA	NA	2.3	NA	3.8	NA
1	Y	2	NA	NA	NA	2.8	NA	4.0	NA
1	Y	3	NA	NA	NA	2.9	NA	4.2	2.5-4.5
1	Y	4	NA	NA	NA	5.0	NA	3.7	2.5-5
Site #	**Armor**	**Transect**	**Foreshore (m)**	**FS slope**	**Terrace (m)**	**T slope**	**Transition Elevation**	**Avg. Slope**	**Armorheight**
2	N	1	20.6	9.64	294	1.2	1.22	1.7	NA
2	N	2	18.35	10.77	292	1.4	1.22	2.0	NA
2	N	3	12.39	16.26	373	1.2	1.22	2.0	NA
2	N	4	23.49	9.28	324	1.5	1.22	2.2	NA
2	Y	1	25.24	7.93	309	1.3	1.22	1.9	NA
2	Y	2	22.9	10.04	359	2.1	1.22	3.3	2.5
2	Y	3	7.93	24.89	509	0.8	1.22	1.3	2.3
2	Y	4	22.49	9.06	606.9	0.8	1.22	1.2	2.6
Site #	**Armor**	**Transect**	**Foreshore (m)**	**FS slope**	**Terrace (m)**	**T slope**	**Transition Elevation**	**Avg. Slope**	**Armorheight**
3	N	1	23.98	8.26	200.4	1.6	1.22	2.3	NA
3	N	2	28.16	7.03	194.1	1.7	1.22	2.3	NA
3	N	3	61.14	3.37	149.2	2.2	1.22	2.5	NA
3	N	4	26.65	7.37	103.7	3.1	1.22	4.0	NA
3	Y	1	31.96	6.69	100.9	3.2	1.22	4.0	3.2
3	Y	2	13.9	13.98	80.4	4.0	1.22	5.5	3.5
3	Y	3	14.16	13.53	59.37	5.5	1.22	7.1	3.6

3	Y	4	13.48	14.55	48.15	6.7	1.22	8.4	4
Site #	**Armor**	**Transect**	**Foreshore (m)**	**FS slope**	**Terrace (m)**	**T slope**	**Transition Elevation**	**Avg. Slope**	**Armorheight**
4	N	1	13.88	14.32	43.3	8.9	1.22	10.4	NA
4	N	2	14.43	16.06	50.39	9.2	1.22	10.7	NA
4	N	3	12.3	15.87	56.86	8.5	1.22	10.0	NA
4	N	4	12.96	14.74	41.72	8.2	1.22	9.9	NA
4	Y	1	7.33	25.67	41.91	9.6	1.22	12.4	2.5
4	Y	2	10.34	18.63	50.71	7.4	1.22	9.5	2.5
4	Y	3	10.12	19.48	51.53	7.7	1.22	9.7	2.4
4	Y	4	8.831	22.46	45.07	8.1	1.22	10.6	NA

Site 1 is a narrow fringe beach with a steep foreshore and a 150-200 m wide terrace. The foreshore slope could not be accurately measured, but the terrace had a 3-5% slope (Table 5). The terrace has a relatively convex shape with the slope increasing with depth (Figure 12, 13). On the armored shore, the base of the armoring was obscured, but would fall somewhere between 2.5 and 5m elevation (Table 5).

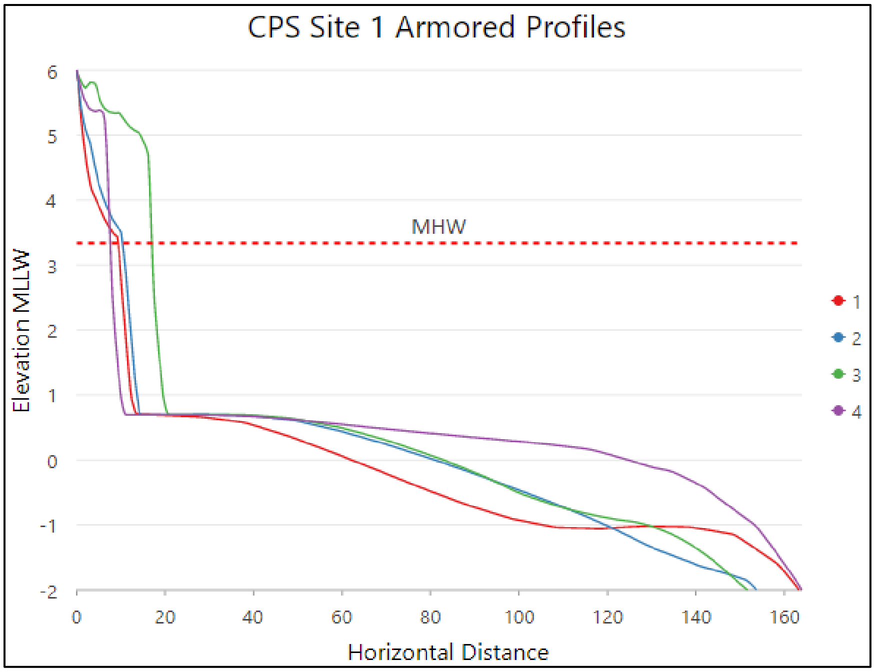


Figure 12: Central Puget Sound Site 1 armored site profiles measured from 6 m to -2 m MLLW. Mean High Water for reference indicated by dashed red line.

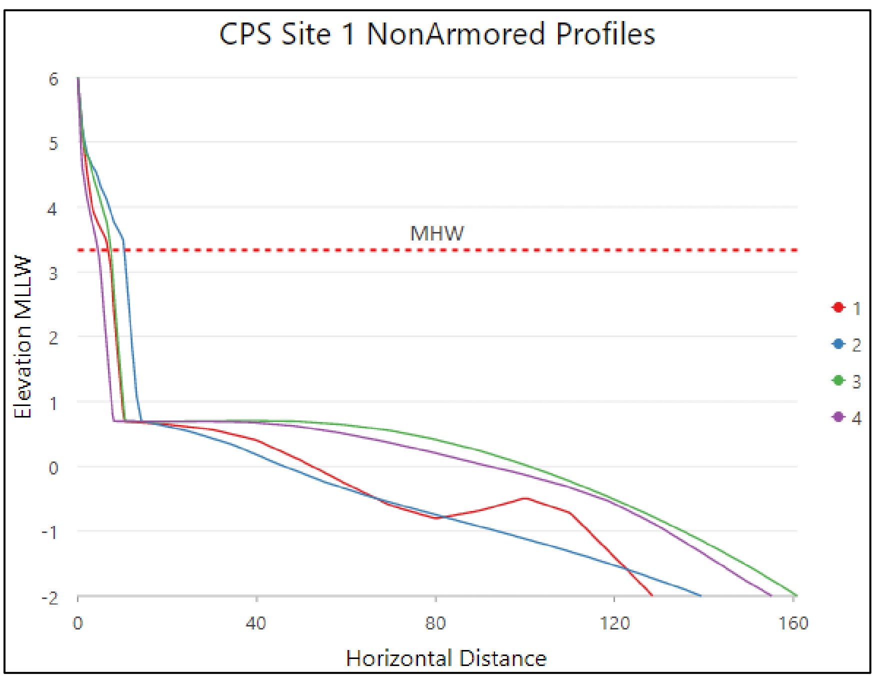


Figure 13: Central Puget Sound Site 1 Non-armored site profiles measured from 6 m to -2 m MLLW. Mean High Water for reference indicated by dashed red line.

Site 2 is a flat fringe beach with an 8-25 m wide foreshore and a 300-600 m wide terrace. The foreshore slope was around 10-16% on unarmored and 8-24% on the armored side. The terrace slope was around 1.5% at both unarmored and armored sites. The terrace shape was very flat to slightly convex (Figure 14, 15). Armoring elevation was around 2.5 m on the armored site (Table 5).

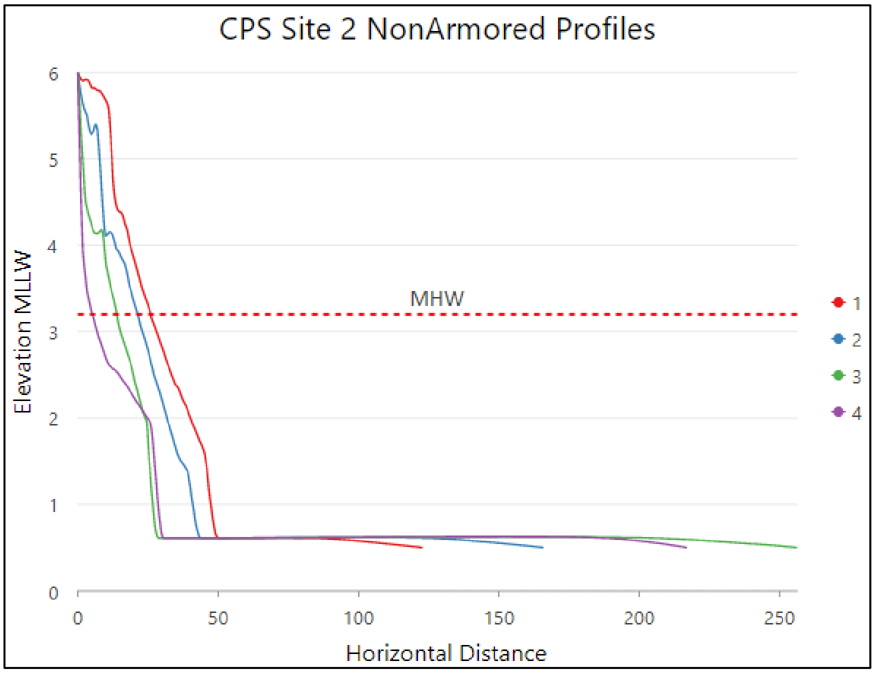


Figure 14: Central Puget Sound Site 2 armored site profiles measured from 6 m to 0.5 m MLLW. Mean High Water for reference indicated by dashed red line.

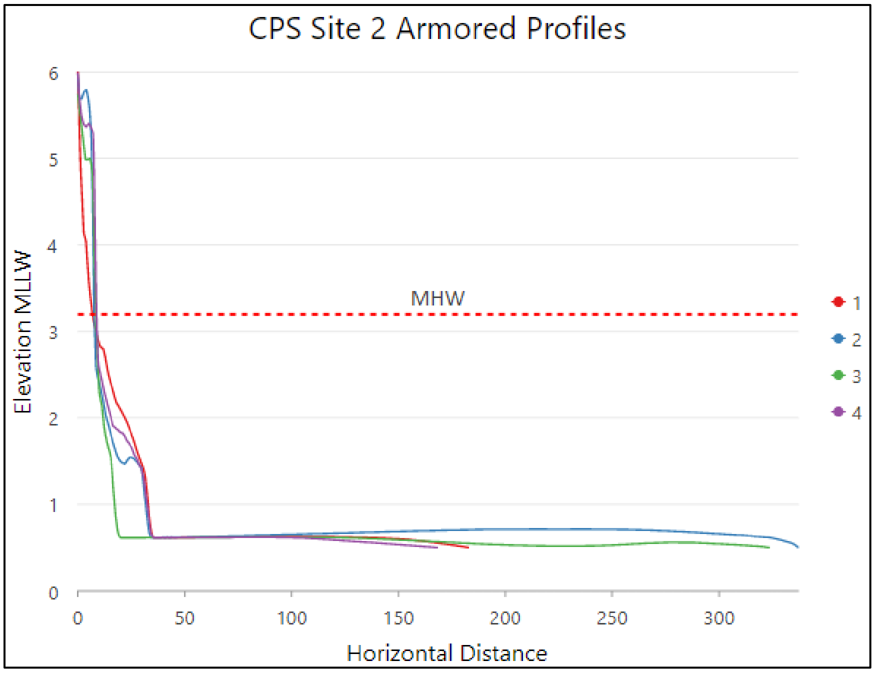


Figure 15: Central Puget Sound Site 2 Non-armored site profiles measured from 6 m to 0.5 m MLLW. Mean High Water for reference indicated by dashed red line

Site 3 is a very narrow fringe beach with a 14-60 m wide foreshore and a 50-200 m terrace. The foreshore was wider at the unarmored side with around 24-60 m width as compared to the 14-30 m wide armored beach. Foreshore slope was around 3-8% on the unarmored beach and 7-14% on the armored beach. The terrace slope was approximately 2-3% on the unarmored beach and 3-7% on the armored beach. The terrace had a convex shape with slope increasing with depth (Figure 16, 17). Armoring elevation was estimated at around 3-4 m (Table 5).

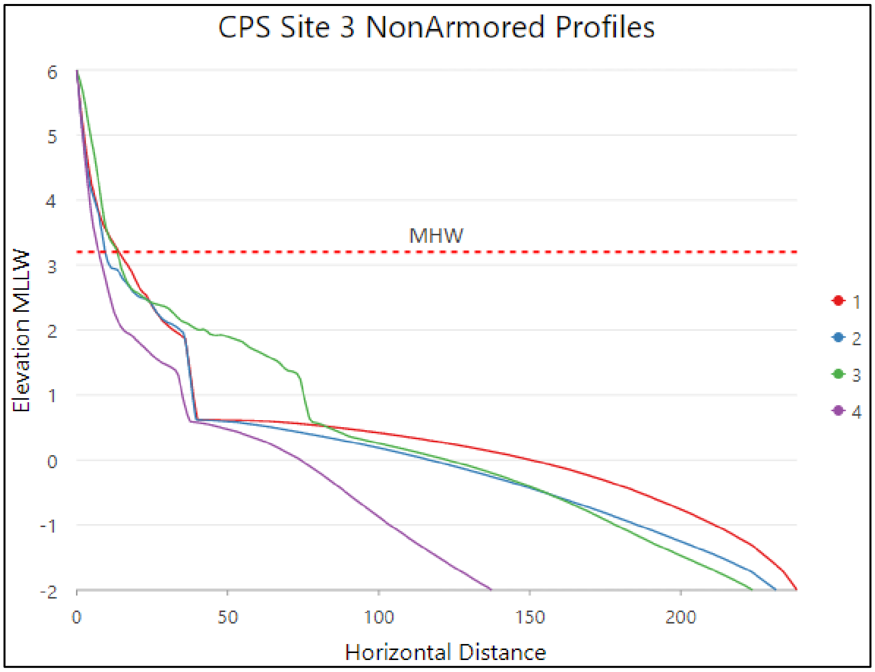


Figure 16: Central Puget Sound Site 3 Non-armored site profiles measured from 6 m to -2 m MLLW. Mean High Water for reference indicated by dashed red line.

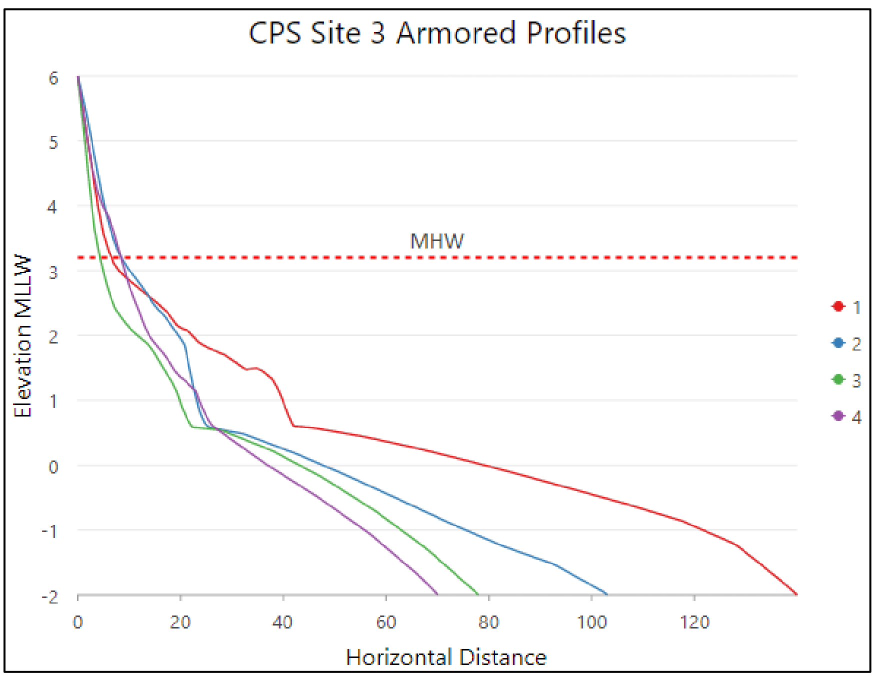


Figure 17: Central Puget Sound Site 3 Armored site profiles measured from 6 m to -2 m MLLW. Mean High Water for reference indicated by dashed red line.

Site 4 is a very narrow fringe beach with a steep foreshore and steep terrace. The foreshore at the unarmored site was around 12-14 m wide with a 14-16% slope. At the armored beach the foreshore was 7-10 m wide with a 19-25% slope. The terrace at both site pairs was 40-55 m wide with a 7-9% slope. Armoring elevation was estimated to be around 2.5 m (Table 5). The terrace has an even to concave shape with little to no increase in slope with depth (Figure 18, 19). This site is located at a very shallow section of the Puget Sound and it is difficult to visualize any deep end of the terrace due to the lack of a characteristic steep transition from terrace to deeper water.

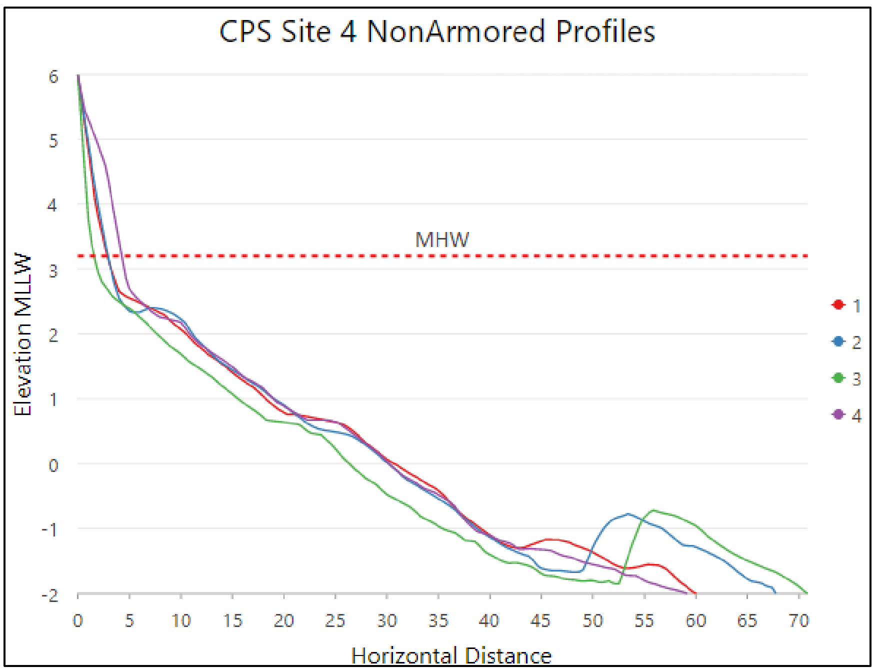


Figure 18: Central Puget Sound Site 4 Non-armored site profiles measured from 6 m to -2 m MLLW. Mean High Water for reference indicated by dashed red line.

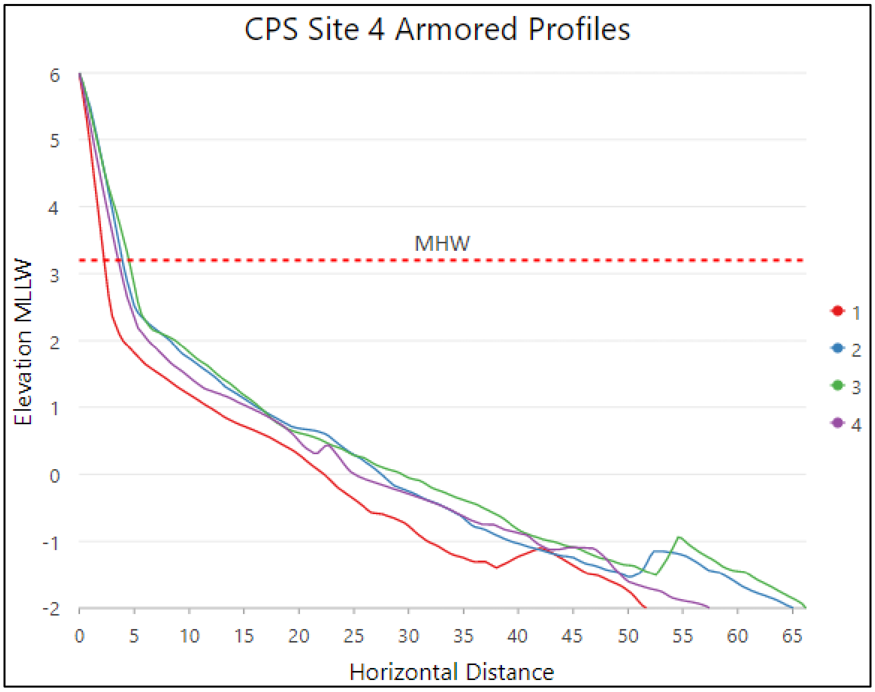


Figure 19: Central Puget Sound Site 4 Armored site profiles measured from 6 m to -2 m MLLW. Mean High Water for reference indicated by dashed red line.

SLAMM

The results from the SLAMM analysis were less useful than anticipated for investigating eelgrass habitat change. While it was understood prior to analysis that there was no equivalent to an eelgrass habitat category within the model, the outputs revealed less applicable information than expected. Most of the land categories in SLAMM either were not present at the locations or do not apply to the analysis and many had null or unchanged values. The categories that are most applicable are “Tidal Flat”, “Estuarine Beach”, and “Estuarine Open Water”. The degree of conversion of tidal flats and beaches to open water can to some degree be assumed to indicate the amount of conversion to available habitat for eelgrass. However, the model unfortunately does not provide an elevation output and so the lower limits and total area of the eelgrass habitat are indiscernible from within the estuarine open water category output (Figure 20). Model outputs also appeared to show very little difference between the scenarios. For site 2 and 3 the results for RCP 2.6, 4.5 and 8.5 are nearly identical and show little to no change between the emission scenarios. (Appendix B). These results may indicate errors in the selection of model parameters and scenario preparation, or they may illustrate some of the limitations of using the program. The restriction of the model to small shoreline areas with low wetland category complexity is likely not what the model creators intended. Due to these issues the use of this program was abandoned to focus on other study methods and only sites 1-3 were analyzed.

The most useful results can be summarized by comparison of the habitat change differences between armored and unarmored sites while the detailed results are available in the appendices. Armored sites 1 and 3 showed greater losses of tidal flat and estuarine beach and corresponding increases in estuarine open water when compared to their unarmored site pairs (Appendix B). At site 2 both the armored and unarmored sites lost 100% of their tidal flat and estuarine beach, but the unarmored site had a more than 16% greater increase in estuarine open water (Appendix B).

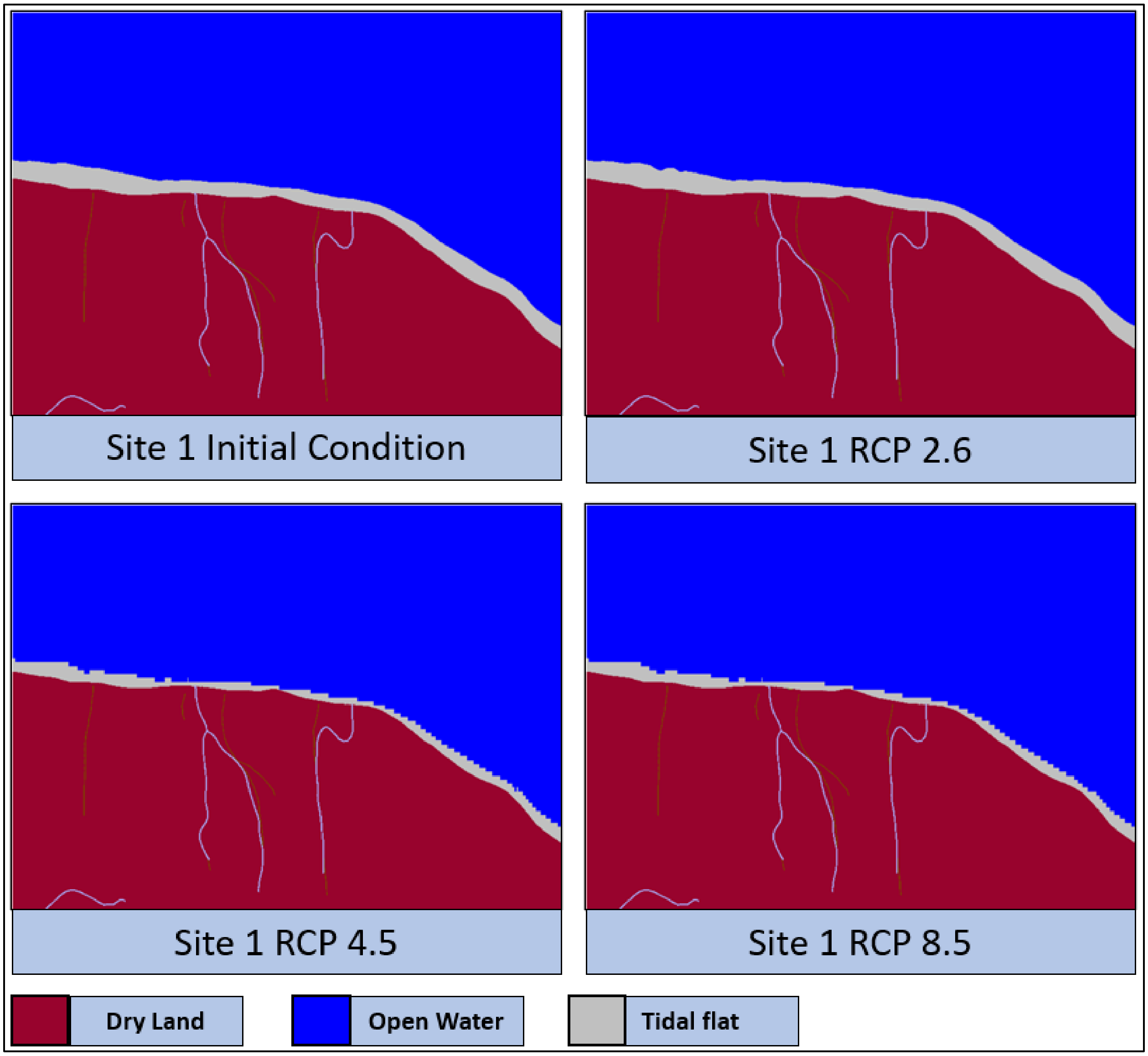


Figure 20: Example of map results from SLAMM analysis of CPS site 1. Panels show entire modeled area of site 1 including both armored and unarmored site pairs. Individual armored and unarmored site results tables located in Appendix B.

Discussion

Results of this study indicate that there is likely a significant percentage of *Z. marina* habitat in the Puget Sound that is adjacent to armored shorelines and will be subject to their influence on beach morphology. Nearly a third of estimated eelgrass habitat is on shoreline that is at least 50% armored, and in a highly developed region like the Puget Sound there is high potential that armoring will continue as SLR progresses (Dethier et al., 2016; Smith & Liedtke, 2022). Like other literature has indicated, the simulations of SLR have shown positive changes in the total area of available habitat in the majority of sites and scenarios (Glick et al., 2007; Kairis & Rybczyk, 2009; Smith & Liedtke, 2022).

The projections of habitat change from the ArcGIS analysis showed substantial variability between sites in both overall change and comparisons of site pairs. While habitat expansion occurred as expected in 3 out of 4 sites, percent change ranged between 9-52% for RCP 2.6 and 38-255% for RCP 8.5 (Table 4). Projections displayed less habitat expansion at the armored locations in two out of the three sites that showed overall habitat increases. At sites 2 and 3 the armored beaches showed a lower positive percent change in each scenario. At sites 1 and 4 the unarmored pairs do not appear to offer greater protection to habitat as they resulted in less expansion or greater loss in the case of site 4. The steep and narrow Site 3 had the lowest positive percent change in RCP 8.5 for both armored and unarmored sites and the flatter wider Site 2 had the largest percentages of expansion.

The results support the idea that steep slopes near to the shoreline will naturally limit the total area of habitat expansion as the ideal depth is confined to a narrower band of land surface. However, any conclusions regarding armoring as a determinant of beach morphology should not be made with these limited results. Shoreline armoring could be a cause of steeper beach slope in these locations; however, it is also possible that locations with steeper slopes are more likely to need stabilization and the relationship between armor and higher slopes may not be causal. Despite this uncertainty regarding the role of armoring in determining the slope represented in the elevation model, literature supports the idea that armoring causes increased slope (Dethier et al., 2016; Shipman et al., 2010).

Beach profiles appear to have a large effect on the amount of habitat expansion in any given SLR scenario, even in less severe scenarios. In the Central Puget Sound, the majority of eelgrass is found on locations with fringe type profiles, and all the sites used in this study were categorized as fringe type sites (Christiaen et al., 2022). Previous studies of flats type sites have found significant habitat expansion in SLR scenarios, but fringe sites are understudied (Kairis & Rybczyk, 2009; Poppe & Rybczyk, 2022). The results from this study show high variability between each fringe site. Very steep sites may show habitat loss, but flatter fringe beach locations with a large “low wide terrace”, like Site 2, appear to provide large areas for new habitat in the preferred habitat depth for *Z. marina*. In the Puget Sound, even flat beaches are often characterized by steep foreshores which appear to begin around 1 m MLLW (Finlayson, 2006). This steep shore will likely slow the rate of habitat expansion, especially if it is resistant to erosion as in the case of an armored shore. Steep and narrow fringe locations that have less terrace, like site 4, may experience little expansion or even habitat loss as the preferred habitat range is compressed against the shoreline. If SLR progresses near or past 1 meter, then reductions in expanded habitat may begin to occur from the lower limit of habitat as water deepens on the terrace. Accretion and erosion processes will occur over time as SLR progresses, and may alter the beach profile to elevate the terrace and foreshore, but this plasticity is likely reduced on armored beaches (Smith & Liedtke, 2022).

These results may also show that profile shape on the low wide terrace may be a predictor of projected habitat gain or loss. At sites 1-3, where there was projected habitat gain, the terrace profiles had a relatively convex shape that exhibited increasing slope with increasing depth. At the only site with projected habitat losses, site 4, the terrace profile had a relatively straight to concave shape that did not gradually increase slope with depth. SLR on concave profiles will push habitat onto steeper slopes and reduce available habitat area in the preferred depth range. Alternatively, SLR on convex profiles will result in habitat expansion over the decreasing slope until impeded by the foreshore transition.

The preferred habitat area for *Z. marina* appeared to remain below the foreshore and on the low wide terrace in all scenarios. Unfortunately, this result may have been forced by the boundary of the seam in the elevation data. However, the foreshore to terrace transition typically occurs near 1 meter MLLW in Puget Sound, which is above where any of the scenarios used would have shown projected habitat expansion (Finlayson, 2006). If SLR remains below 1 meter, then eelgrass preferred habitat will stay on what is currently the low wide terrace. This part of the shoreline profile is typically characterized by finer sand and sediment and should provide suitable substrate. If SLR surpasses 1 meter rise, then habitat may encroach upon the foreshore where grain size is larger. On unarmored beaches erosion and sedimentation could decrease grain size over time, but this would be more difficult at armored locations.

Another factor to consider, especially at flat sites, is the rate of habitat expansion and the ability of *Z. marina* to migrate into potential habitat. Eelgrass has been estimated to have a lateral spreading migration rate of around 12-15cm per year, which would result less than 10-12 m expansion by 2100 (Kairis & Rybczyk, 2009; Neckles et al., 2005). In contrast the lateral habitat expansion modeled would be about 10-100 m at sites 1 and 3 and up to around 350 m at site 2.

This means that the primary method of new habitat colonization would have to be through seed dispersal. Spreading eelgrass through seed has been known to result in rapid expansion or recolonization of beds, but the rates of this type of spread are variable and rely heavily on factors such as flowering intensity, environmental conditions and new shoot mortality (Neckles et al., 2005; Olesen & Sand-Jensen, 1994)

As expected, projections did not show *Z. marina* habitat directly overlapping with armoring because of the low tidal and subtidal range of eelgrass, but the distance between the two closed significantly. Most armoring was located near the Mean High Water line (around 3 m in Puget Sound) with some areas extending down to nearly 2 m MLLW. Projections did show that the preferred habitat range would move from 50-250m distance from the armoring to within 10-15m in the RCP 8.5 scenario at every location. The severity of negative armoring impacts are thought to be greater when armoring is located lower along the beach profile (Shipman et al., 2010). This increasing proximity of *Z. marina* to armoring will expand the risk of exposure to the negative effects of wave energetics, increased substrate grain size, and turbidity (Poppe & Rybczyk, 2022; Shipman et al., 2010). While the future conditions of beach slope, profile shape, and habitat area are uncertain and dependent on individual location and fluctuating sediment, the closing distance between habitat and armoring is a certainty in the face of rising sea levels.

Project limitations and Assumptions

While considering the results and implications of this study it is important to reiterate potential inaccuracies resulting from the data and methods used in this study. Firstly, some older and lower resolution data like the Shorezone survey were used as a basis for estimating eelgrass presence. Secondly the digital elevation model source used as the basis for SLR projections was formed from separate topographic and bathymetric datasets which may have resulted in a narrow band of steep slope with generalized values that passed through each study site. Thirdly, erosion and accretion processes were not modeled in this study and its results are based upon the assumption of unchanged bathymetry from 2015 to 2100. The analysis conducted in this uses extant digital elevation models that do not change in the varying SLR scenarios; modeling erosion or sedimentation processes in various scenarios could be beneficial in future work.

During the initial stages of this research project the intention was to use the Sea Level Affecting Marshes Model (SLAMM) as a method of modeling beach erosion. As erosion and accretion processes are one of the main differences between armored and unarmored shores, modeling these changes would have been greatly beneficial for the results and conclusions of the study. It was understood initially that the program could not directly model eelgrass habitat but, considering its use in Smith and Leidtke (2022) and Glick et al. (2006), it appeared promising for providing at least a basis for comparison to other survey and analysis results. However, using the SLAMM program proved to be more time and labor intensive than initially anticipated, and its results indicated that user inexperience and model limitations made the data output ineffective for this study.

It is important to note that these projections assume that eelgrass will retain the same preferred habitat range while under the influence of other climate change impacts. Estimates of climate change induced sea level rise include calculations of thermal expansion which implies that any significant increase of sea level will have a corresponding increase of water temperature (Oppenheimer et al., 2019). Thermal changes also can cause alterations to water chemistry and water quality. Increased temperature and low water quality are known to have negative effects on eelgrass health. While eelgrass may have available habitat according to geomorphological and bathymetric characteristics, that does not guarantee overall environmental suitability for the species.

Future studies of eelgrass habitat expansion would benefit greatly from continued survey and data collection on as many shorelines as possible. At the Puget Sound regional scale there are large datasets like Shorezone and CoNED that can be incredibly useful but can also contain data that is over 20 years old. New surveys should include accurate elevation models of the shoreline at the land/ water interface between MHHW and MLLW. This elevation band is very difficult to digitally map because water reflectance restricts aerial remote sensing and the shallow depth restricts boat borne remote sensing, but new technologies like green laser LIDAR are making advances in making these elevation models possible (OCM Partners, 2023). It may also be possible to use the separate elevation models used in the CoNED DEM and use different methods of interpolation to generalize the land/ water interface more accurately. The CoNED project used a convex hull method which may have misrepresented the curvature of the beach surface at the foreshore/ terrace transition, and future studies could determine a more suitable tool to create a smoother transition between the datasets.

Conclusion

This study explored the effects of global sea level rise on the habitat of *Z. marina* and the degree to which shoreline armoring will impact the species response to this rising threat. The results of this study indicate that nearly one third of known eelgrass habitat is potentially exposed to the effects of armoring as shown by the overall extent of armoring present in Puget Sound. Habitat change projections show habitat expansion at a majority of sites as sea levels increase. However, results are inconclusive about the differences in *Z. marina* habitat response to SLR between armored and unarmored beaches. Fringing habitat locations with steep elevation profiles were shown to have high variability in the level of habitat change, but profile shape was shown to be an indicator of potential gain or loss. Of potentially more concern than overall habitat area changes is the increasing proximity of eelgrass habitat to armored surfaces, as effects are unknown regarding eelgrass's ability to effectively colonize habitat near these anthropogenic structures.

Some of the insights provided by this study into potential eelgrass habitat changes may be useful for land management and ecosystem restoration. Most studies have found that eelgrass habitat will expand with sea level rise at flat locations, but this study suggests that outcomes on fringe locations may be more difficult to predict. While shoreline armoring may not individually present significant concerns to *Z. marina* at this time, it is important to be aware that rising sea levels could increase the risks of impact. When land managers and conservationists evaluate plans for SLR mitigation or ecosystem restoration at locations with armoring and eelgrass presence, they should be sure to consider the increasing proximity of armoring to habitat in the future.

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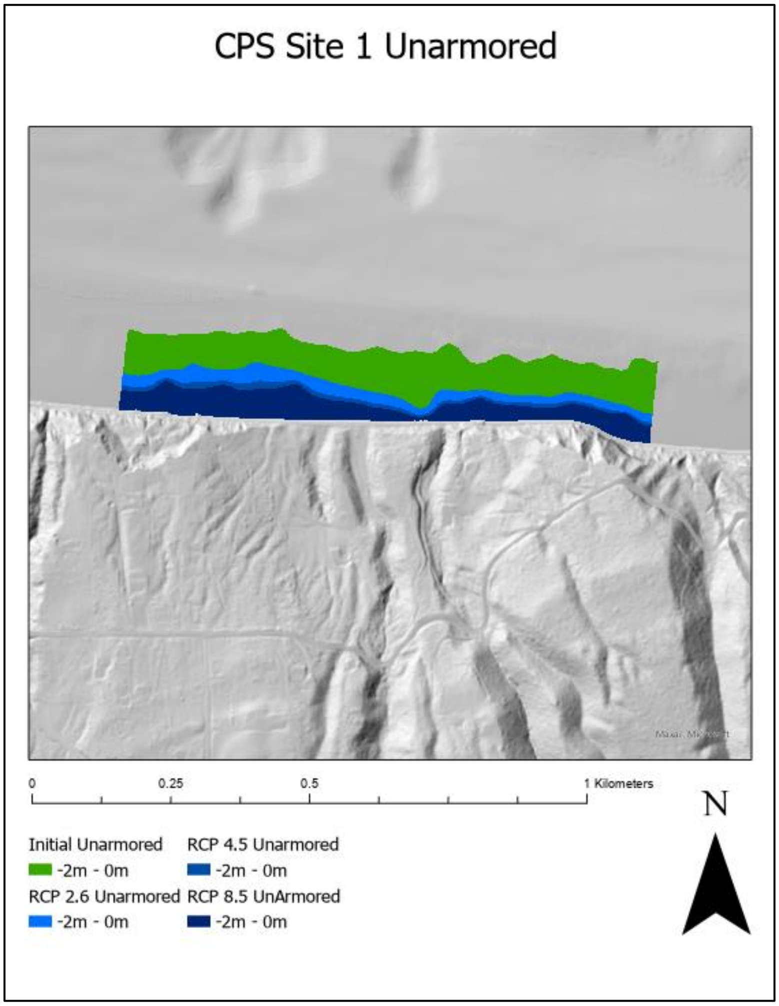
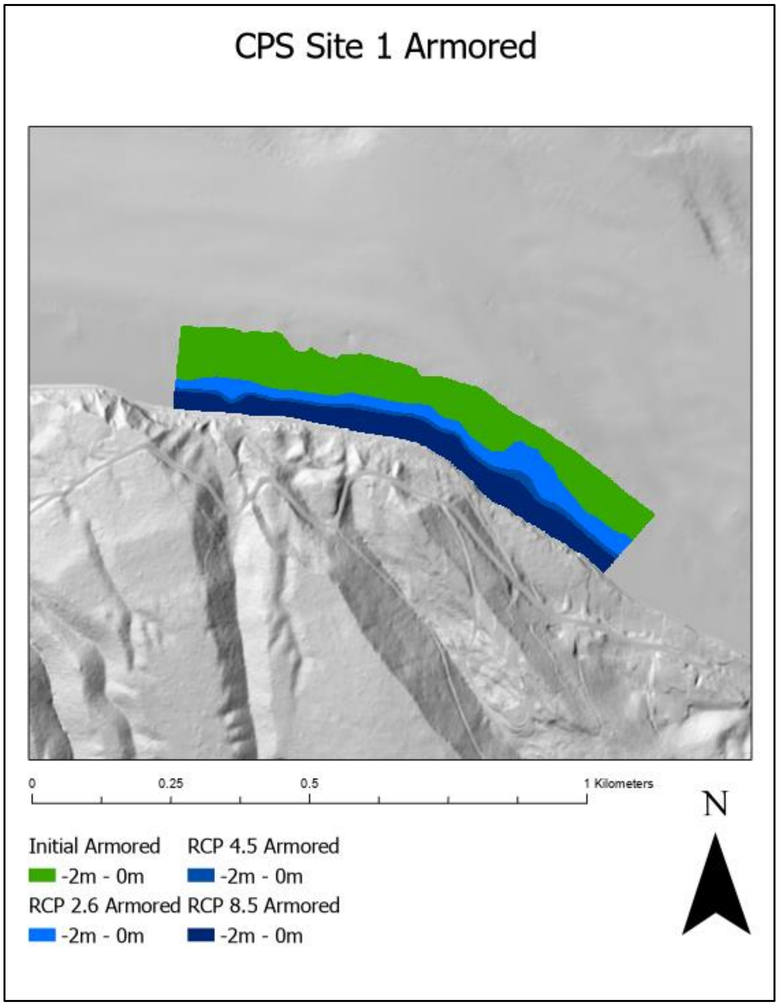
Appendix A.

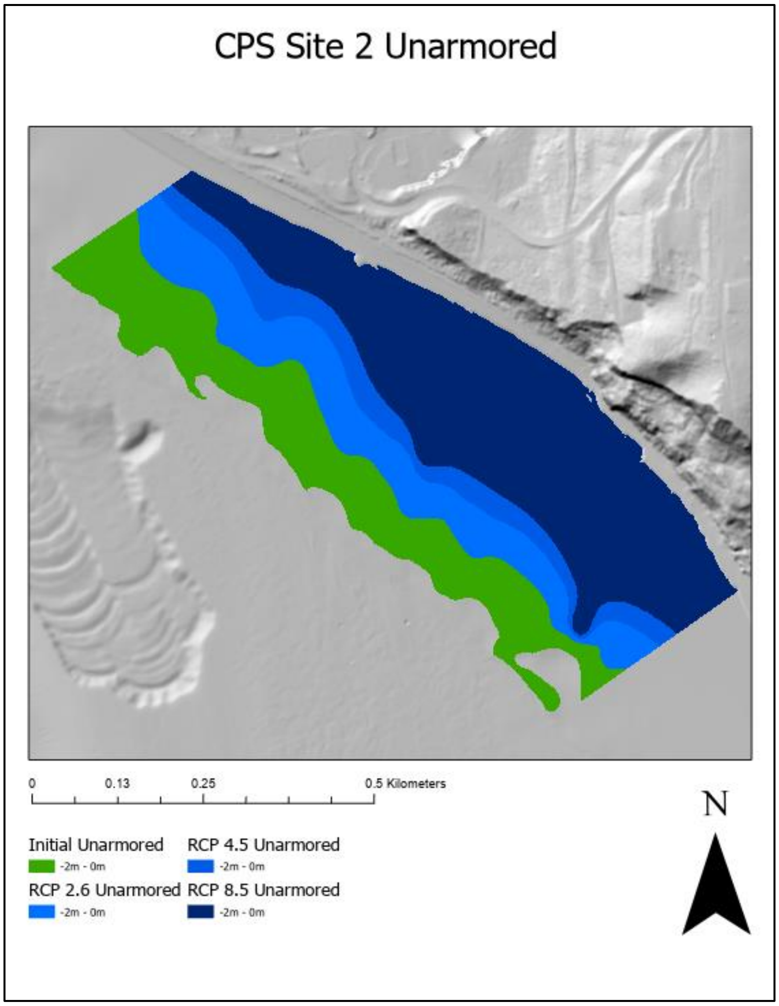
ArcGIS Pro projection maps



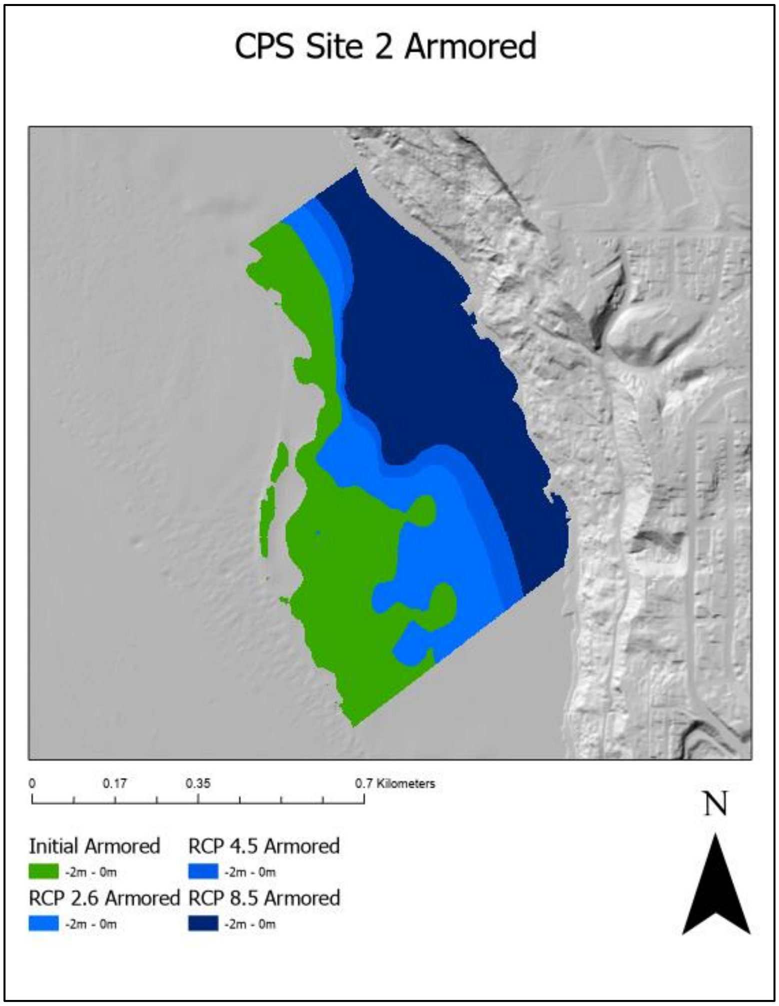
Appendix A 1. CPS unarmored site 1 projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible.



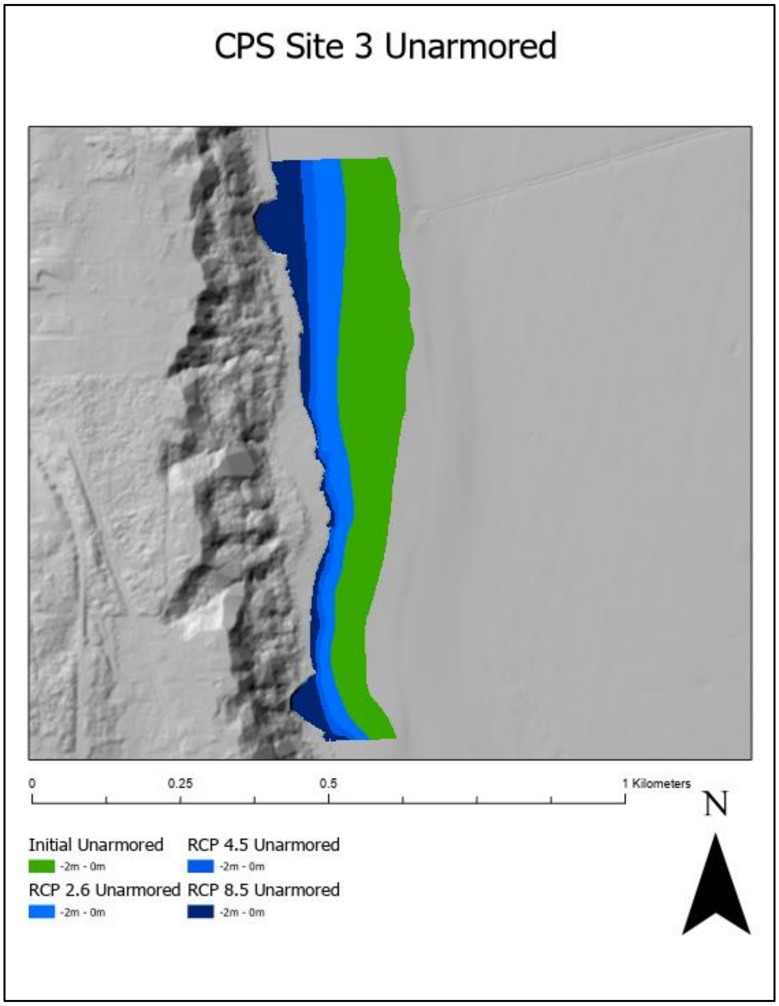
Appendix A 2. CPS armored site 1 projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible



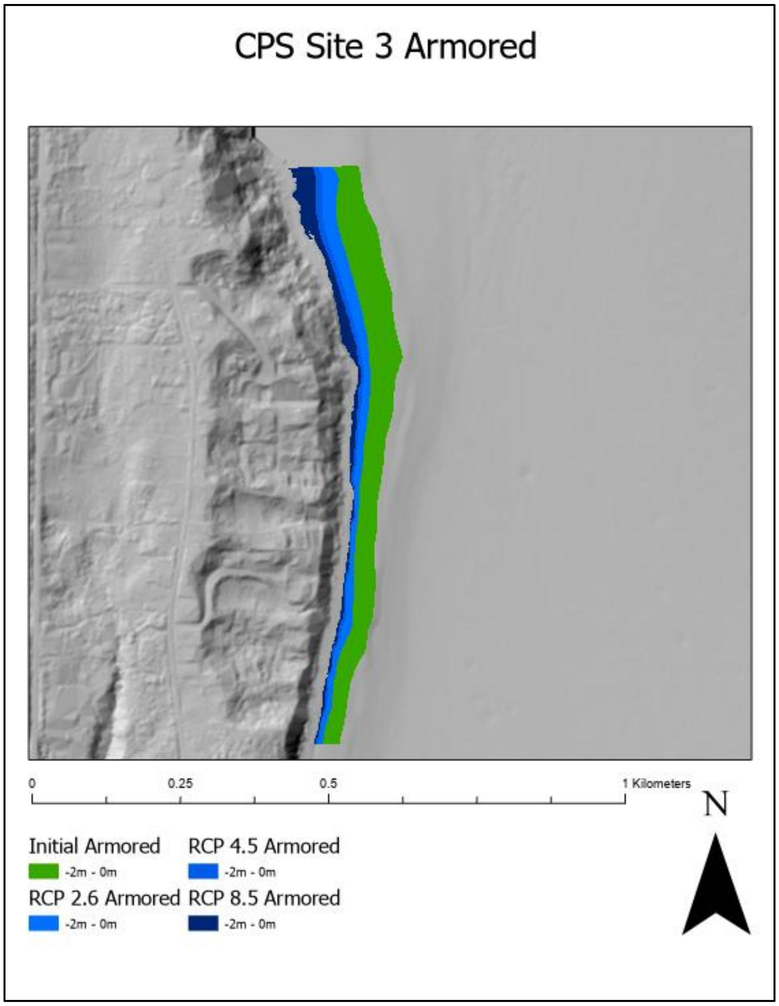
Appendix A 3. CPS unarmored site 2 projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible



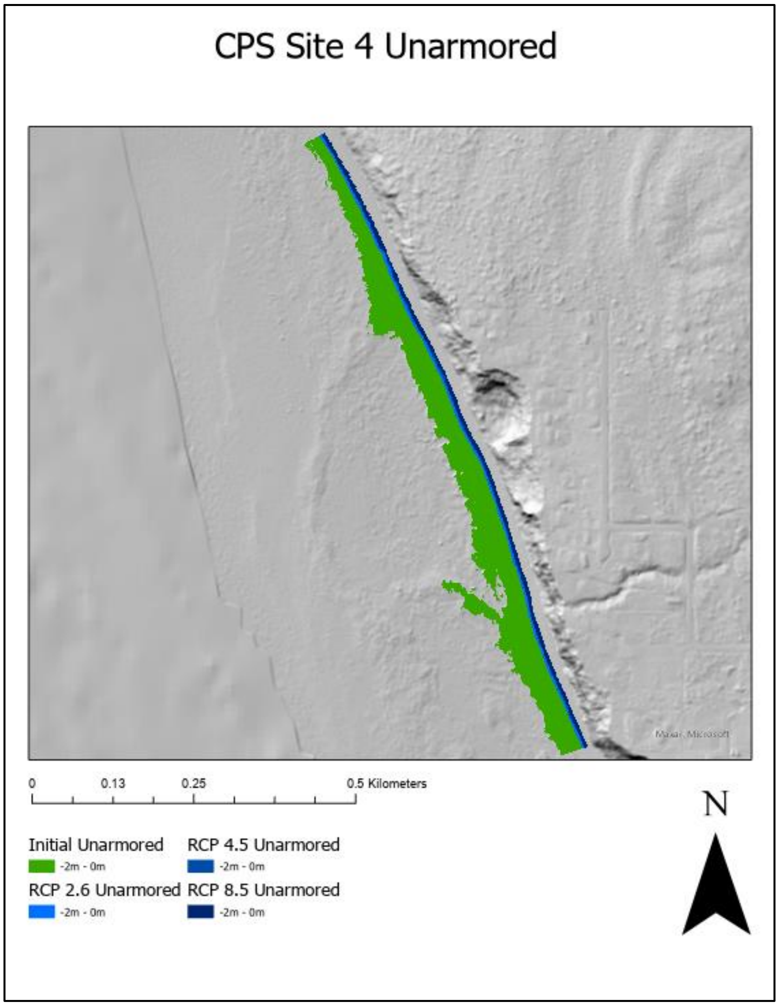
Appendix A 4. CPS armored site 2 projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible



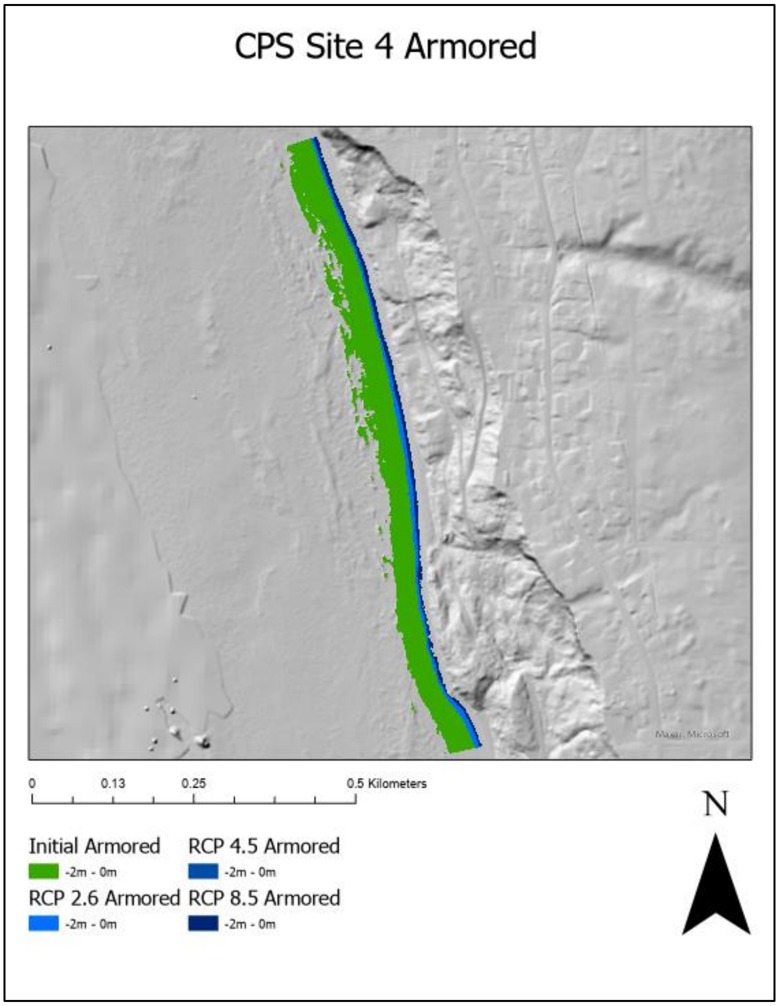
Appendix A 5. CPS unarmored site 3 projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible



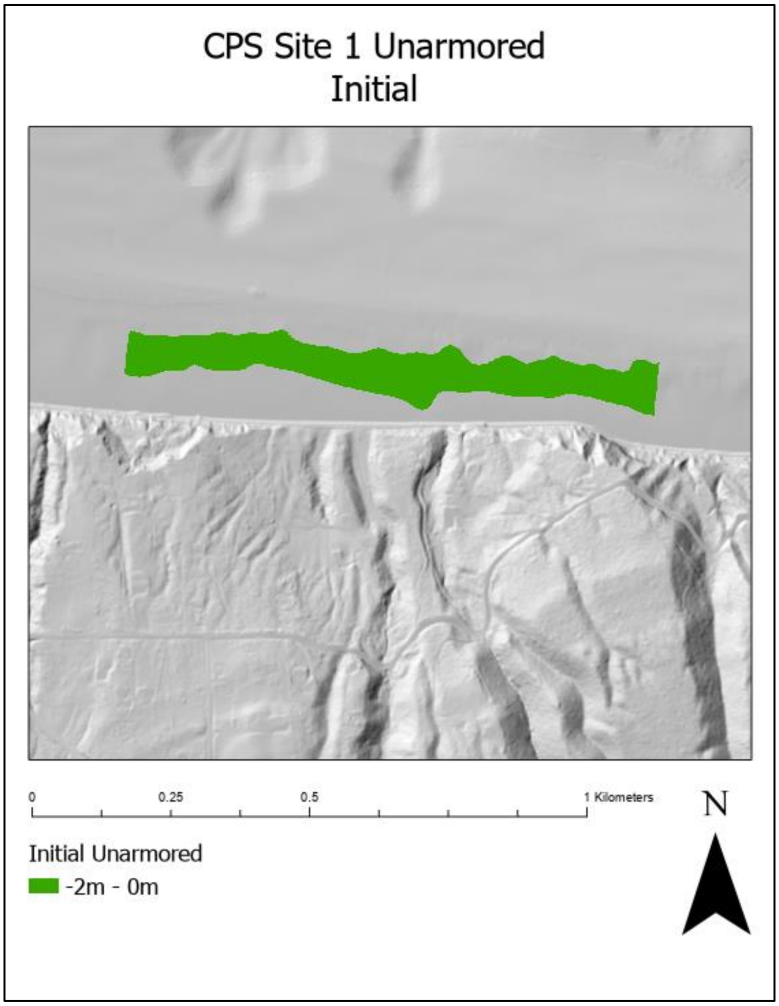
Appendix A 6. CPS armored site 3 projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible



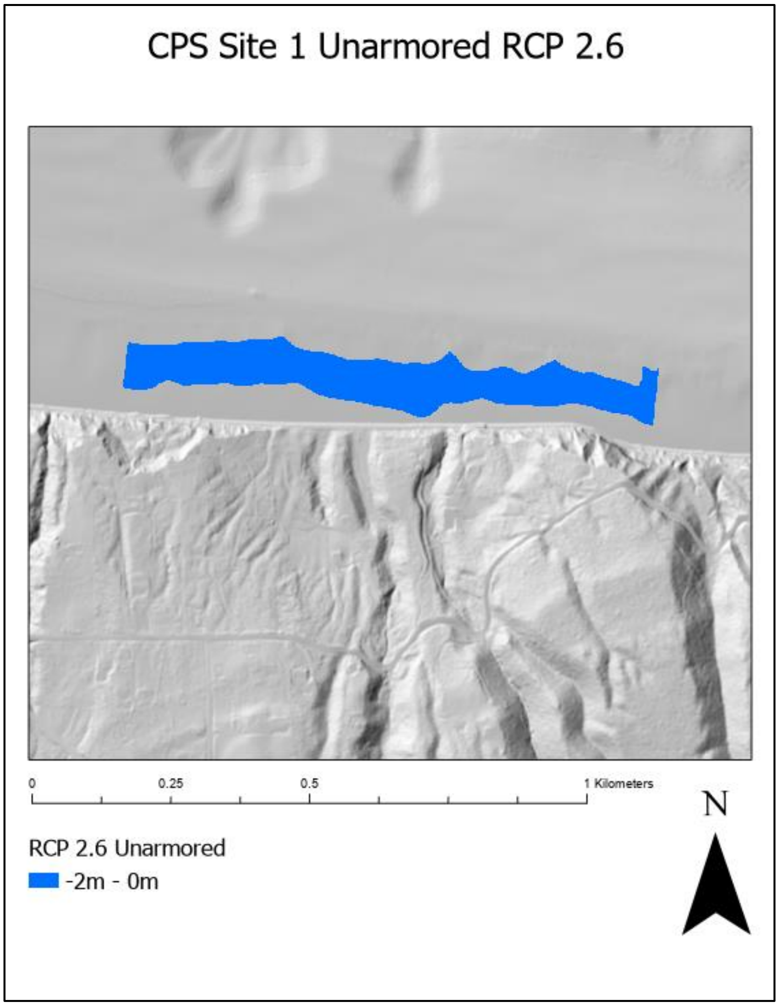
Appendix A 7. CPS unarmored site 4 projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible



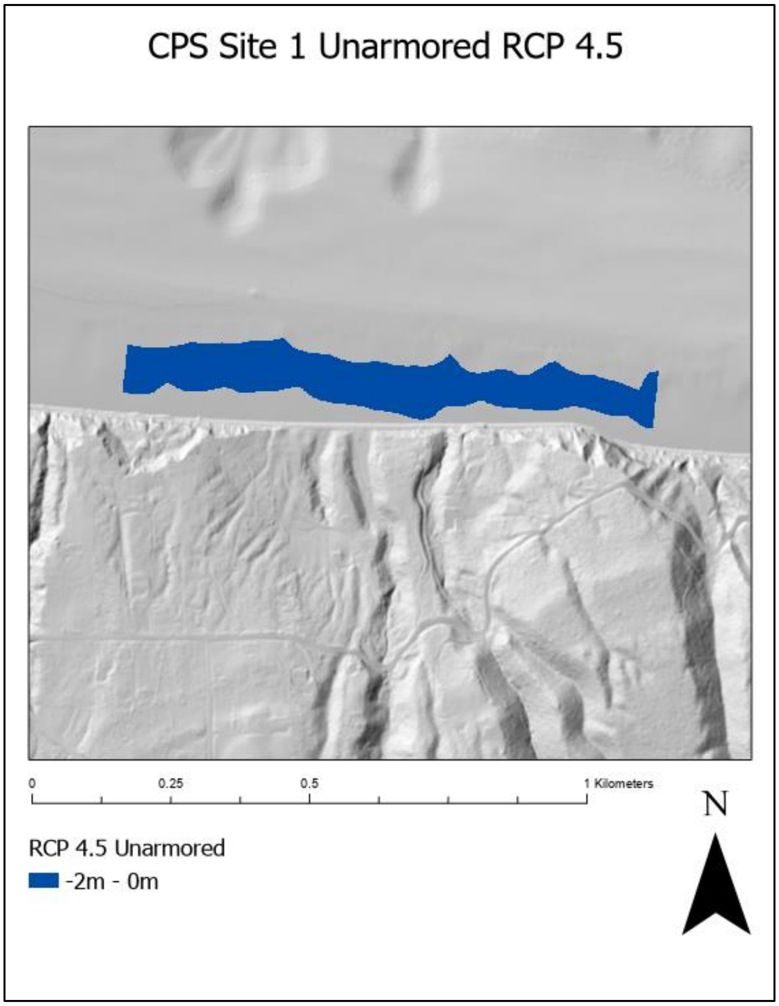
Appendix A 8. CPS armored site 4 projected habitat area for Initial (DEM date 2015), RCP 2.6, 4.5 and 8.5. Projected habitat area layers are stacked so that only the Initial habitat area and areas of shoreward expansion are visible



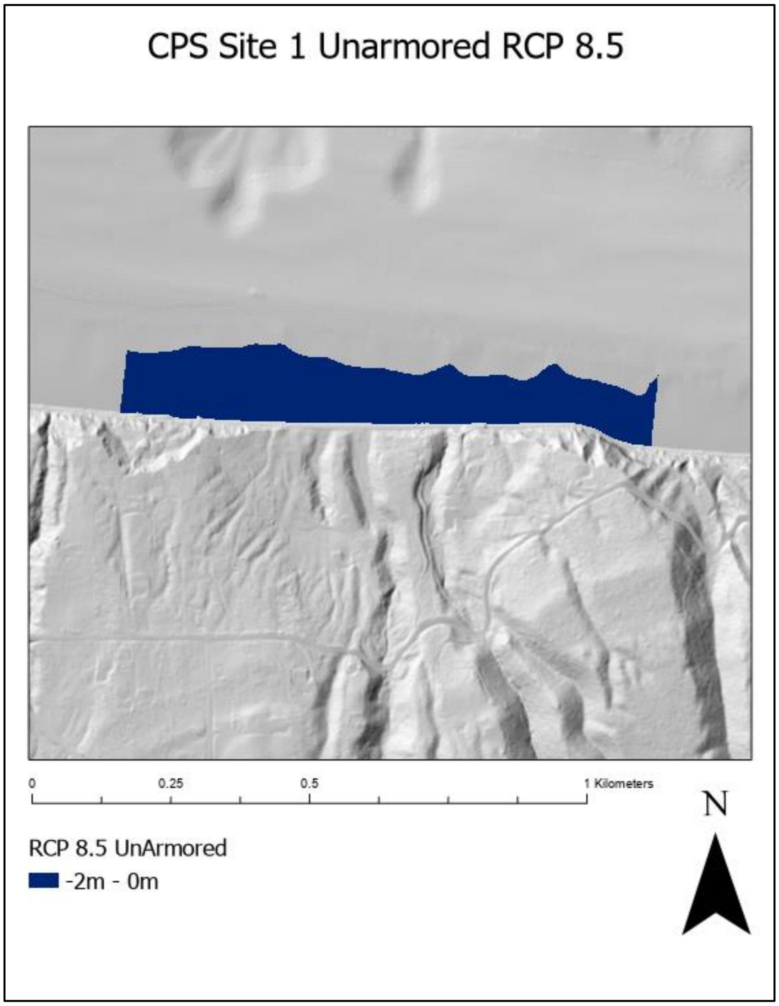
Appendix A 9. CPS unarmored site 1 projected habitat area for Initial (DEM date 2015).



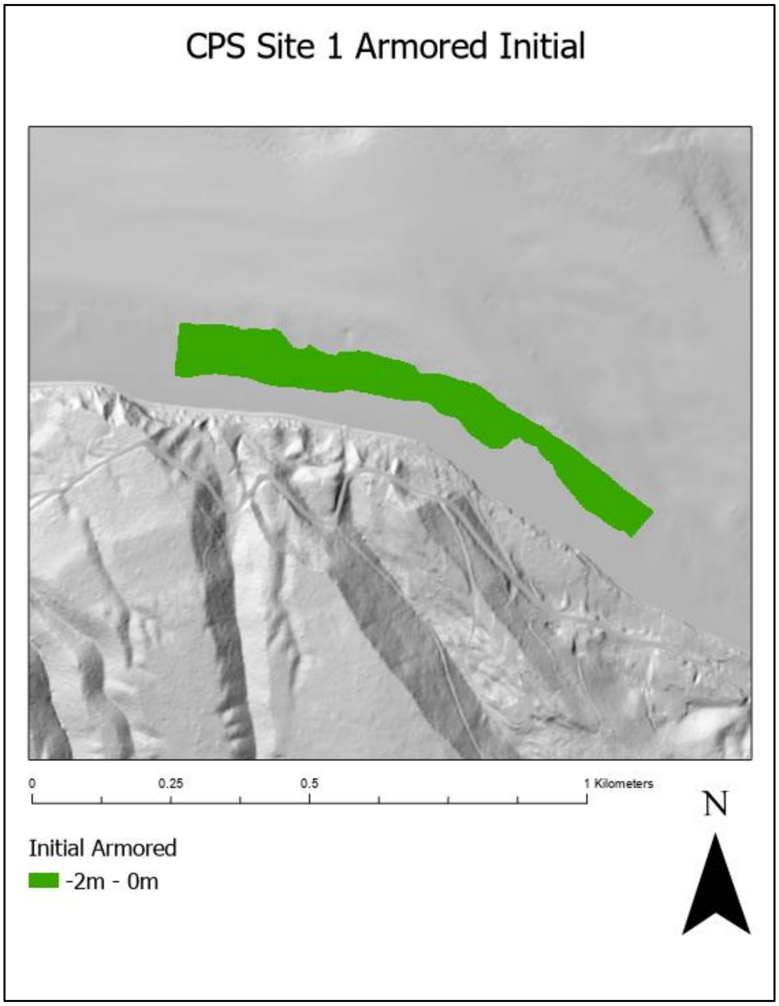
Appendix A 10. CPS unarmored site 1 projected habitat area for RCP 2.6.



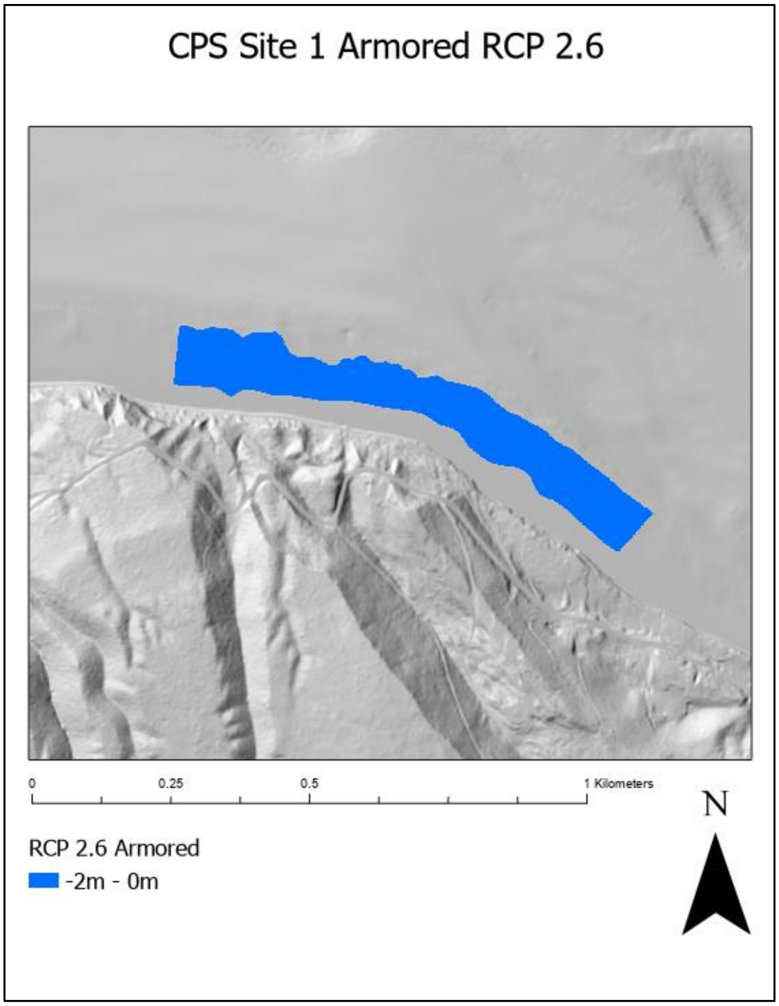
Appendix A 11. CPS unarmored site 1 projected habitat area for RCP 4.5



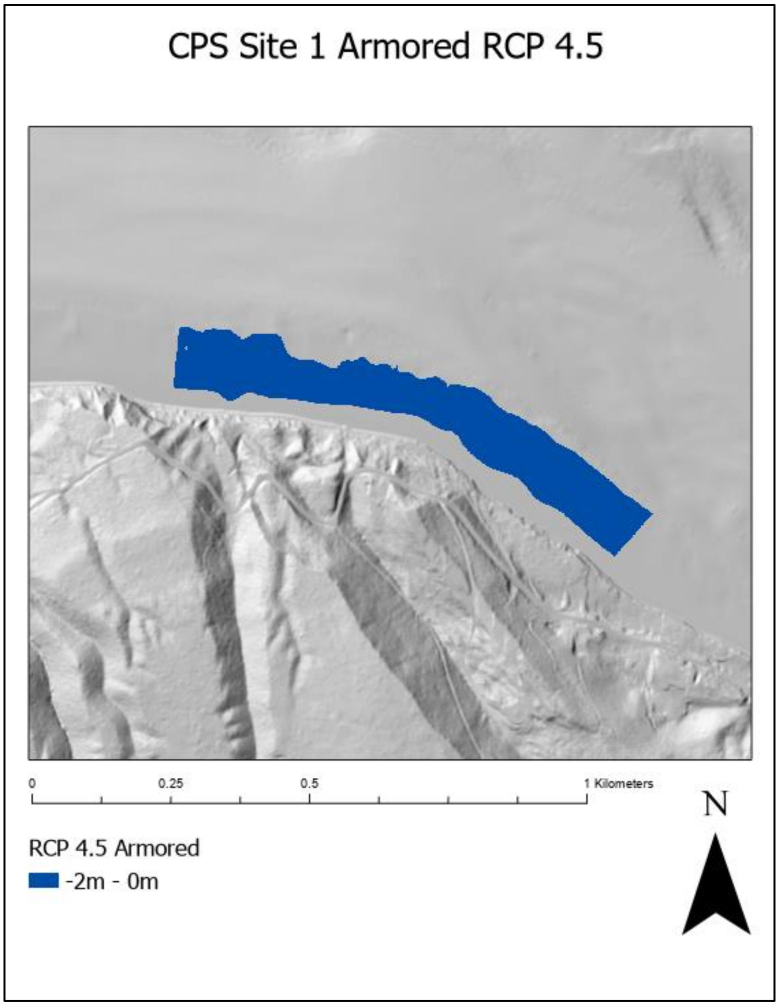
Appendix A 12. CPS unarmored site 1 projected habitat area for RCP 8.5



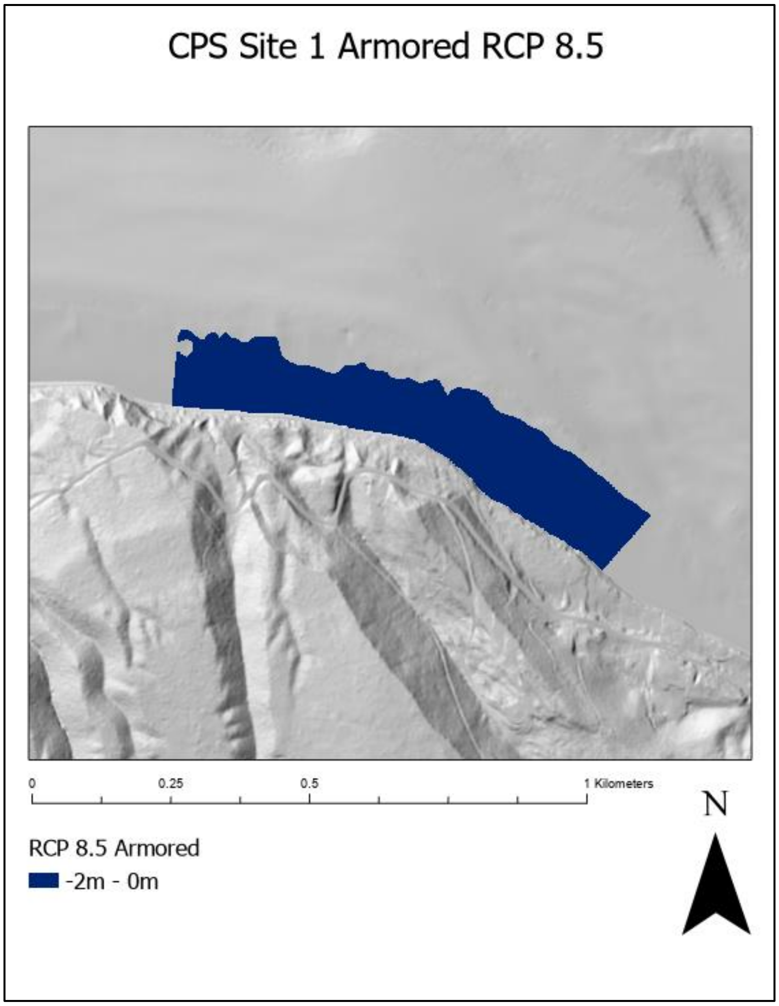
Appendix A 13. CPS armored site 1 projected habitat area for Initial (DEM date 2015).



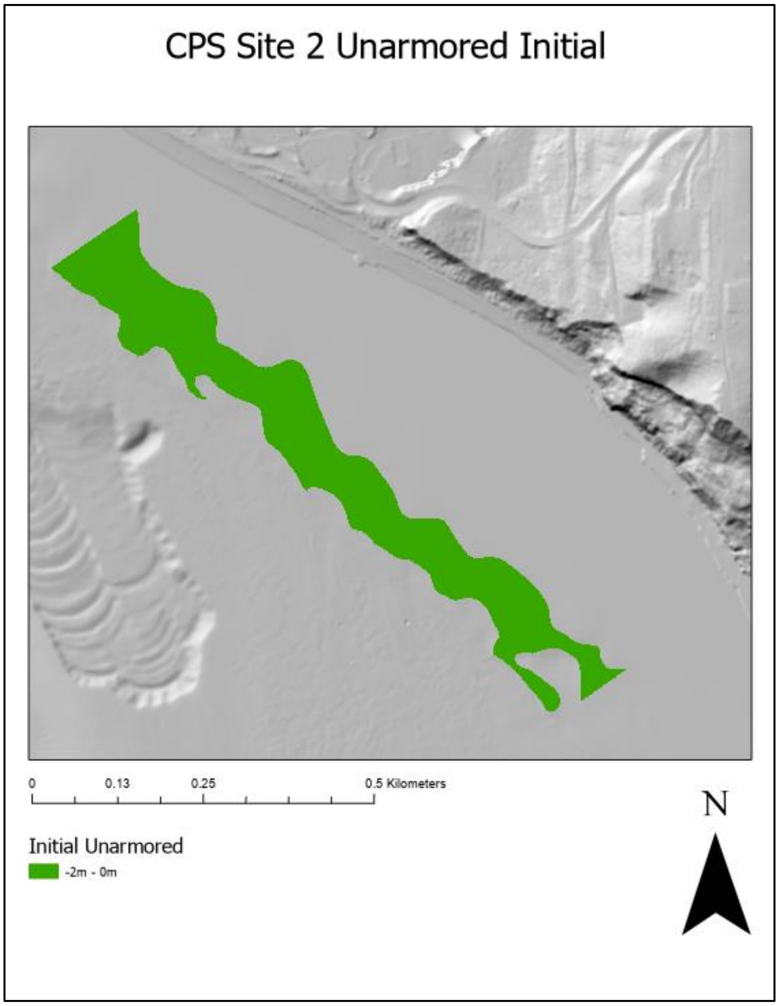
Appendix A 14. CPS armored site 1 projected habitat area for RCP 2.6.



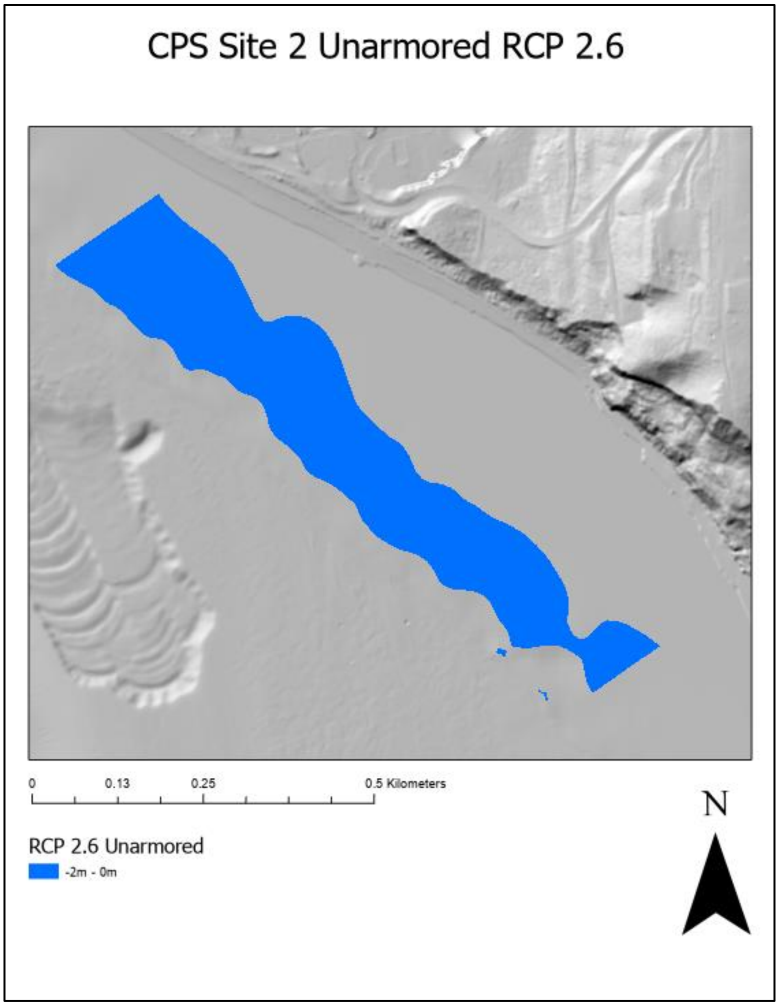
Appendix A 15. CPS armored site 1 projected habitat area for RCP 4.5



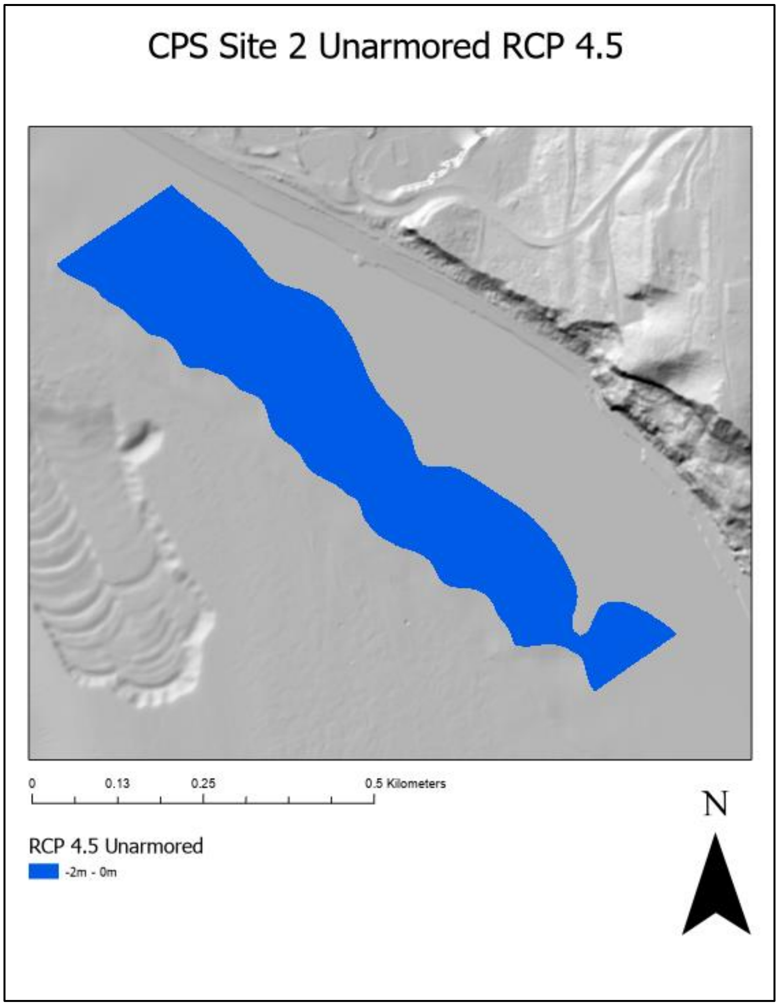
Appendix A 16. CPS armored site 1 projected habitat area for RCP 8.5



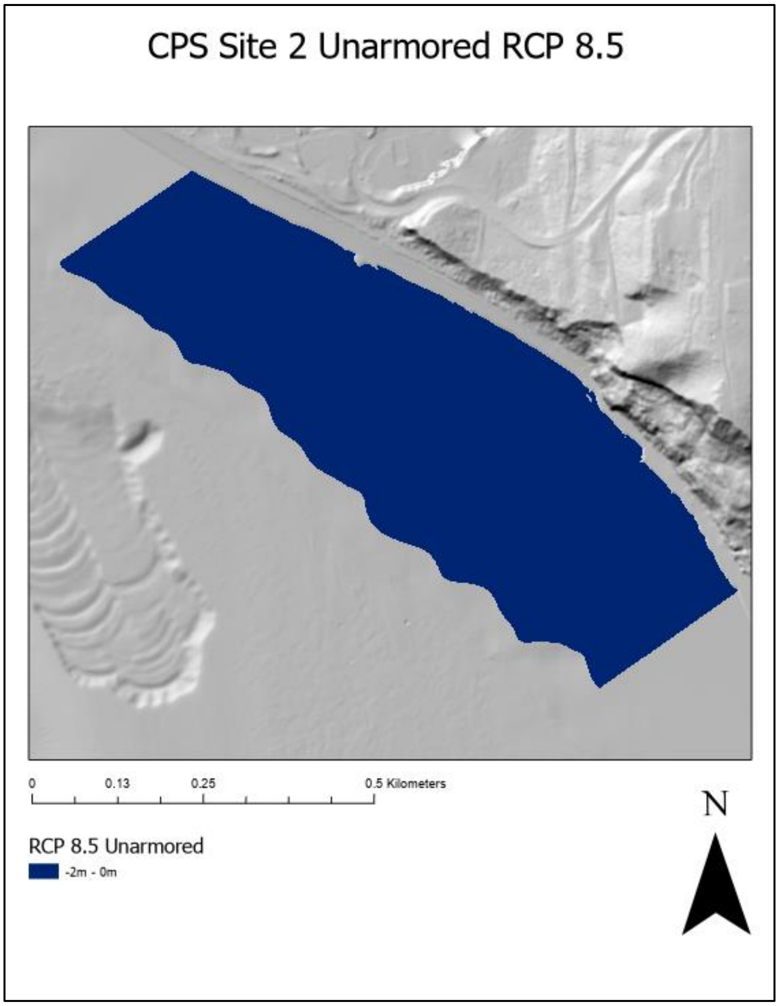
Appendix A 17. CPS unarmored site 2 projected habitat area for Initial (DEM date 2015).



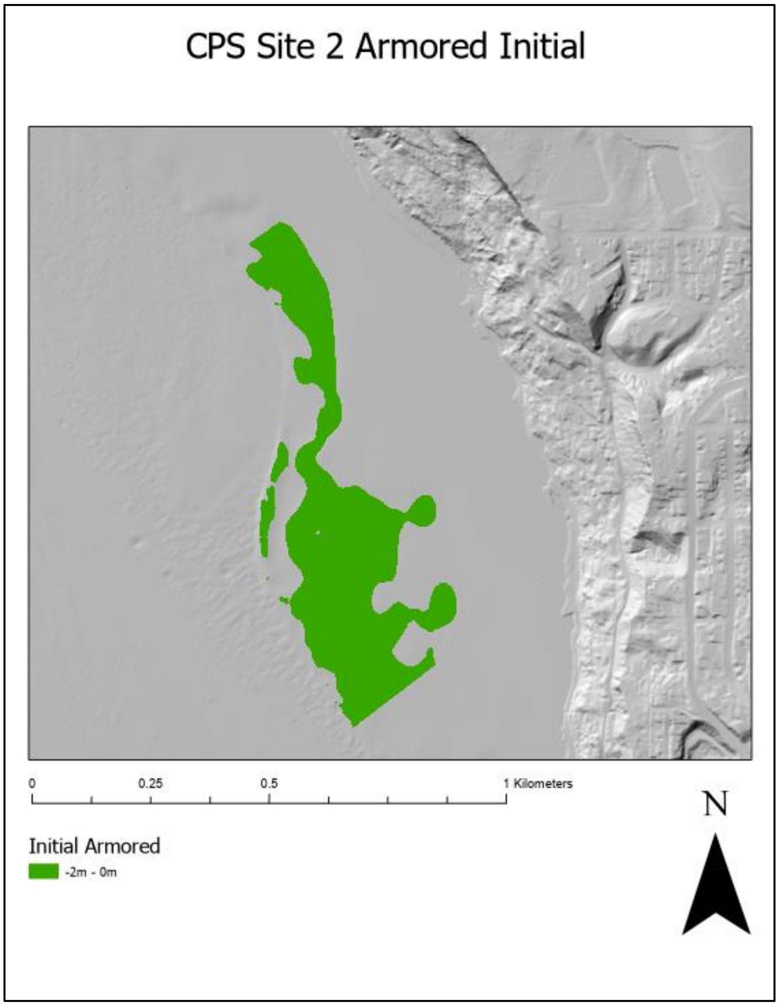
Appendix A 18. CPS unarmored site 2 projected habitat area for RCP 2.6.



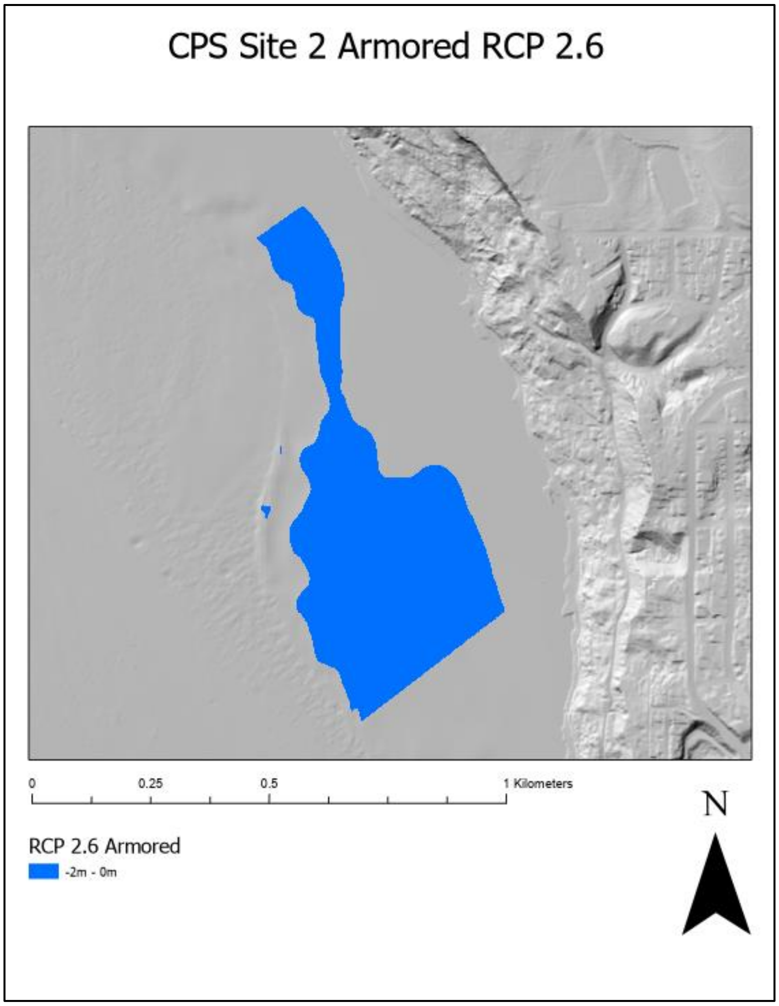
Appendix A 19. CPS unarmored site 2 projected habitat area for RCP 4.5



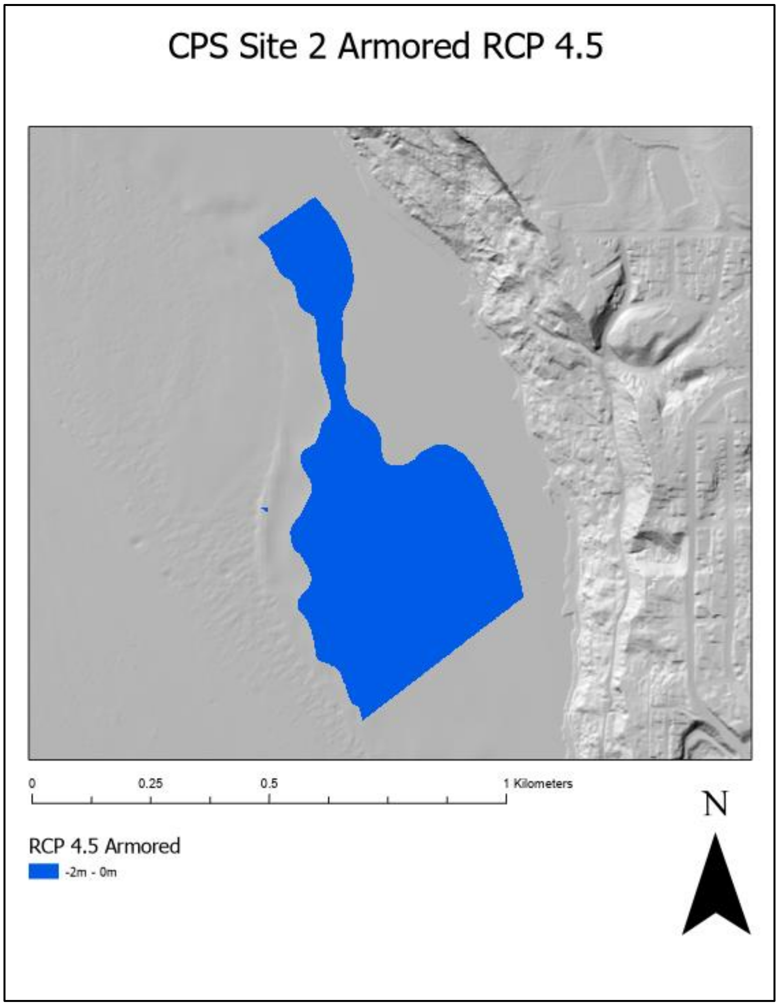
Appendix A 20. CPS unarmored site 2 projected habitat area for RCP 8.5



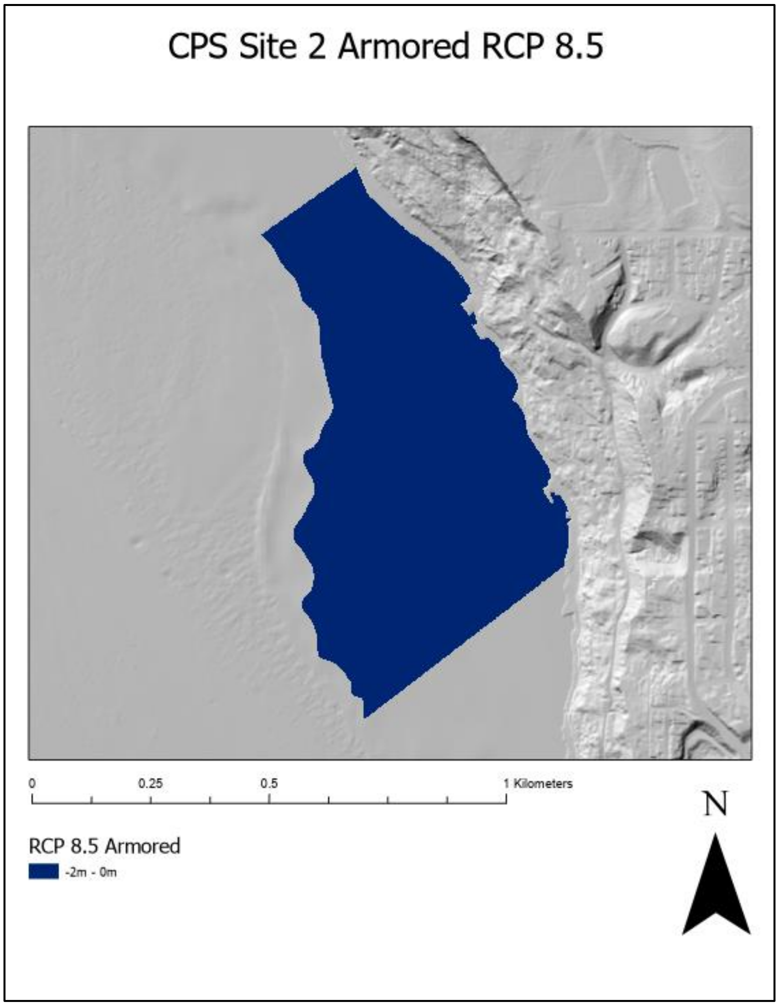
Appendix A 21. CPS unarmored site 2 projected habitat area for Initial (DEM date 2015).



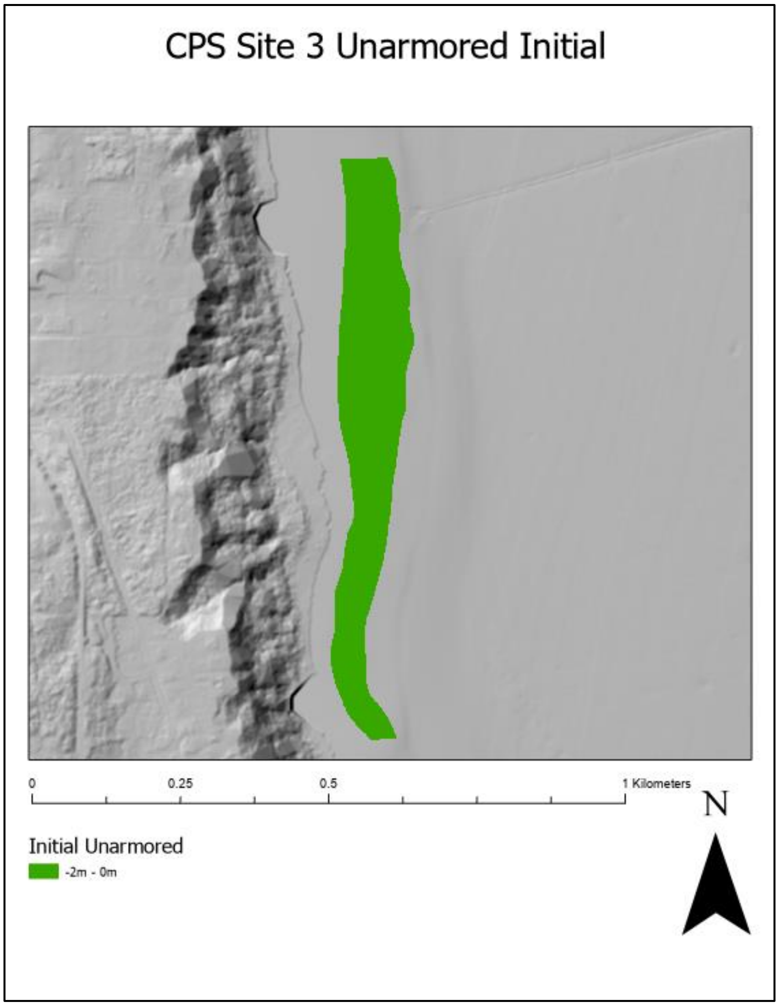
Appendix A 22. CPS armored site 2 projected habitat area for RCP 2.6.



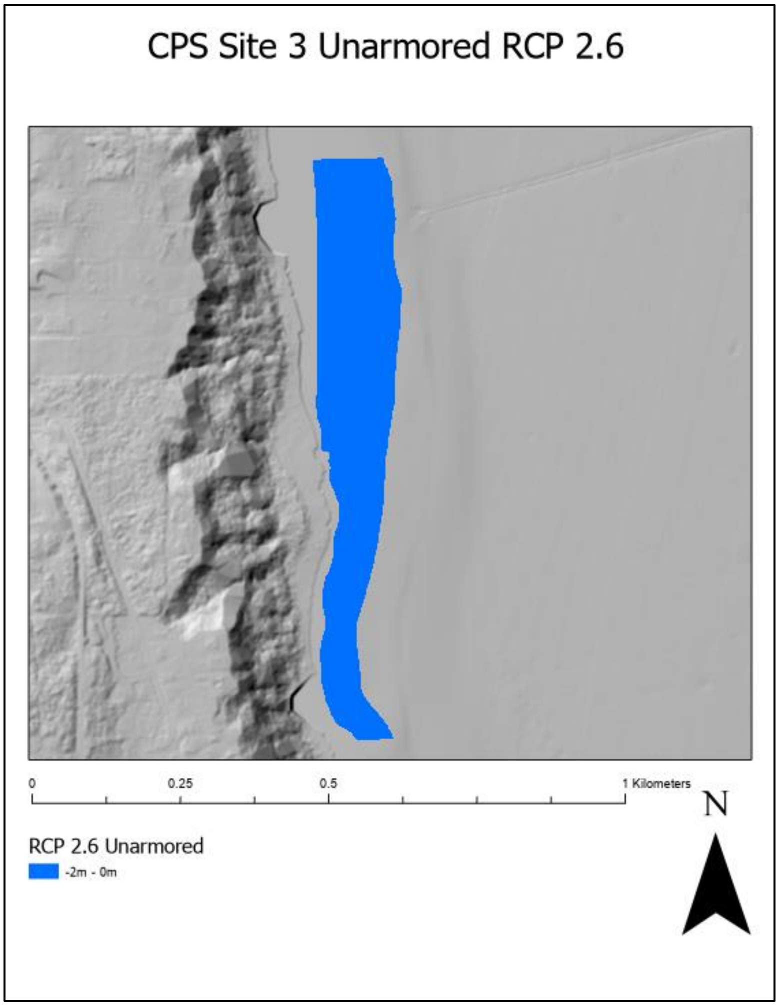
Appendix A 23. CPS armored site 2 projected habitat area for RCP 4.5



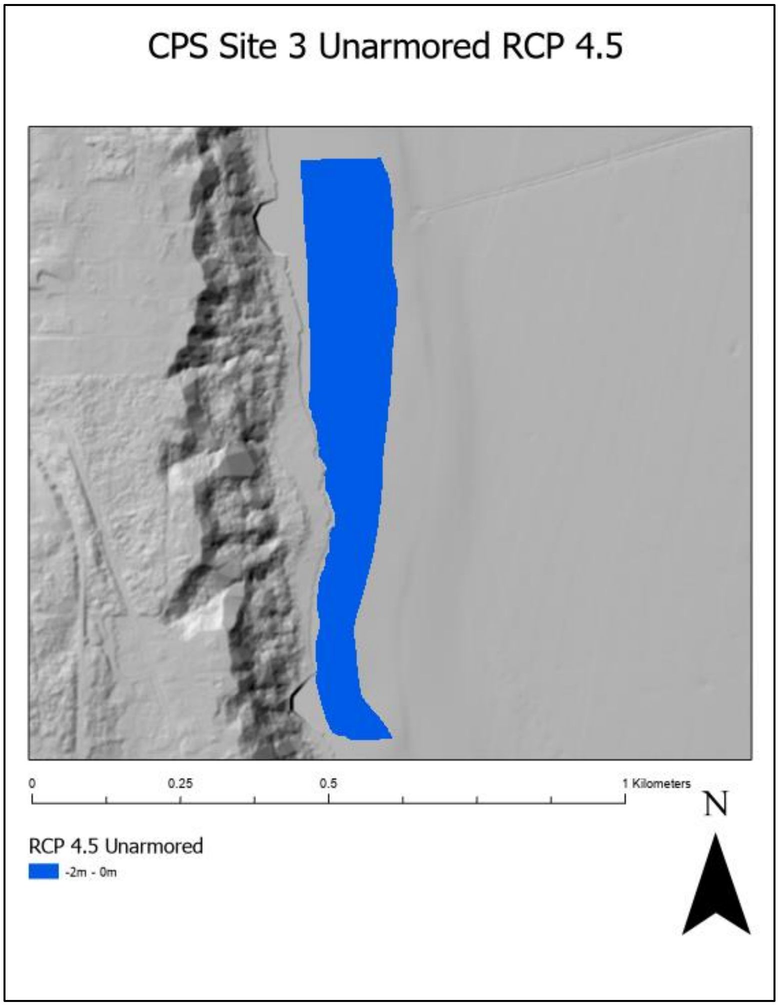
Appendix A 24. CPS armored site 2 projected habitat area for RCP 8.5



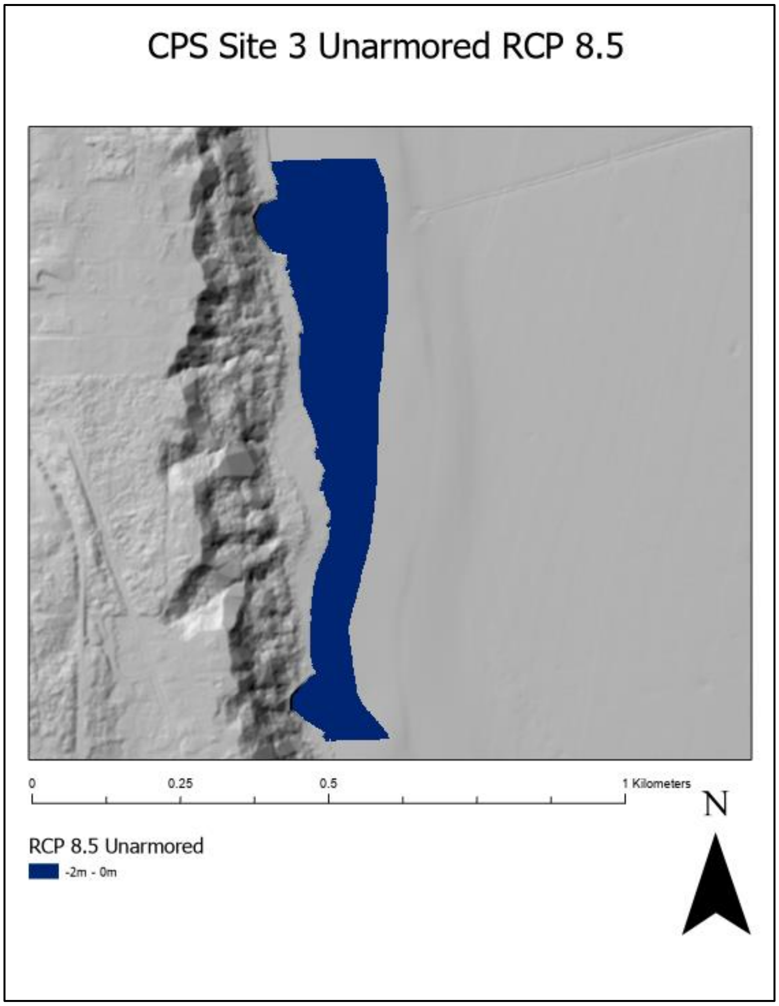
Appendix A 25. CPS unarmored site 3 projected habitat area for Initial (DEM date 2015).



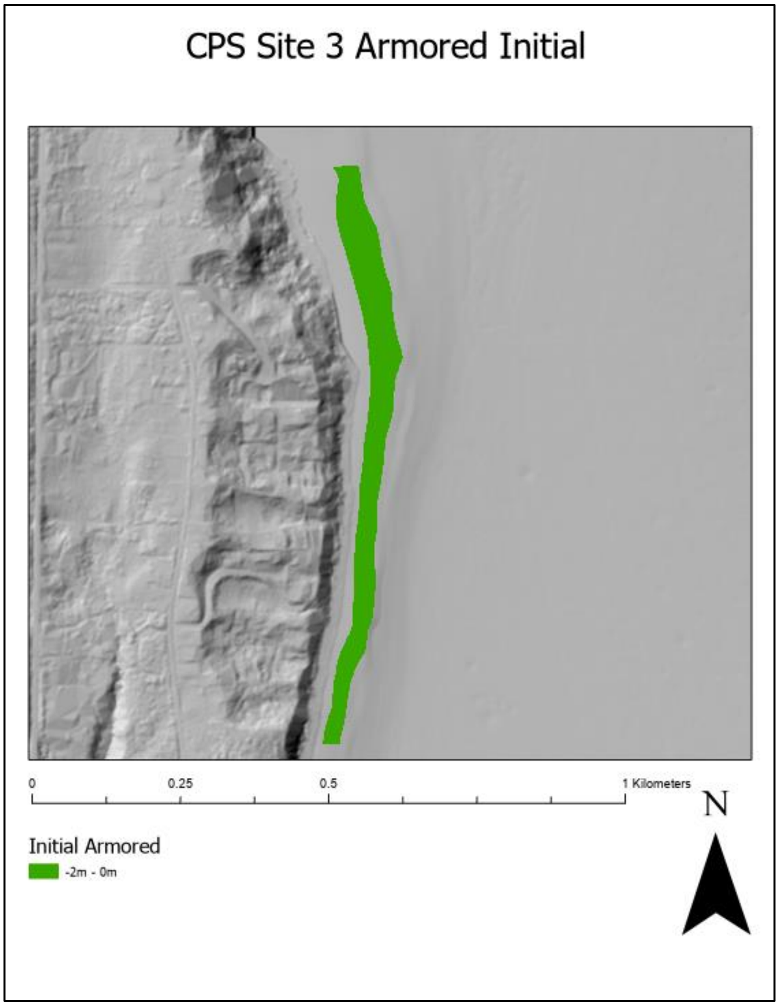
Appendix A 26. CPS unarmored site 3 projected habitat area for RCP 2.6.



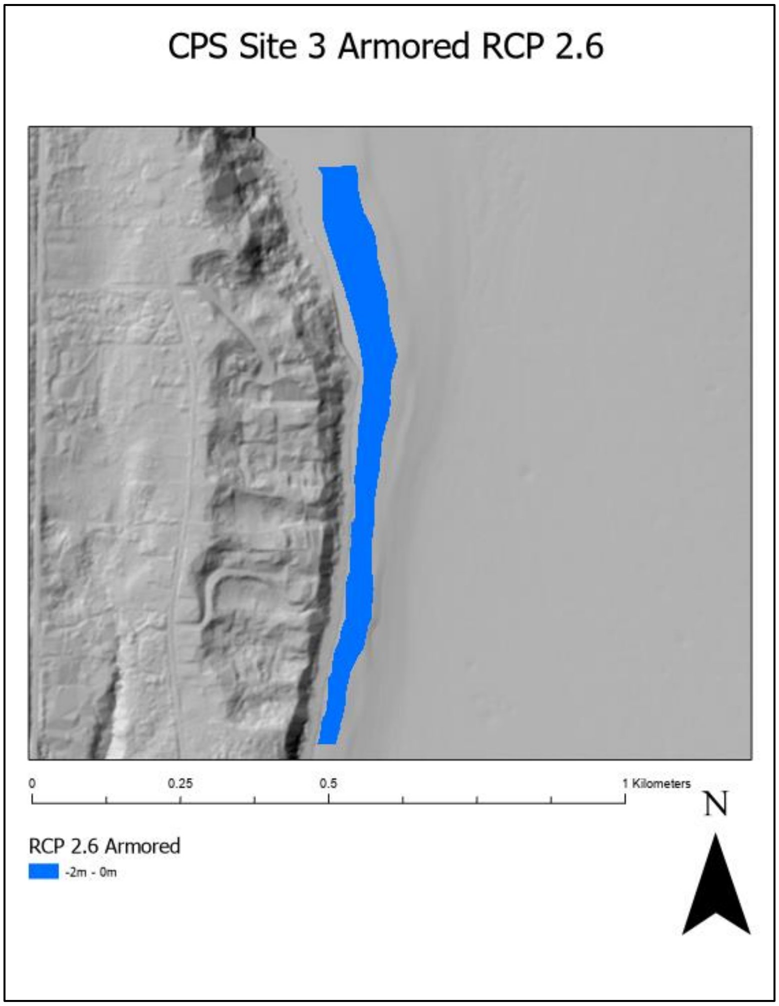
Appendix A 27. CPS unarmored site 3 projected habitat area for RCP 4.5.



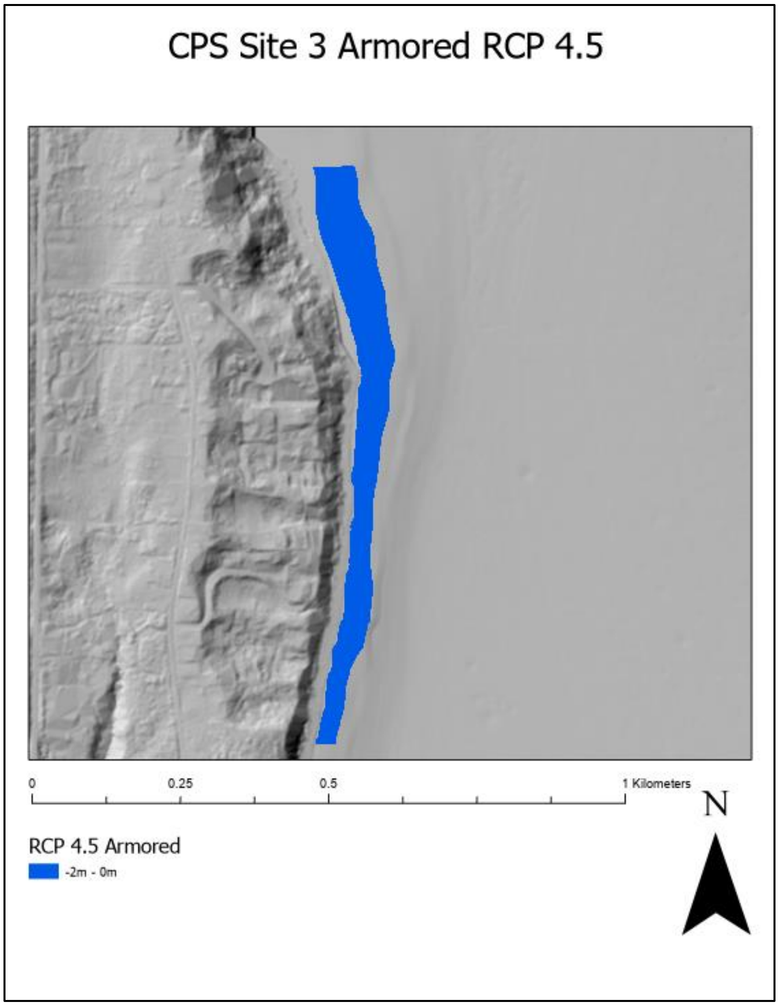
Appendix A 28. CPS unarmored site 3 projected habitat area for RCP 8.5.



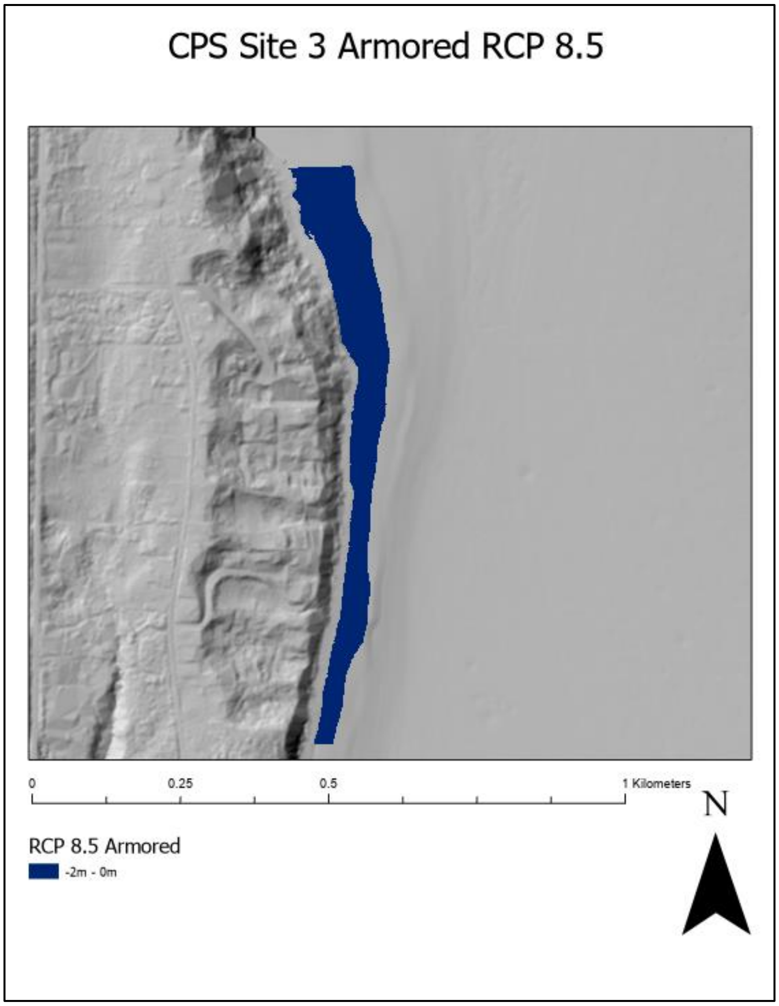
Appendix A 29. CPS armored site 3 projected habitat area for Initial (DEM date 2015).



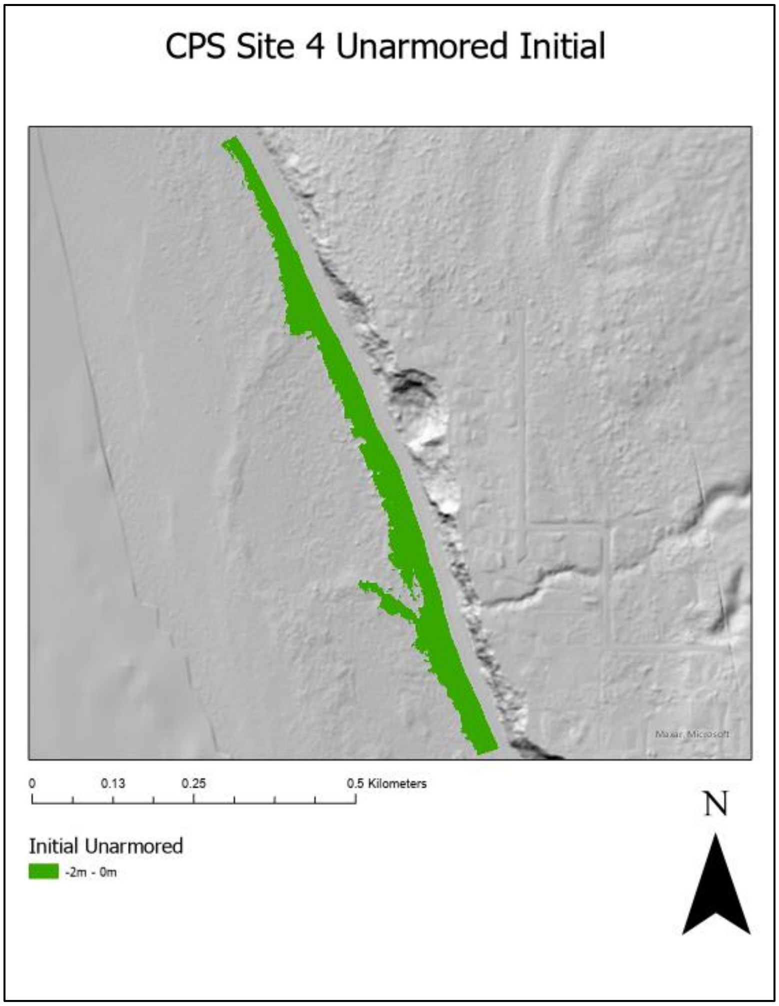
Appendix A 30. CPS armored site 3 projected habitat area for RCP 2.6.



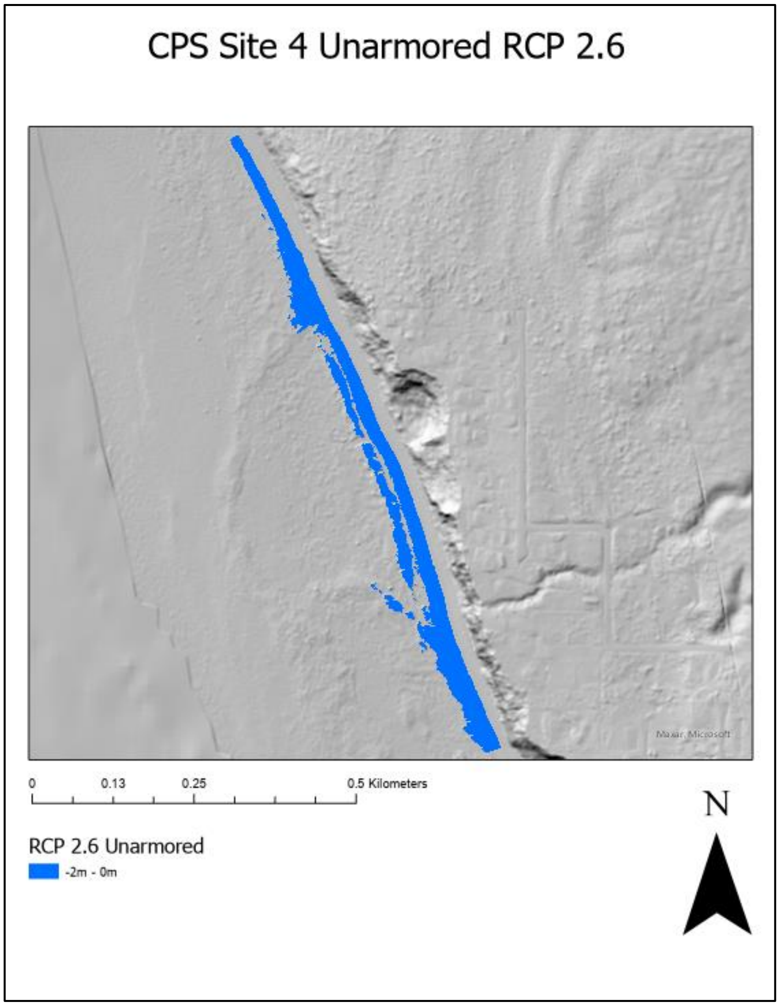
Appendix A 31. CPS armored site 3 projected habitat area for RCP 4.5



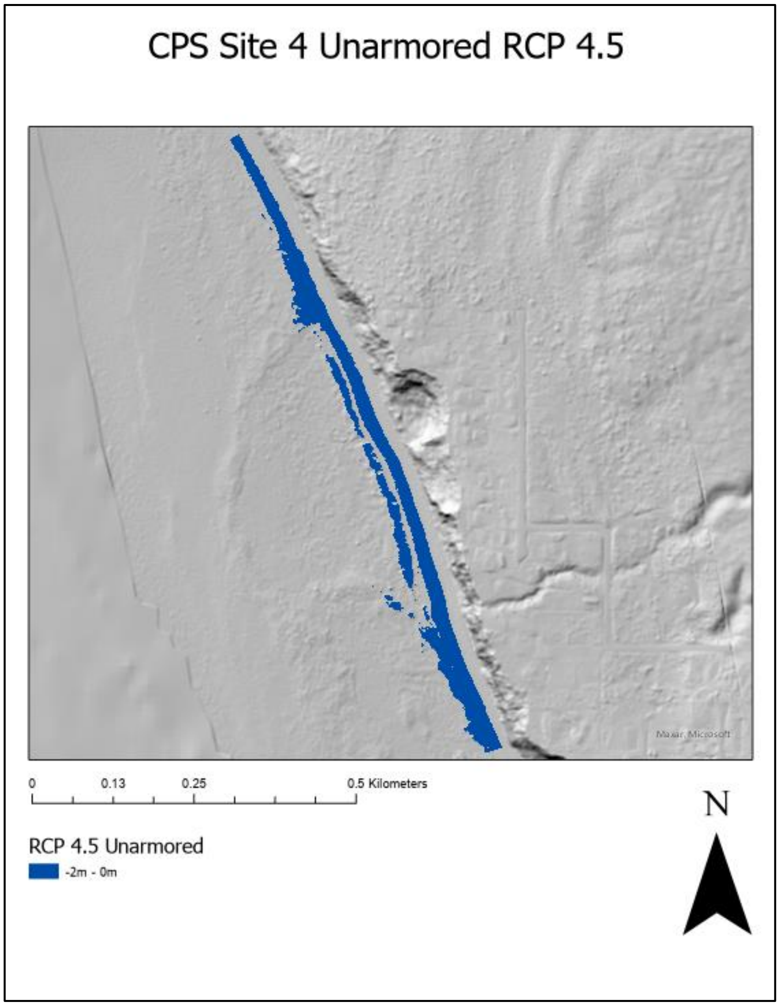
Appendix A 32. CPS armored site 3 projected habitat area for RCP 8.5



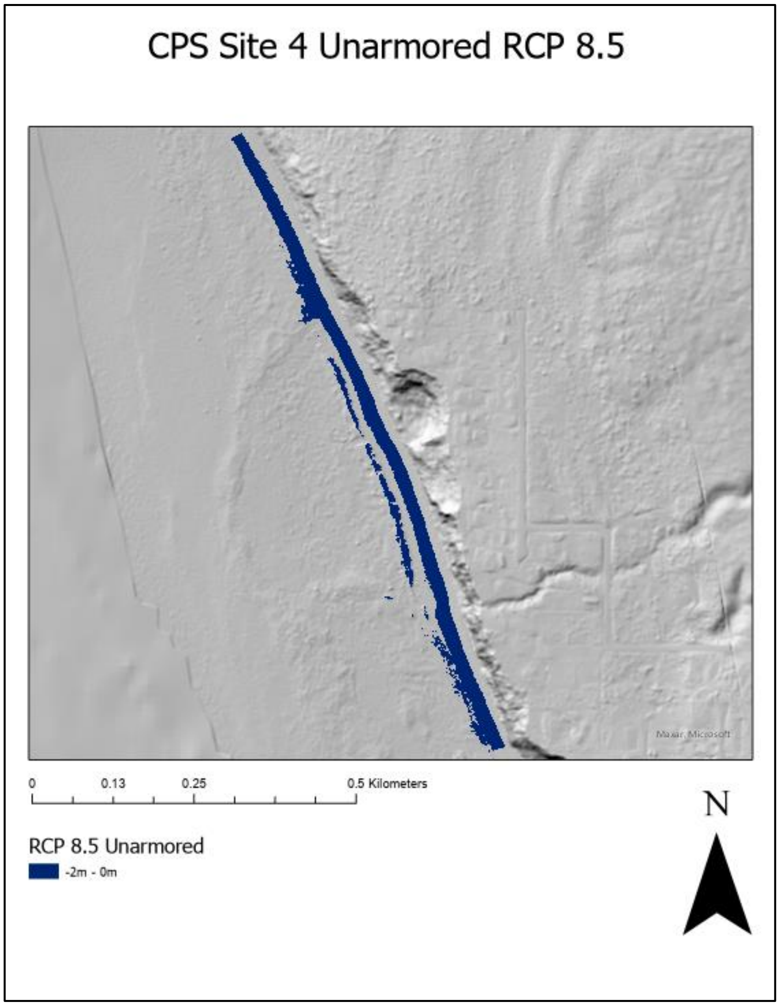
Appendix A 33. CPS unarmored site 4 projected habitat area for Initial (DEM date 2015).



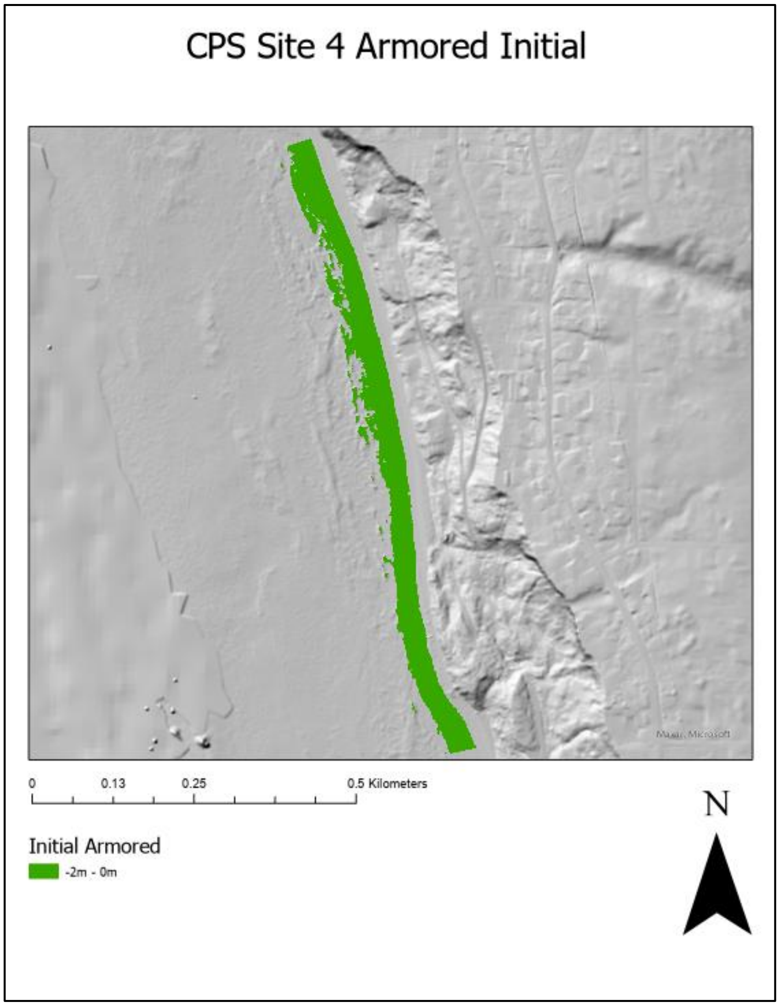
Appendix A 34. CPS unarmored site 4 projected habitat area for RCP 2.6.



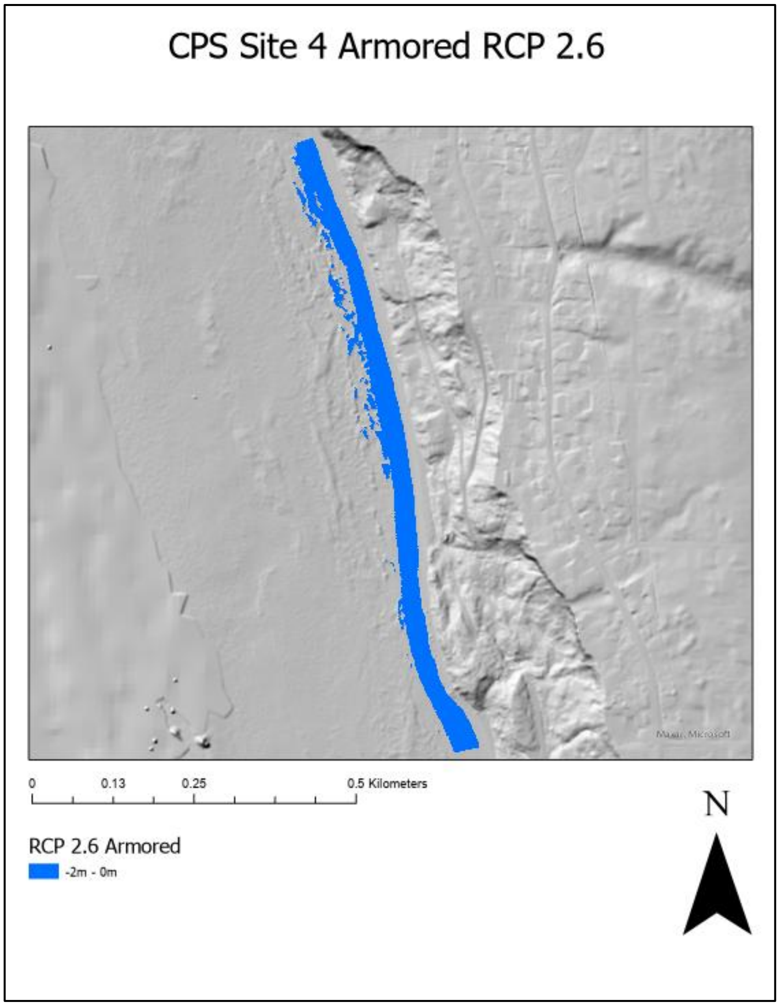
Appendix A 35. CPS unarmored site 4 projected habitat area for RCP 4.5



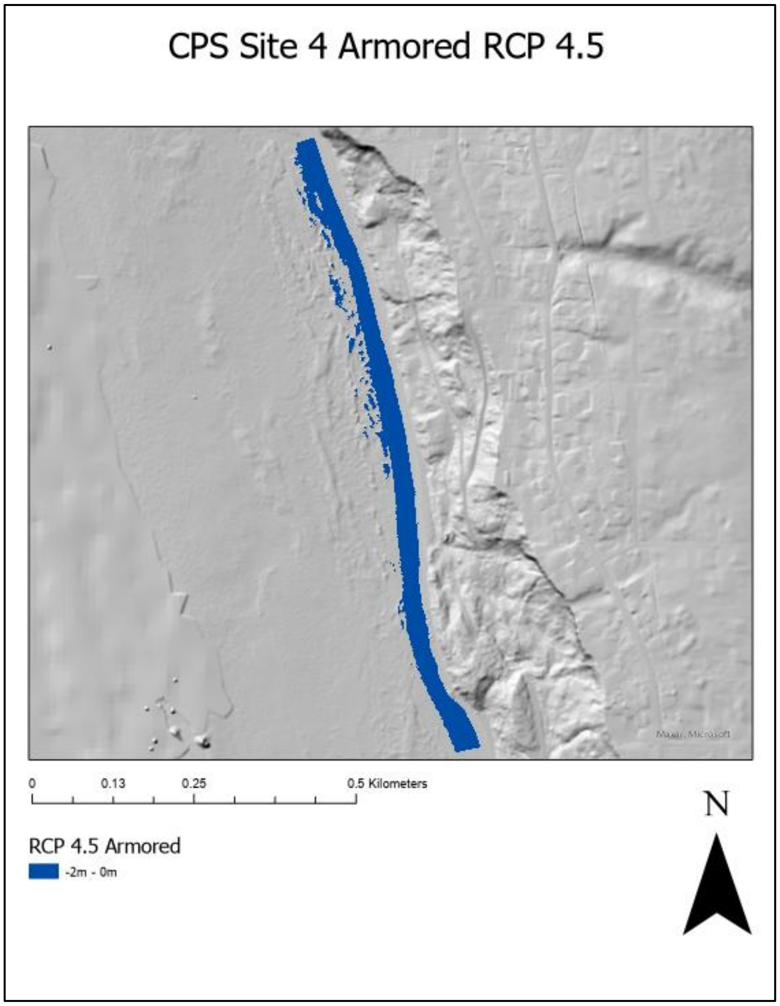
Appendix A 36. CPS unarmored site 4 projected habitat area for RCP 8.5



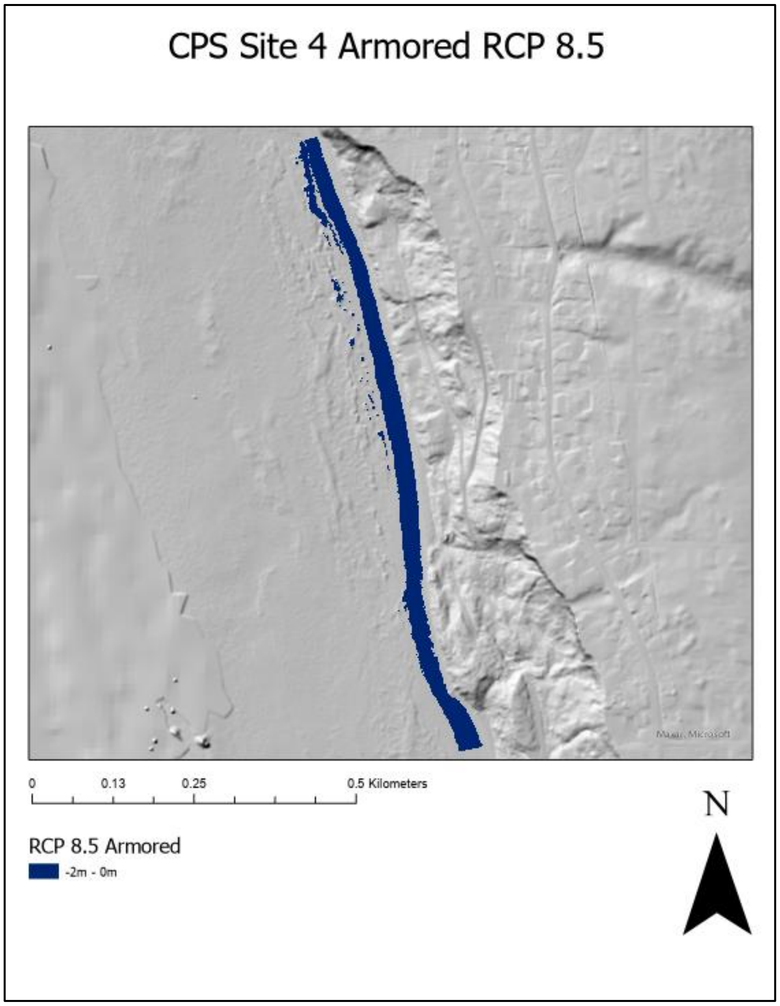
Appendix A 37. CPS armored site 4 projected habitat area for Initial (DEM date 2015).



Appendix A 38. CPS armored site 4 projected habitat area for RCP 2.6.



Appendix A 39. CPS armored site 4 projected habitat area for RCP 4.5



Appendix A 40. CPS armored site 4 projected habitat area for RCP 8.5

Appendix B.

SLAMM Analysis Results

Central Puget Sound Site 1 SLAMM Projections of Wetland Habitat Change by 2100									
Scenario by 2100	Initial	1 meter	1 meter	RCP2.6	RCP2.6	RCP4.5	RCP4.5	RCP8.5	RCP8.5
Raster 1 Unarmored	Initial Hectares	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change
Developed Dry Land	2.760	-0.062	-0.023	0.000	0.000	0.000	0.000	-0.022	-0.008
Swamp	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Regularly-Flooded Marsh	0.000	0.006	NA	0.000	NA	0.000	NA	0.003	NA
Estuarine Beach	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Tidal Flat	7.095	-4.982	-0.702	-4.982	-0.702	-4.990	-0.703	-4.982	-0.702
Estuarine Open Water	10.318	4.983	0.483	4.982	0.483	4.990	0.484	4.982	0.483
Aggregated Non Tidal	2.760	-0.062	-0.023	0.000	0.000	0.000	0.000	-0.022	-0.008
Open Water	10.352	4.982	0.481	4.982	0.481	4.990	0.482	4.982	0.481
Low Tidal	7.095	-4.982	-0.702	-4.982	-0.702	-4.990	-0.703	-4.982	-0.702
Saltmarsh	0.000	0.006	NA	0.000	NA	0.000	NA	0.003	NA

Appendix B 1. CPS Unarmored Site 1 SLAMM Projections of Wetland Habitat Change by 2100. Percent Change represented in decimal format. "PCT change" = Percent Habitat Change. "NA" = Not Applicable.

CPS 1	Initial	1 meter	1 meter	RCP2.6	RCP2.6	RCP4.5	RCP4.5	RCP8.5	RCP8.5
Raster 2 Armored	Initial Hectares	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change
Developed Dry Land	2.257	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Swamp	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Regularly-Flooded Marsh	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Estuarine Beach	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Tidal Flat	6.080	-4.472	-0.736	-4.472	-0.736	-4.776	-0.786	-4.614	-0.759
Estuarine Open Water	8.374	4.472	0.534	4.472	0.534	4.776	0.570	4.614	0.551
Aggregated Non Tidal	2.257	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Open Water	8.392	4.472	0.533	4.472	0.533	4.776	0.569	4.614	0.550
Low Tidal	6.080	-4.472	-0.736	-4.472	-0.736	-4.776	-0.786	-4.614	-0.759
Saltmarsh	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA

Appendix B 2. CPS Armored Site 1 SLAMM Projections of Wetland Habitat Change by 2100. Percent Change represented in decimal format. "PCT change" = Percent Habitat Change. "NA" = Not Applicable.

Central Puget Sound Site 2 SLAMM Projections of Wetland Habitat Change by 2100									
Scenario by 2100	Initial	1 meter	1 meter	RCP2.6	RCP2.6	RCP4.5	RCP4.5	RCP8.5	RCP8.5
Raster 1 Unarmored	Initial Hectares	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change
Developed Dry Land	0.262	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Swamp	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Regularly-Flooded Marsh	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Estuarine Beach	1.050	-1.050	-1.000	-1.050	-1.000	-1.050	-1.000	-1.050	-1.000
Tidal Flat	14.592	-14.592	-1.000	-14.592	-1.000	-14.592	-1.000	-14.592	-1.000
Estuarine Open Water	56.685	15.642	0.276	15.642	0.276	15.642	0.276	15.642	0.276
Aggregated Non Tidal	0.262	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Open Water	56.685	15.642	0.276	15.642	0.276	15.642	0.276	15.642	0.276
Low Tidal	15.643	-15.642	-1.000	-15.642	-1.000	-15.642	-1.000	-15.642	-1.000
Saltmarsh	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA

Appendix B 3. CPS Unarmored Site 2 SLAMM Projections of Wetland Habitat Change by 2100. Percent Change represented in decimal format. "PCT change" = Percent Habitat Change. "NA" = Not Applicable.

CPS 2	Initial	1 meter	1 meter	RCP2.6	RCP2.6	RCP4.5	RCP4.5	RCP8.5	RCP8.5
Raster 2 Armored	**Initial Hectares**	**Hectares Loss/Gain**	**PCT change**	**Hectares Loss/Gain**	**PCT change**	**Hectares Loss/Gain**	**PCT change**	**Hectares Loss/Gain**	**PCT change**
Developed Dry Land	0.430	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Swamp	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Regularly-Flooded Marsh	3.461	-3.461	-1.000	-3.461	-1.000	-3.461	-1.000	-3.461	-1.000
Estuarine Beach	0.572	-0.572	-1.000	-0.572	-1.000	-0.572	-1.000	-0.572	-1.000
Tidal Flat	4.484	-4.484	-1.000	-4.484	-1.000	-4.484	-1.000	-4.484	-1.000
Estuarine Open Water	78.448	8.517	0.109	8.517	0.109	8.517	0.109	8.517	0.109
Aggregated Non Tidal	0.430	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Open Water	78.448	8.517	0.109	8.517	0.109	8.517	0.109	8.517	0.109
Low Tidal	5.070	-5.056	-0.997	-5.056	-0.997	-5.056	-0.997	-5.056	-0.997
Saltmarsh	3.461	-3.461	-1.000	-3.461	-1.000	-3.461	-1.000	-3.461	-1.000

Appendix B 4. CPS Armored Site 2 SLAMM Projections of Wetland Habitat Change by 2100. Percent Change represented in decimal format. "PCT change" = Percent Habitat Change. "NA" = Not Applicable.

Central Puget Sound Site 3 SLAMM Projections of Wetland Habitat Change by 2100									
Scenario by 2100	Initial	1 meter	1 meter	RCP2.6	RCP2.6	RCP4.5	RCP4.5	RCP8.5	RCP8.5
Raster 2 Unarmored	Initial Hectares	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change
Developed Dry Land	0.036	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Swamp	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Regularly-Flooded Marsh	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Estuarine Beach	11.796	-1.167	-0.099	-1.167	-0.099	-1.167	-0.099	-1.167	-0.099
Tidal Flat	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Estuarine Open Water	13.754	1.167	0.085	1.167	0.085	1.167	0.085	1.167	0.085
Aggregated Non Tidal	0.036	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Open Water	13.754	1.167	0.085	1.167	0.085	1.167	0.085	1.167	0.085
Low Tidal	11.796	-1.167	-0.099	-1.167	-0.099	-1.167	-0.099	-1.167	-0.099
Saltmarsh	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA

Appendix B 5. CPS Unarmored Site 3 SLAMM Projections of Wetland Habitat Change by 2100. Percent Change represented in decimal format. "PCT change" = Percent Habitat Change. "NA" = Not Applicable.

CPS 3	Initial	1 meter	1 meter	RCP2.6	RCP2.6	RCP4.5	RCP4.5	RCP8.5	RCP8.5
Raster 1 Armored	Initial Hectares	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change	Hectares Loss/Gain	PCT change
Developed Dry Land	0.024	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Swamp	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Regularly-Flooded Marsh	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Estuarine Beach	4.521	-1.182	-0.261	-1.157	-0.256	-1.158	-0.256	-1.168	-0.258
Tidal Flat	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA
Estuarine Open Water	7.811	1.182	0.151	1.157	0.148	1.158	0.148	1.168	0.149
Aggregated Non Tidal	0.024	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Open Water	7.811	1.182	0.151	1.157	0.148	1.158	0.148	1.168	0.149
Low Tidal	4.521	-1.182	-0.261	-1.157	-0.256	-1.158	-0.256	-1.168	-0.258
Saltmarsh	0.000	0.000	NA	0.000	NA	0.000	NA	0.000	NA

Appendix B 6. CPS Armored Site 3 SLAMM Projections of Wetland Habitat Change by 2100. Percent Change represented in decimal format. "PCT change" = Percent Habitat Change. "NA" = Not Applicable.